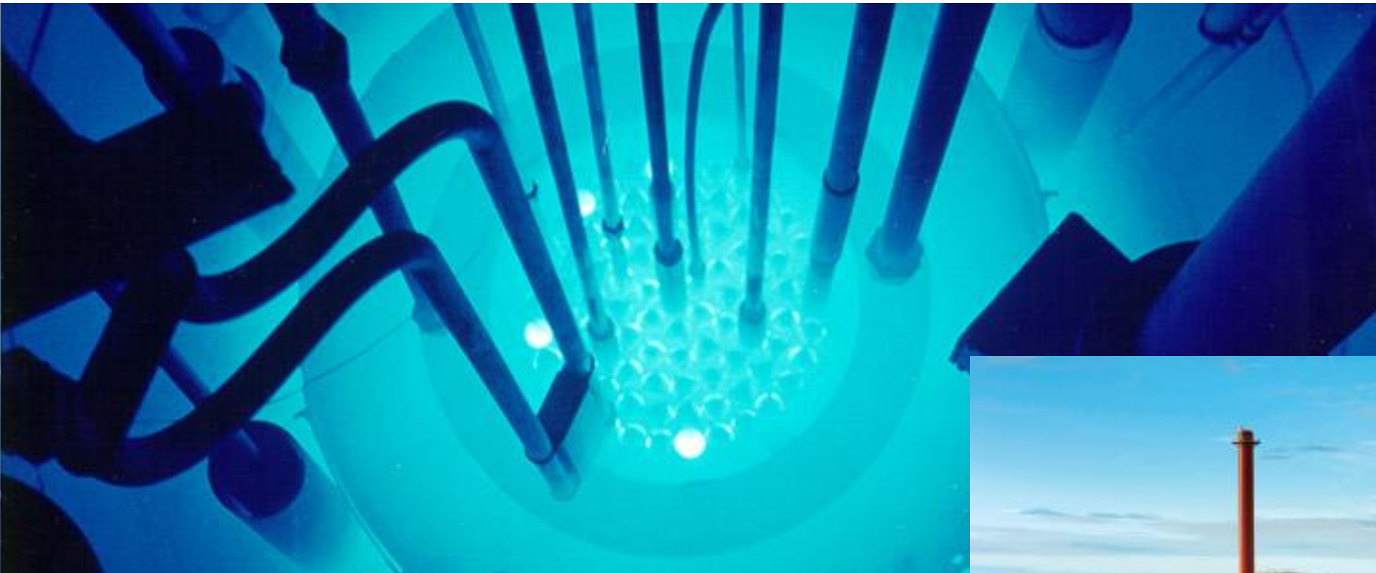
Energy from nuclear fission: basics



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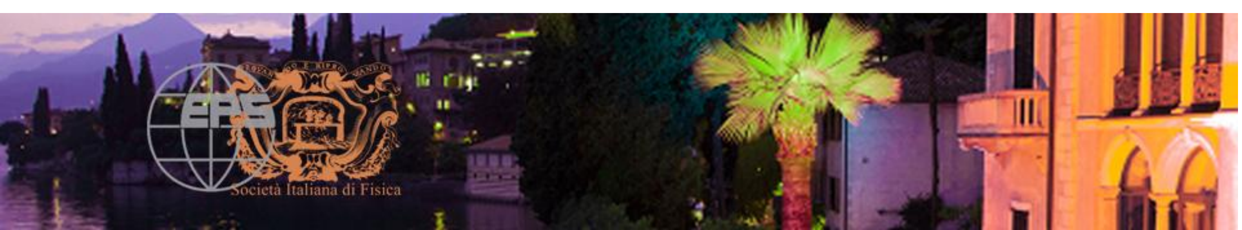
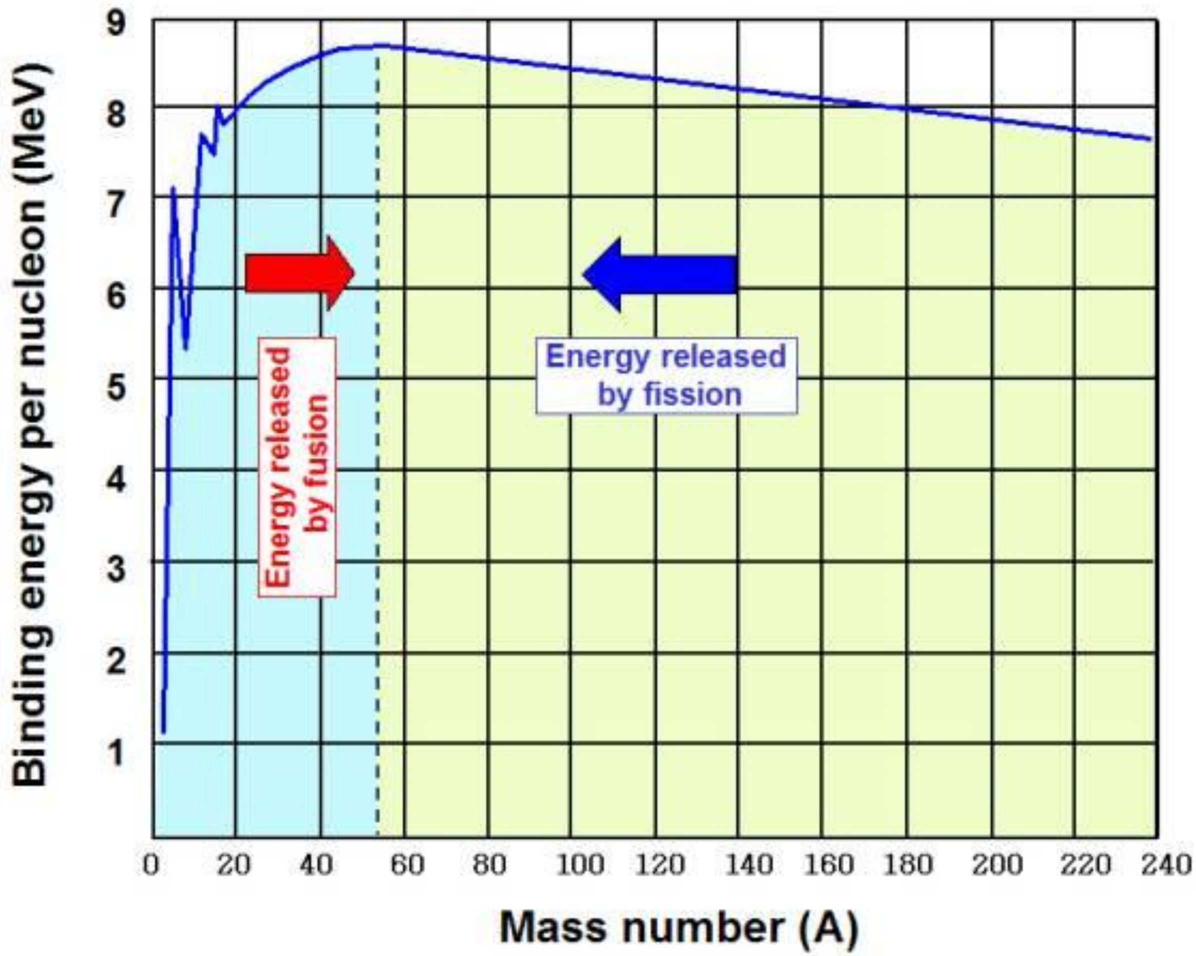


Why can fission produce energy ?

Nuclear mass and nuclear binding energy $M(Z,A) = ZM_p + (A - Z)M_n + B(Z,A)$

B(Z,A) < 0 !!! i.e. a nucleus weighs less than the sum of proton and neutron masses

$$\varepsilon \equiv \frac{|B(Z,A)|}{A}$$



How can fission produce energy ?

$M(Z,A) \rightarrow M(Z_1, A_1) + M(Z_2, A_2)$; $Z = Z_1 + Z_2$; $A = A_1 + A_2$

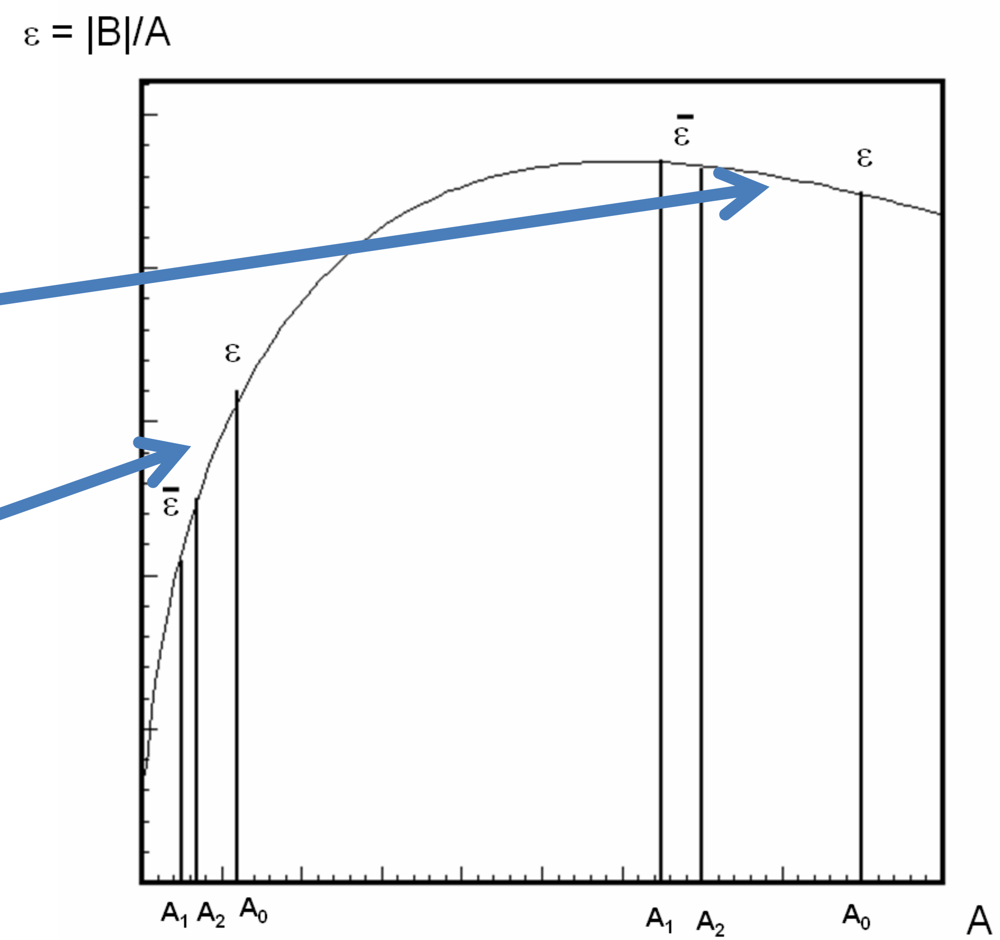
Energy balance (Q-value) $Q_{fiss} = M(Z,A) - M(Z_1,A_1) - M(Z_2,A_2)$

$$= B(Z,A) - B(Z_1,A_1) - B(Z_2,A_2) = -\varepsilon A + \varepsilon_1 A_1 + \varepsilon_2 A_2 = -\varepsilon A + \bar{\varepsilon} A = (\bar{\varepsilon} - \varepsilon) A$$

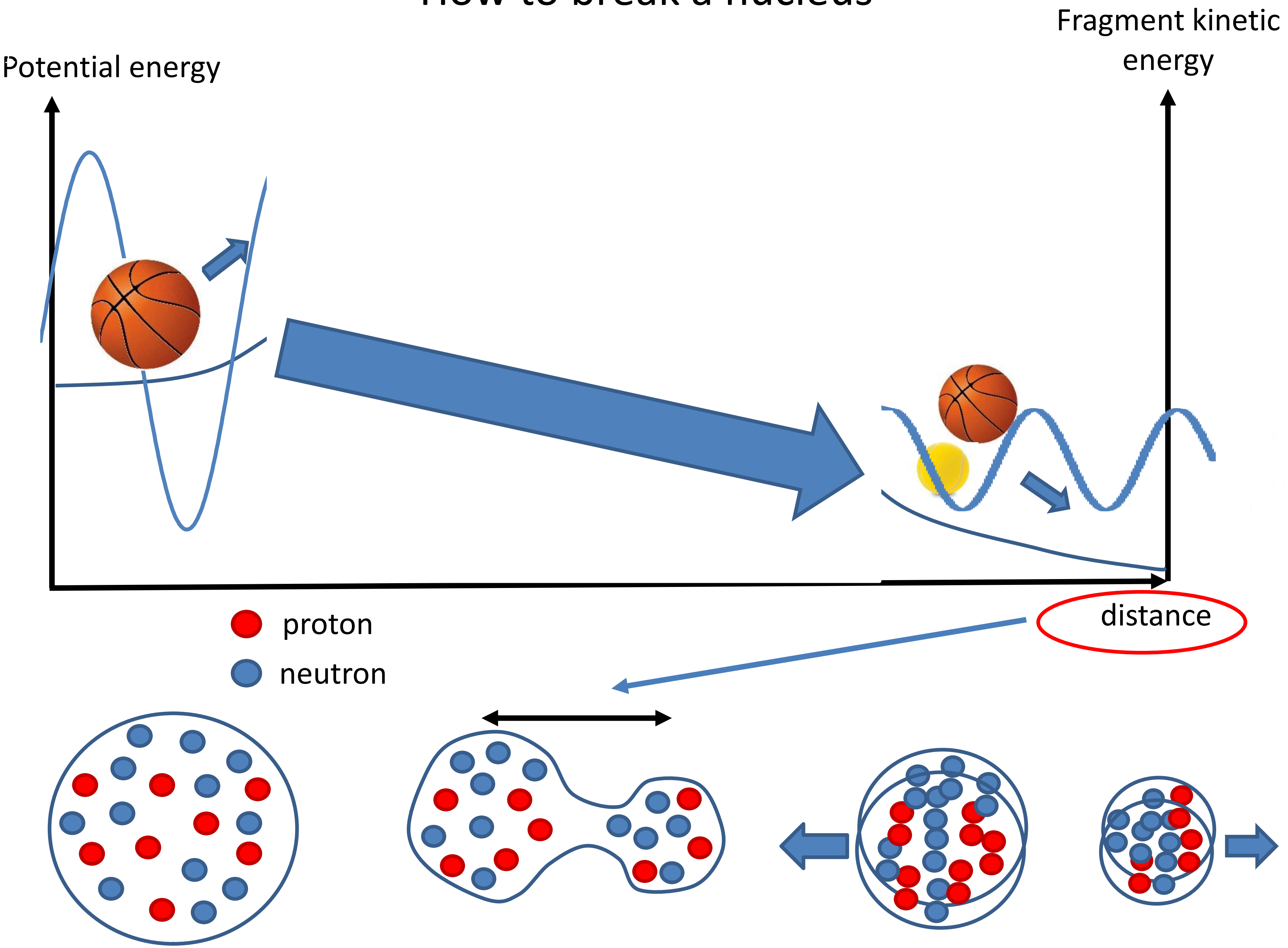
$$\bar{\varepsilon} = \frac{\varepsilon_1 A_1 + \varepsilon_2 A_2}{A_1 + A_2}$$

$Q_{fiss} > 0$

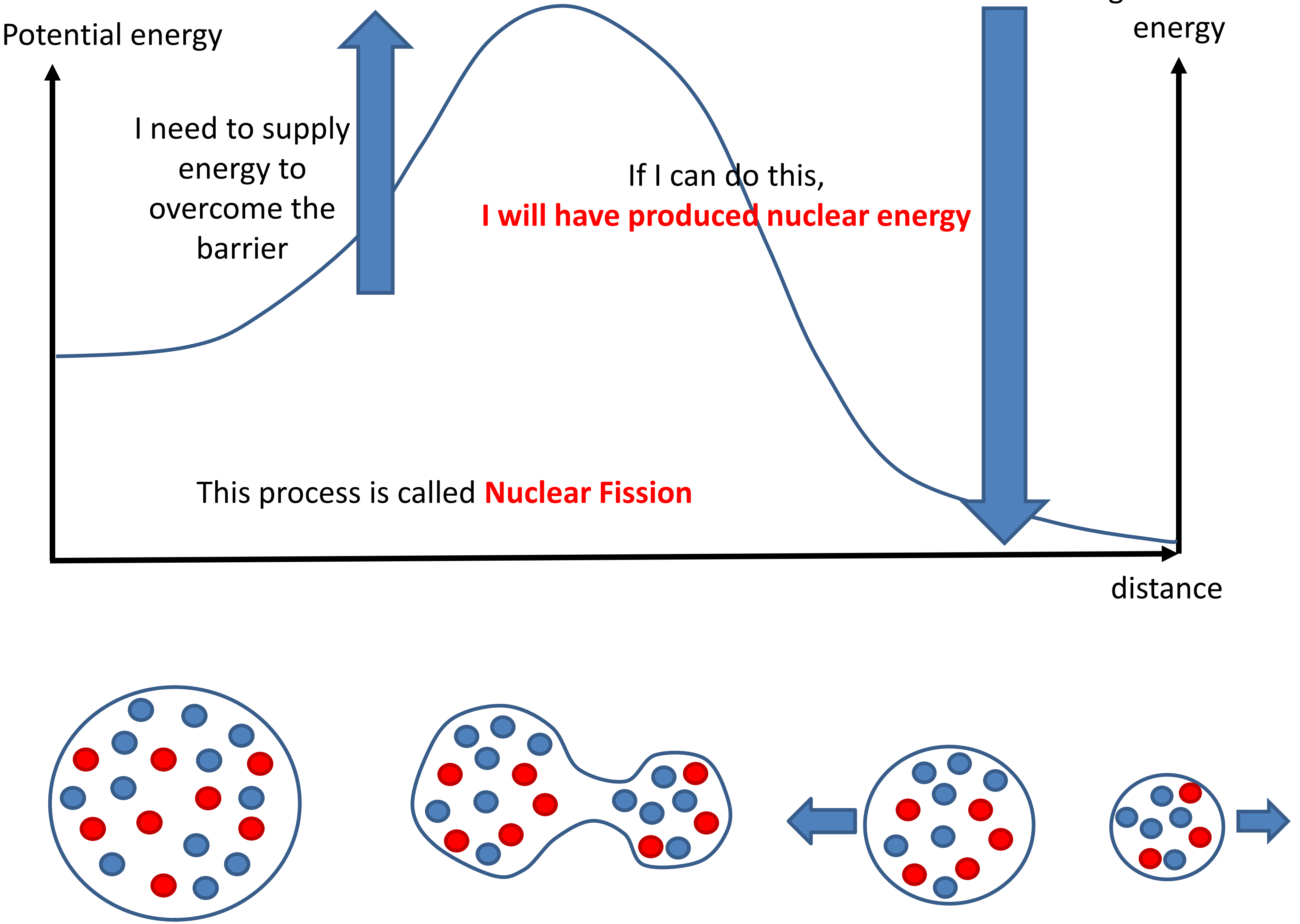
$Q_{fiss} < 0$



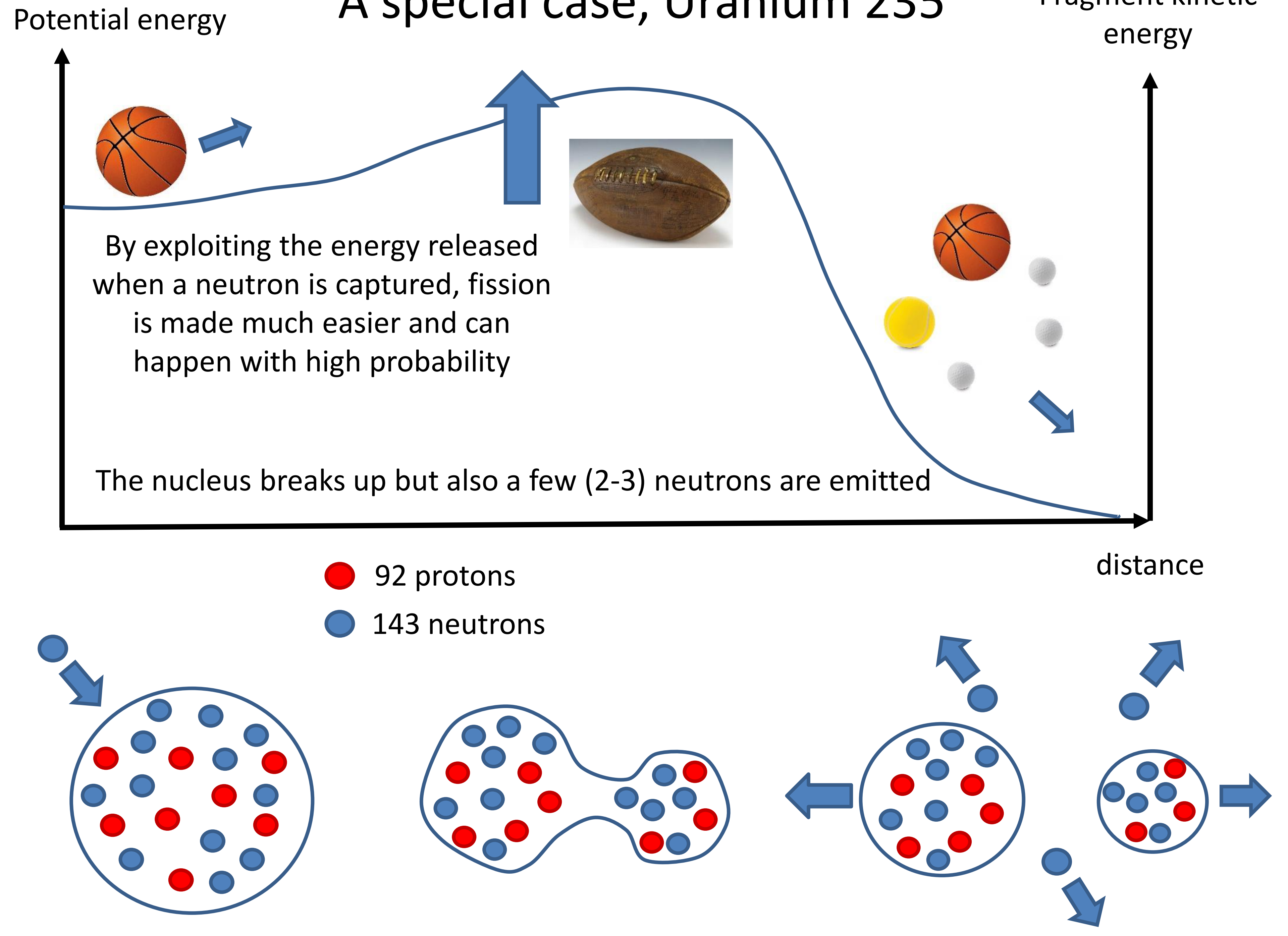
How to break a nucleus



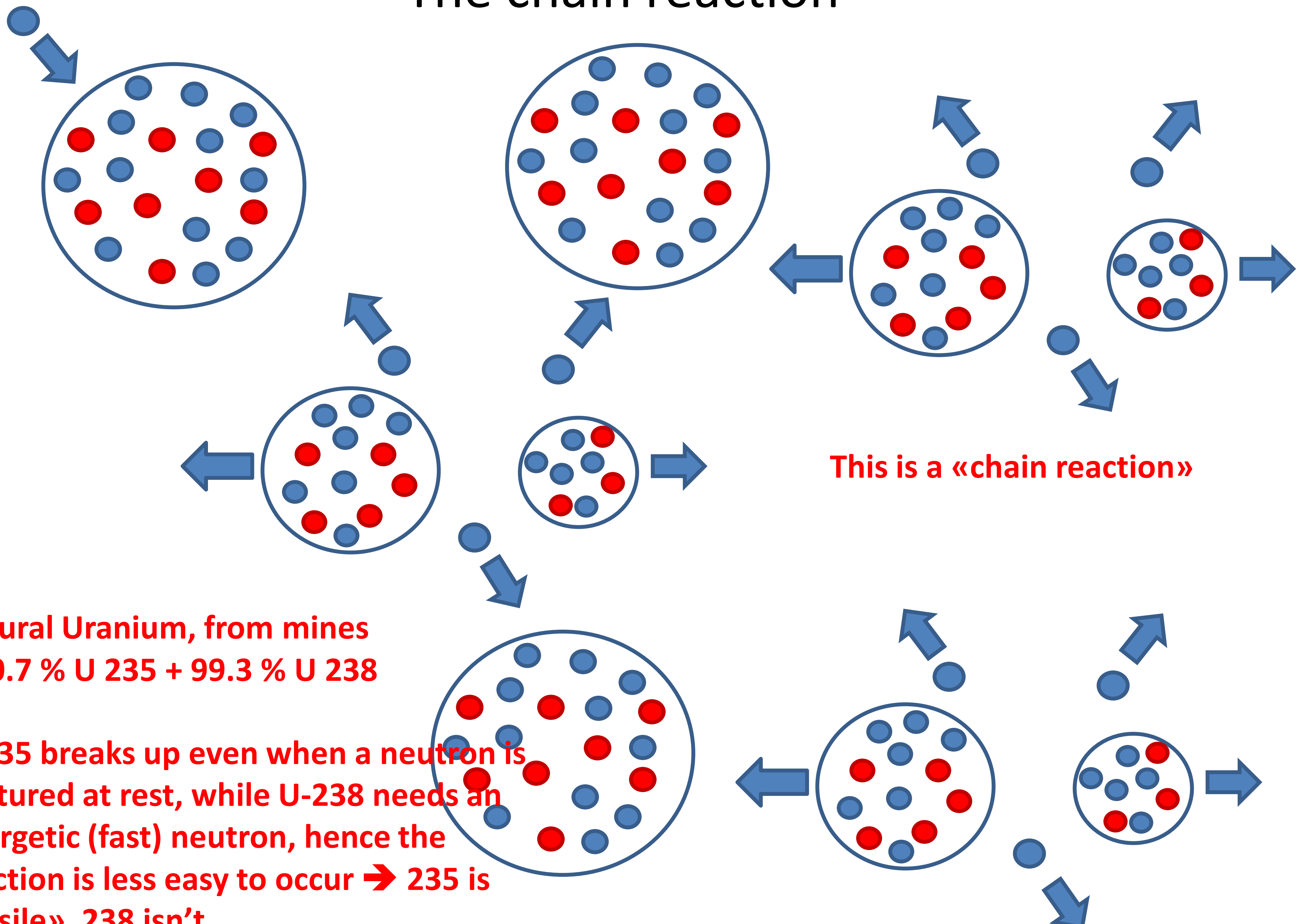
How to break a nucleus



A special case, Uranium 235



The chain reaction



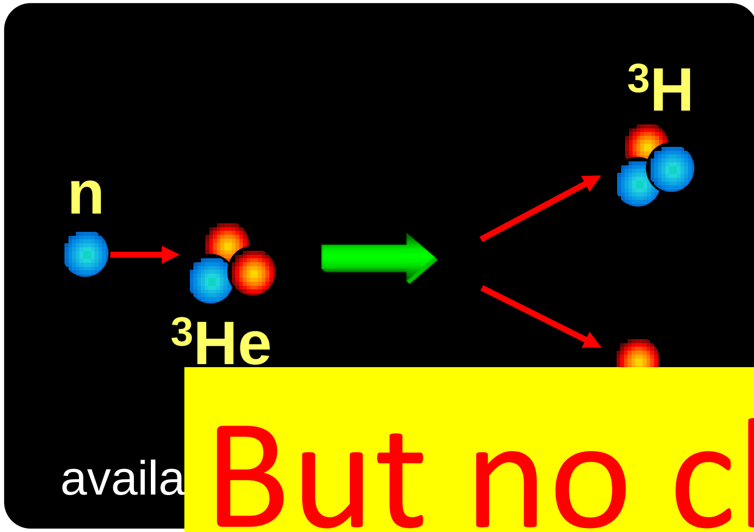
This is a «chain reaction»

Natural Uranium, from mines
→ 0.7 % U 235 + 99.3 % U 238

U-235 breaks up even when a neutron is captured at rest, while U-238 needs an energetic (fast) neutron, hence the reaction is less easy to occur → 235 is «fissile», 238 isn't

Fragments are moving → kinetic energy → transferred to atoms → heat

Other neutron absorption processes yielding energy



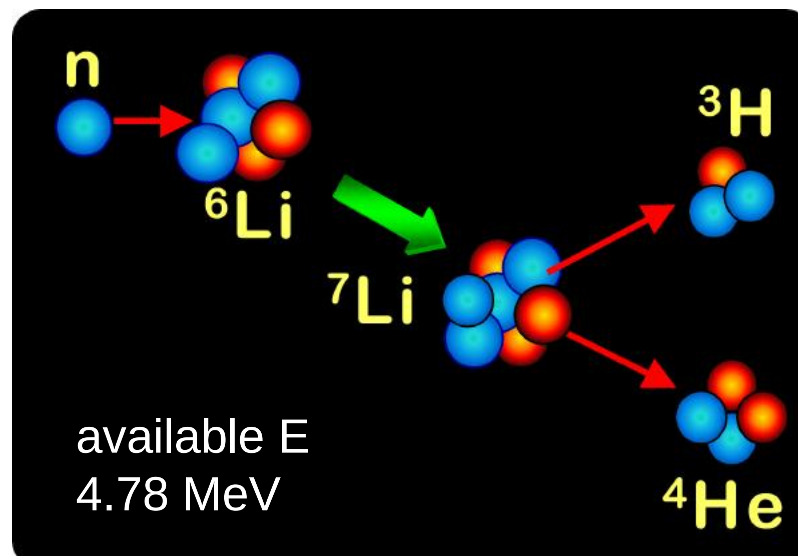
σ(thermal neutrons)
≈ 5330 b (barn, 1 b=10^{-24} cm^2, σ is proportional to the reaction probability, see later)

1 MeV= 1 MegaelectronVolt =
10^6 electronVolt = 10^6 x 1.6x10^{-19} Coulomb Volt =

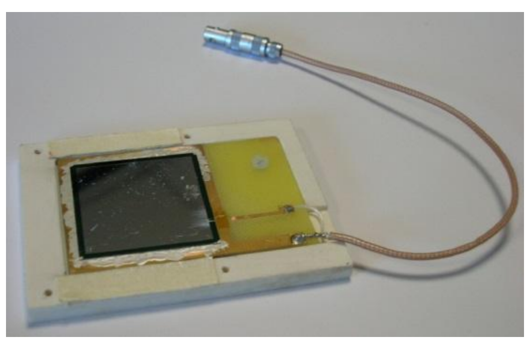
But no chain reaction

≈ 940 b

^{3}He neutron detector



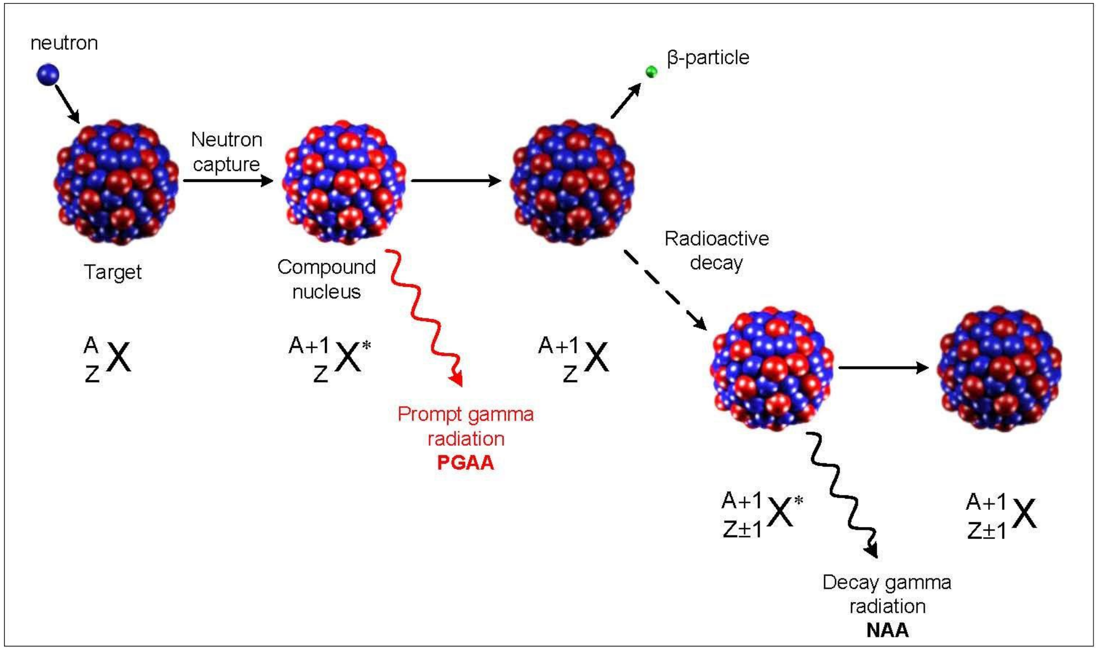
neutron detector based on a LiF film



Another very relevant reaction mechanism is **neutron capture**
→ for heavy nuclei, addition of one more neutron can provide several MeV from binding energy
→ capture is **followed by gamma emission** (radiative capture) or **fission**

By quantum mechanical arguments, it is possible to show that at low energies (if the energy gained from the neutron capture is sufficient to produce the phenomenon of interest)

→ **cross section follows a 1/v law, with v being the relative speed (essentially the n speed)**



Example: Plutonium production from Uranium

$n + {}^{238}U \rightarrow {}^{239}U + \gamma \rightarrow {}^{239}Np + \beta + \text{anti-}\nu \rightarrow {}^{239}\mathbf{Pu} + \beta + \text{anti-}\nu$

Amount of energy and reaction products

When a uranium nucleus fissions into two daughter nuclei fragments, about **0.1 % of uranium mass appears as fission energy of ~200 MeV ($E=Mc^2$)**
➔ **much bigger than any other exoenergetic nuclear reaction** (in absolute terms)

- ~**170 MeV** appears as the **kinetic energy of the daughter nuclei**,
-which fly apart at about 3% of the speed of light

- an **average of 2.5 prompt neutrons are emitted**, with a **mean kinetic energy per neutron of ~2 MeV** (total of 4.8 MeV)

- the **average number of neutrons emitted is called ν (order of 2-3)**

- **~25 MeV** are released in form of **prompt gamma ray photons and fission product β decay**

Chemical reactions vs nuclear fission

$C + O_2 = CO_2 + Q$ *(Q = 3.6 eV),*

$CH_4 + 2O_2 = CO_2 + 2H_2O + Q$ *(Q = 9.22 eV),*

$^{235}U + n = F_1 + F_2 + \nu n + Q$ *($Q \sim 200$ MeV)*

→ *Fission gives between 20 and 50 million times more energy*

Physics: nuclear cross sections

Cross section: quantity that characterizes a nuclear reaction (elastic, inelastic scattering, etc.) connected to the range of the involved forces; **effective area of a nuclear target**

Here we will consider the **total cross section**, defined as follows:

Given a **flux** $\dfrac{dN_{in}}{dSdt}$

number of incident particles per unit surface and unit time on a single nucleus (target)

and given an **interaction rate** $\dfrac{dN_{reac}}{dt}$

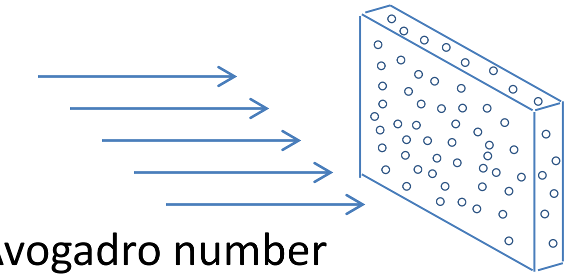
number of interacting particles (scattered or absorbed projectiles) per unit time, then

$$\sigma = \frac{\dfrac{dN_{reac}}{dt}}{\dfrac{dN_{in}}{dSdt}}$$

σ → physical dimensions of a surface

Nuclear cross sections

Macroscopic target comprising several nuclei with **density ρ (es. gr/cm3) and thickness x**, struck by a particle beam of intensity I (particles/sec) →



$$R = \frac{dN_{reac}}{dt} = I\,\frac{\rho\, x}{A} N_A \sigma$$

where A is the target atomic weight (es. in gr.) e N_A is the Avogadro number

$\frac{\rho}{A} N_A$ is the **number density of nuclei** in the target (i.e. number of nuclei per unit volume)

This is all valid for a small thickness x

For a target of arbitrary thickness, first divide it in thin slices of thickness dx →

$$dR = \frac{dN_{reac}}{dt} = I(x)\frac{\rho}{A} N_A \sigma\, dx$$

$$dI = -I(x)\frac{\rho}{A} N_A \sigma\, dx$$

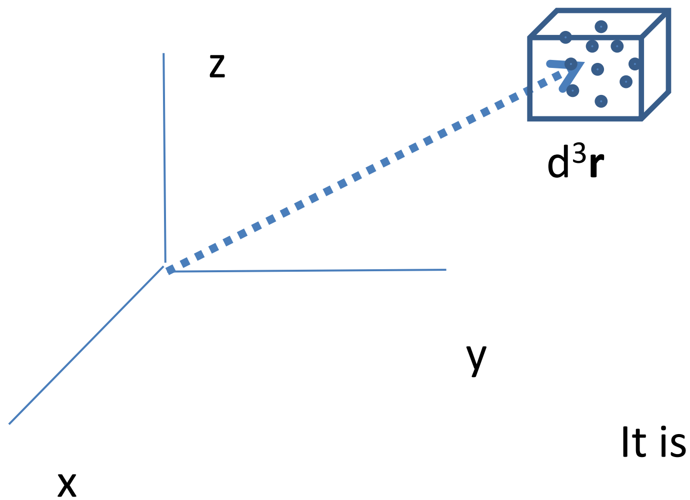
$$I(x) = I(0)\exp(-\frac{\rho}{A} N_A \sigma\, x)$$

➡ $\Sigma \equiv \frac{\rho}{A} N_A \sigma$ **Macroscopic cross section = prob.ty of interaction per unit length**

$1/\Sigma$ **= Mean free path** $\Sigma\, \mathrm{v} =$ **Frequency with which reactions occur, v= projectile speed**

Neutron density and flux

Neutron density ≡ $n(\mathbf{r},E,t)$ [cm^{-3}] ≡
expected number of neutrons with energy between E and E+dE, in the volume $d^3\mathbf{r}$ about $\mathbf{r}$, at a time t



Reaction density ≡ $R(\mathbf{r},E,t)$ ≡
Number of reactions in the volume $d^3\mathbf{r}$ about $\mathbf{r}$, at a time t, initiated by neutrons with energy between E and E+dE = $n(\mathbf{r},E,t)\,\Sigma v$

We give a special name to the quantity $n(\mathbf{r},E,t)v$
It is called the **neutron "flux" $\phi(r,E,t) \equiv n(r,E,t)v$ [$cm^{-2}\,s^{-1}$]**

Reaction density ≡ number of reactions per unit volume ≡ $R(r,E,t) = \Sigma\,\phi$

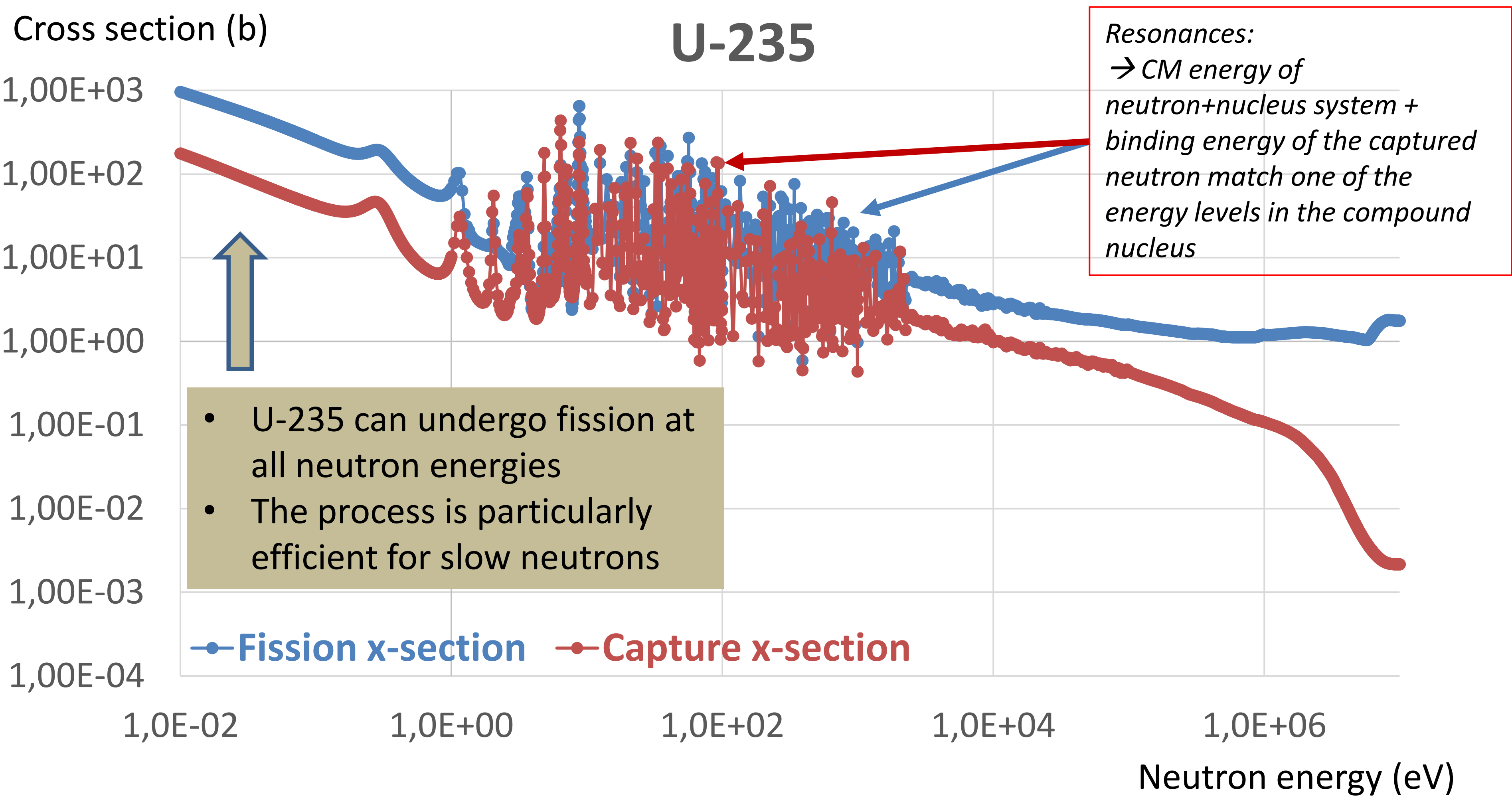
Suppose you've got a reactor with 1 GW thermal power = 10^9 Joule/sec
Assume each fission releases order of 200 MeV energy = 3.2×10^{-11} Joule
→ In the reactor the fission rate is about 3×10^{19} fissions/sec
→Almost 10^{20} neutrons/sec emitted, about 2×10^{20} neutrinos/sec
→ $\phi \sim 10^{14}$ neutrons $cm^{-2}\,s^{-1}$

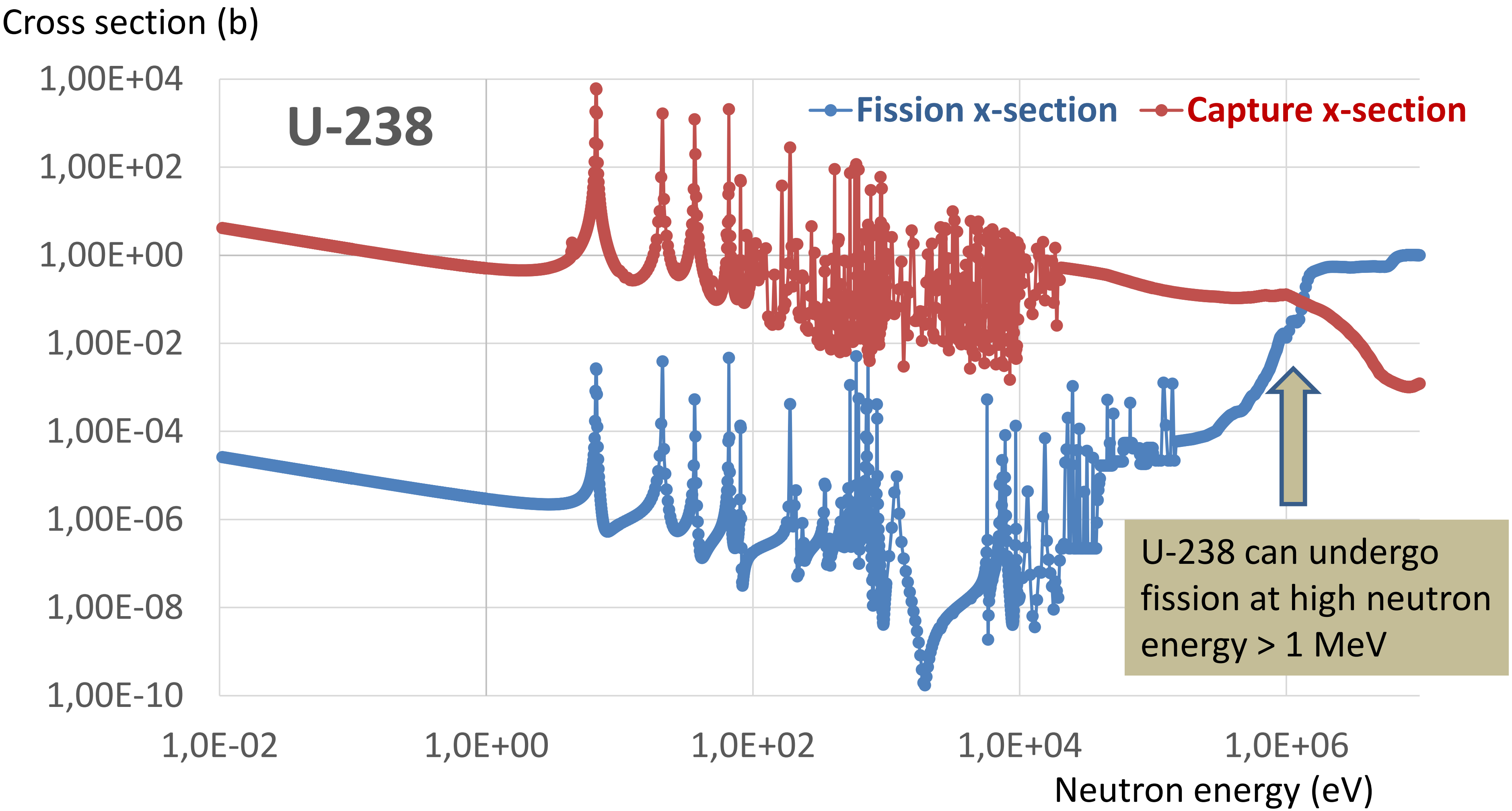
Nuclear cross sections

Since the nuclear radius is roughly 10^{-12} cm, the geometrical cross sectional area of the nucleus is roughly **10^{-24} cm^2 = 1 barn**

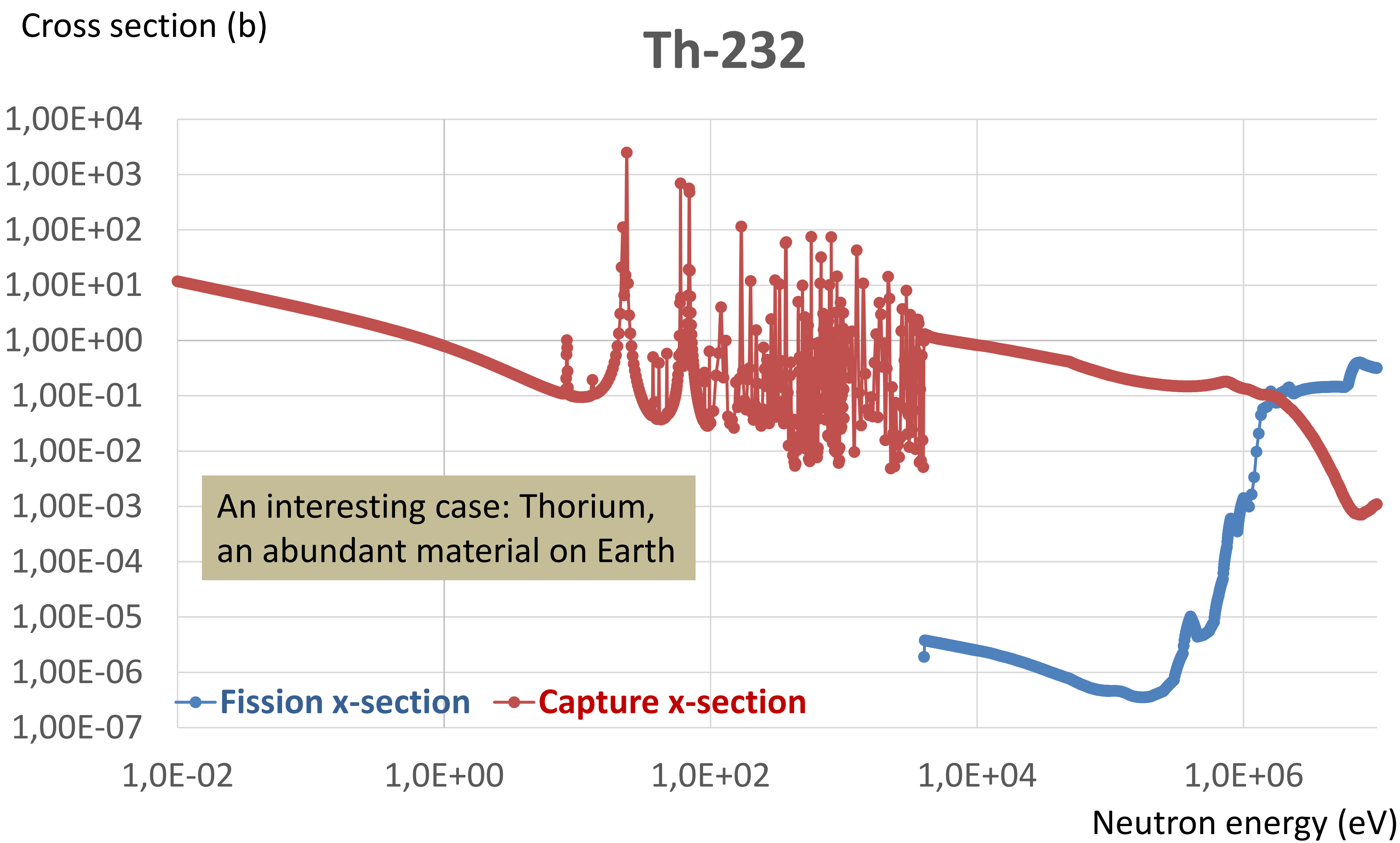
Hence we might expect that nuclear cross sections are of the order of 10^{-24} cm^2 ≡ 1 barn

However, quantum mechanical effects can make nuclear cross sections a lot bigger…





Cross section (b)
U-238
Fission x-section
Capture x-section
1,00E+04
1,00E+02
1,00E+00
1,00E-02
1,00E-04
1,00E-06
1,00E-08
1,00E-10
1,0E-02
1,0E+00
1,0E+02
1,0E+04
1,0E+06
Neutron energy (eV)
U-238 can undergo fission at high neutron energy > 1 MeV


Cross section (b)
Th-232
1,00E+04
1,00E+03
1,00E+02
1,00E+01
1,00E+00
1,00E-01
1,00E-02
1,00E-03
1,00E-04
1,00E-05
1,00E-06
1,00E-07
An interesting case: Thorium, an abundant material on Earth
Fission x-section
Capture x-section
1,0E-02
1,0E+00
1,0E+02
1,0E+04
1,0E+06
Neutron energy (eV)

Fissile, fissionable, fertile isotopes

- Heavy nuclei with a high fission cross section at low (thermal) neutron energies are called **fissile** (e.g. ^{233}U, ^{235}U, ^{239}Pu,…)

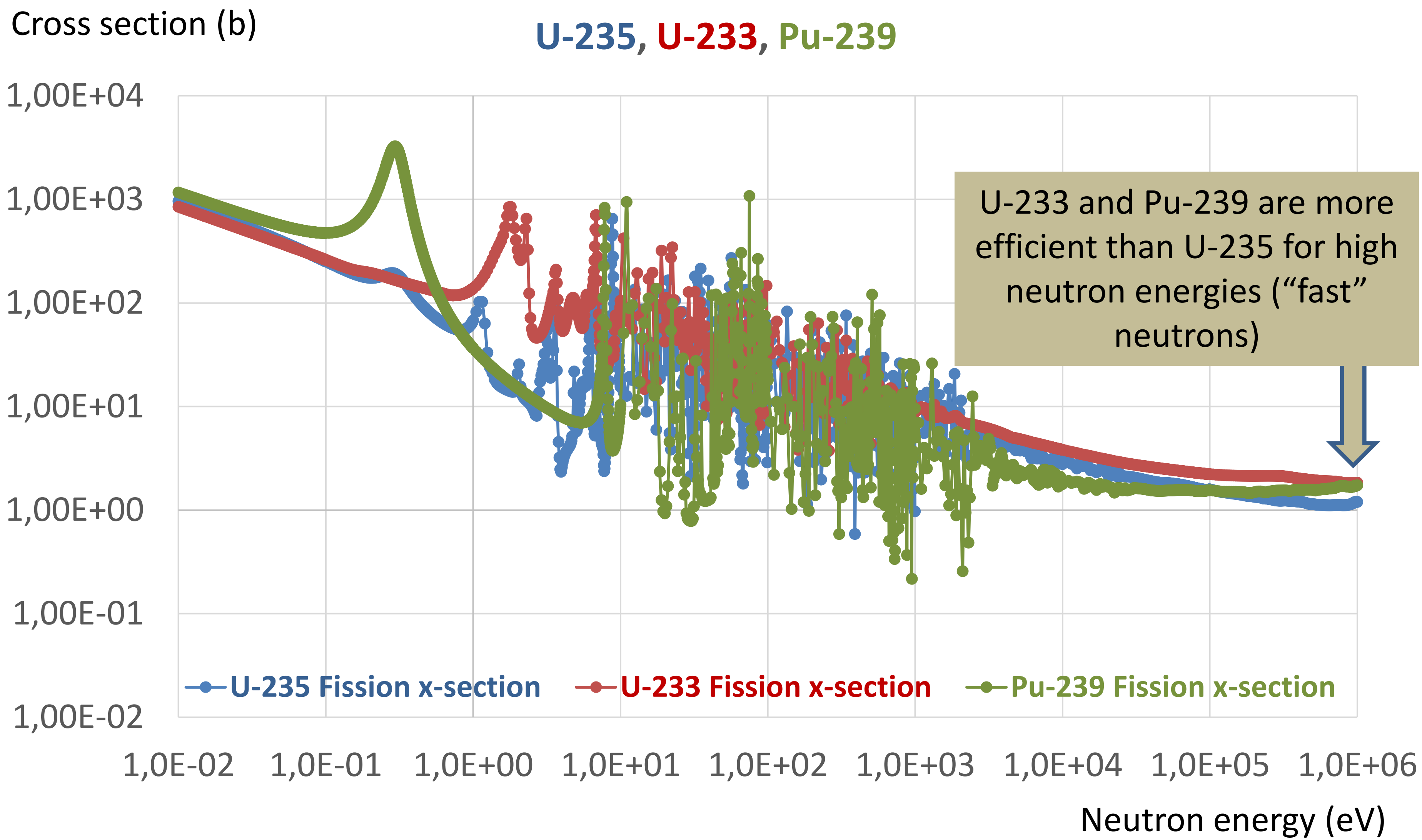
- Those with a non-zero fission cross section only at higher neutron energies are called **fissionable** (e.g. ^{238}U,…)

- Those that can produce a fissile isotope via neutron radiative capture and β decay are called **fertile**, i.e. they can be used to **produce fuel** (e.g. ^{238}U,…)

- $n + {}^{238}U \rightarrow {}^{239}U + \gamma \rightarrow {}^{239}Np + \beta + \text{anti-}\nu \rightarrow$ **^{239}Pu** $+ \beta + \text{anti-}\nu$ → fissile

- $n + {}^{232}Th \rightarrow {}^{233}Th + \gamma \rightarrow {}^{233}Pa + \beta + \text{anti-}\nu \rightarrow$ **^{233}U** $+ \beta + \text{anti-}\nu$ → fissile

- ✓ Natural Uranium → 0.7 % ^{235}U + 99.3 % ^{238}U → **most reactors need 3-5 % ^{235}U → "enrichment" process**
- ✓ Plutonium production is also called "breeding"
- ✓ Under certain conditions, a reactor can produce more Pu than it consumes → it is called "breeder"



Cross section (b)
U-235, U-233, Pu-239
1,00E+04
1,00E+03
1,00E+02
1,00E+01
1,00E+00
1,00E-01
1,00E-02
U-233 and Pu-239 are more efficient than U-235 for high neutron energies ("fast" neutrons)
U-235 Fission x-section
U-233 Fission x-section
Pu-239 Fission x-section
1,0E-02
1,0E-01
1,0E+00
1,0E+01
1,0E+02
1,0E+03
1,0E+04
1,0E+05
1,0E+06
Neutron energy (eV)

Burning-breeding-burning: the Uranium-Plutonium cycle and the long lifetime radioactive waste production (1 GW_e LWR)

$^{244,245}Cm$ 1.5 Kg/yr

^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

LLFP 76.2 Kg/yr

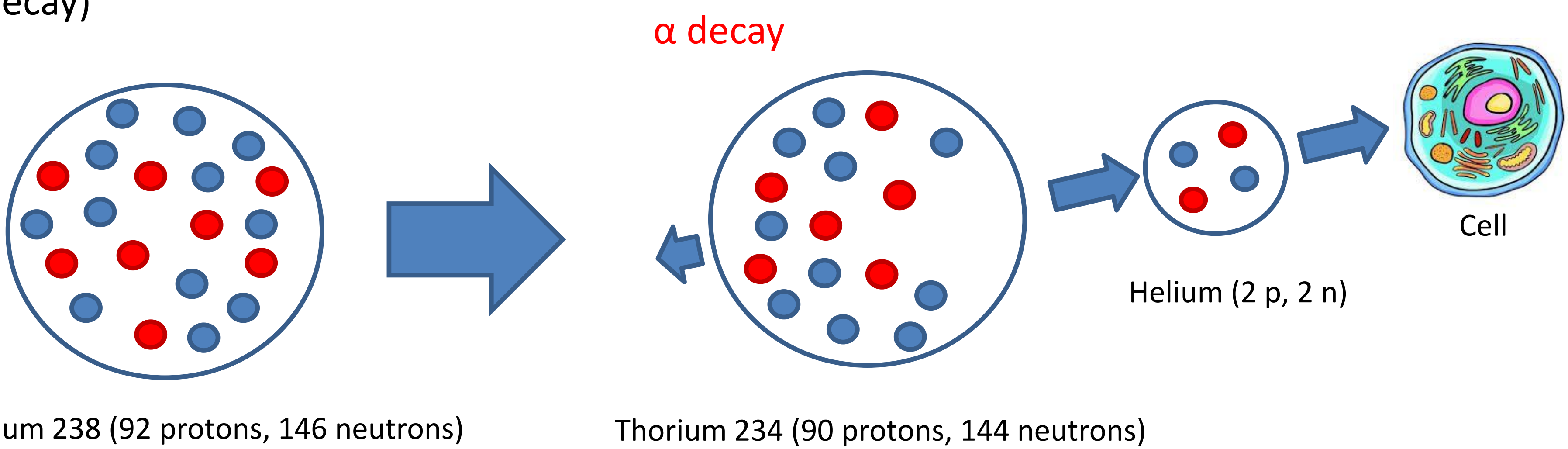
Fissile fuel

LLFP=Long Life Fission Products

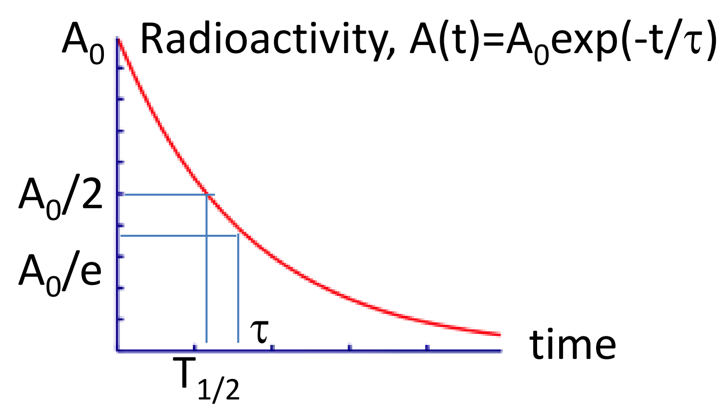
Transuranics = Minor Actinides + **Pu**

Transuranics and waste

- ✓ Operating a fission reactor means that long-lived radioactive nuclides are produced
- ✓ Many transuranics are long-lived and undergo α decay (followed by γ emissions)
- ✓ Such radioactive nuclei can be dangerous for the environment and the human health (due to direct exposure in the case of γ's and due to ingestion or inhalation in the case of α and β decay)



Nuclide	Half-life $T_{1/2}$ (years)
Pu-239	24,000
Pu-242	3.7×10^5
Am-241	433



IAEA Scheme for Classification of Radioactive Waste (2009)

1. Exempt waste (EW) – such a low radioactivity content, which no longer requires controlling

2. Very short-lived waste (VSLW) – can be stored for a limited period of up to a few years to allow its radioactivity content to reduce by radioactive decay. It includes waste containing radionuclides with very short half-lives often used for research and medical purposes

3. Very low level waste(VLLW) – usually has a higher radioactivity content than EW but may, nonetheless, not need a high level of containment and isolation. Typical waste in this class includes soil and rubble with low levels of radioactivity which originate from sites formerly contaminated by radioactivity

4. Low level waste (LLW) - this waste has a high radioactivity content but contains limited amounts of long-lived radionuclides. **It requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near-surface facilities**. It covers a very broad range of waste and may include short-lived radionuclides at higher levels of activity concentration, and also long-lived radionuclides, but only at relatively low levels of activity concentration

5. Intermediate level waste (ILW) – because of its radioactivity content, particularly of long-lived radionuclides, it requires a greater degree of containment and isolation than that provided by near surface disposal. **It requires disposal at greater depths, of the order of tens of metres to a few hundred metres**

6. High level waste (HLW) – this is waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. **Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal**

Breeding and burning: the Thorium-Uranium cycle

Much lower production of Transuranics

Remember that

- ✓ *1 GW(th) = 1 GW thermal power*
- ✓ *1 GW(e) = 1 GW electrical power*
- ✓ *typically, for a fossil-fueled or nuclear power plant, a conversion factor between ~ 30 to 60 % has to be applied to go from thermal to electrical power*

How much fuel ?

Suppose you've got a **reactor with 1 GW thermal power (1 GW_{th} → ~ 300 Mw_e) = 10^9 Joule/sec**
Assume each fission releases order of 200 MeV energy = 3.2×10^{-11} Joule
→In the reactor the fission rate is about 3×10^{19} fissions/sec
→ which means that e.g. 3×10^{19} (nuclei of ^{235}U)/sec disappear (actually a bit more because of radiative capture)

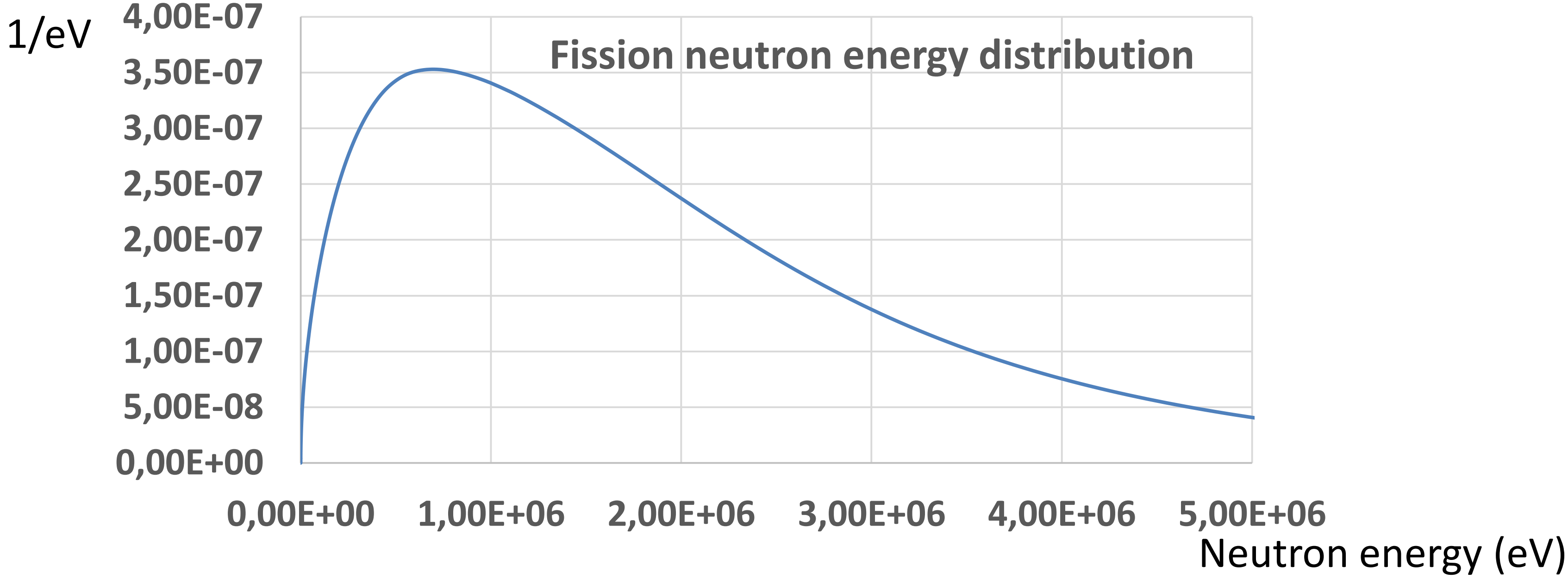
Fuel	Istantaneous consumption (per second)	Yearly consumption (90 % load factor)
Uranium	0.012 g	340 Kg
Natural Gas	25 m^3	700 million m^3
Crude oil	0.02 tons	0.7 million tons
Lignite	100 Kg	2.8 million tons
Coal	40 Kg	1.1 million tons

For a thermal reactor (see later) loaded with mixed UO_2 fuel (density about 11 gr/cm^3) comprising 4 % ^{235}U and 96 % ^{238}U, this corresponds to 8500 Kg of fuel → 0.8 m^3

In practice, there has to be much more as the chain reaction needs the presence of fissile nuclei at all times → the reactor has to be critical at all times
However, ^{235}U consumption is partly compensated by Plutonium (^{239}Pu) breeding

(*) load factor=percentage of time when the reactor is actually producing electricity

Fission spectrum, fast and slow neutrons



It is customary to adopt the following classification:

- **slow neutrons**: those with kinetic energy T_n < 1 eV
- in particular **thermal neutrons** have T_n around 0.025 eV or 25 meV (the value of kT, where k is the Boltzmann constant and T is the temperature
- **epithermal neutrons**: 1 eV < T_n < 100 keV (0.1 MeV)
- **fast neutrons**: 0.1 MeV < T_n < 20 MeV

Obviously neutrons in general can have energies above 20 MeV but this is an extreme limit in reactor physics (e.g. neutrons from D+T fusion have 14 MeV fixed energy)

Slowing down neutrons (moderation)

It is easy to show in non-relativistic kinematics that **after a scattering off a nucleus with mass number A**, the kinetic energy of the neutron changes according to the ratio

$$\frac{T_n'}{T_n} = \frac{m_n^2 + m_A^2 + 2m_n m_A cos\theta_{CM}}{(m_n + m_A)^2}$$

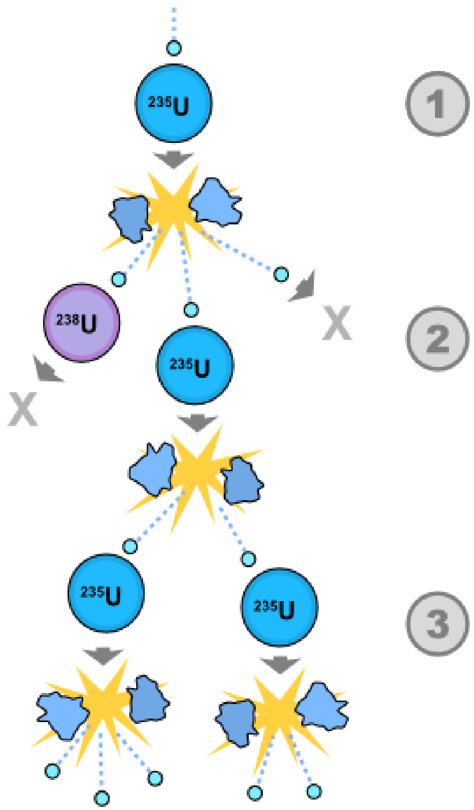
Assuming an isotropic CM cross section that does not depend on $\cos\theta_{CM}$, the corresponding term averages out to zero, so that we can write on average

$$\frac{T_n'}{T_n} = \frac{m_n^2 + m_A^2}{(m_n + m_A)^2}$$ ➔ Assuming $M_A \cong Am_n$ ➔ $$\frac{T_n'}{T_n} = \frac{1 + A^2}{(1 + A)^2}$$

For a **heavy nucleus A>>1** → $\mathbf{T_n' \cong T_n}$ or in other words, the neutron has to undergo many collisions in order to significantly lose energy.
Consider instead the case **A=1** → (target containing hydrogen, i.e. protons as nuclei) $\mathbf{T_n' = T_n/2}$
i.e. on average a neutron will lose half of its energy at each collision and therefore few collisions are sufficient to rapidly decrease its energy

➔ **Moderators = light materials containing hydrogen = water, paraffin or graphite**

The chain reaction and the critical reactor



The chain reaction:
- must not diverge (more and more fissions at each "generation")
- must not die away (less and less fissions at each generation)

→ precisely one neutron from each fission has to induce another fission event

The remaining fission neutrons will then either be
- absorbed by radiative capture or
- will leak out from the system

Suppose we can count the number of neutrons in one generation and in the next one
Then

$$k \equiv \frac{\text{number of neutrons in one generation}}{\text{number of neutrons in the preceding generation}}$$

- The condition **k=1** corresponds to a **critical reactor**
- **k>1** is a **supercritical reactor** (chain reaction diverges)
- **k<1** is a **subcritical reactor** (chain reaction dies away)

"Simple-minded" reactor kinetics

$$\frac{dn(t)}{dt} = P(t) - L(t)$$

n(t)=neutron population at time t
P(t)= neutron production at time t (mainly as fission products)
L(t)=neutron loss (fission+capture+leakage) at time t

All are functions of time as reactor evolves over time

⇨ Alternative definition $k \equiv \frac{P(t)}{L(t)}$ $\text{Neutron lifetime} \equiv \tau \equiv \frac{n(t)}{L(t)}$

⇨ $\frac{dn(t)}{dt} = \frac{k-1}{\tau} n(t)$ Let's assume k and τ are time independent (not true…)

$$n(t) = n_0(t) \exp\left(\frac{k-1}{\tau} t\right)$$

- **k=1 → steady state →** critical reactor
- **k>1 → increase →** supercritical
- **k<1 → decrease →** subcritical

$$\text{Time constant} \equiv \text{T} \equiv \text{Reactor period} \equiv \frac{\tau}{k-1}$$

Delayed neutrons: crucial for reactor control

Typical neutron lifetime in a thermal power reactor $\sim 10^{-4}$ sec

If k=1.001 ➡ **T=0.1 sec** ➡ **power will increase by 2.7 in 0.1 sec !!**

Actually, **we neglected** the very small amount (< 1 %) of **delayed neutrons**

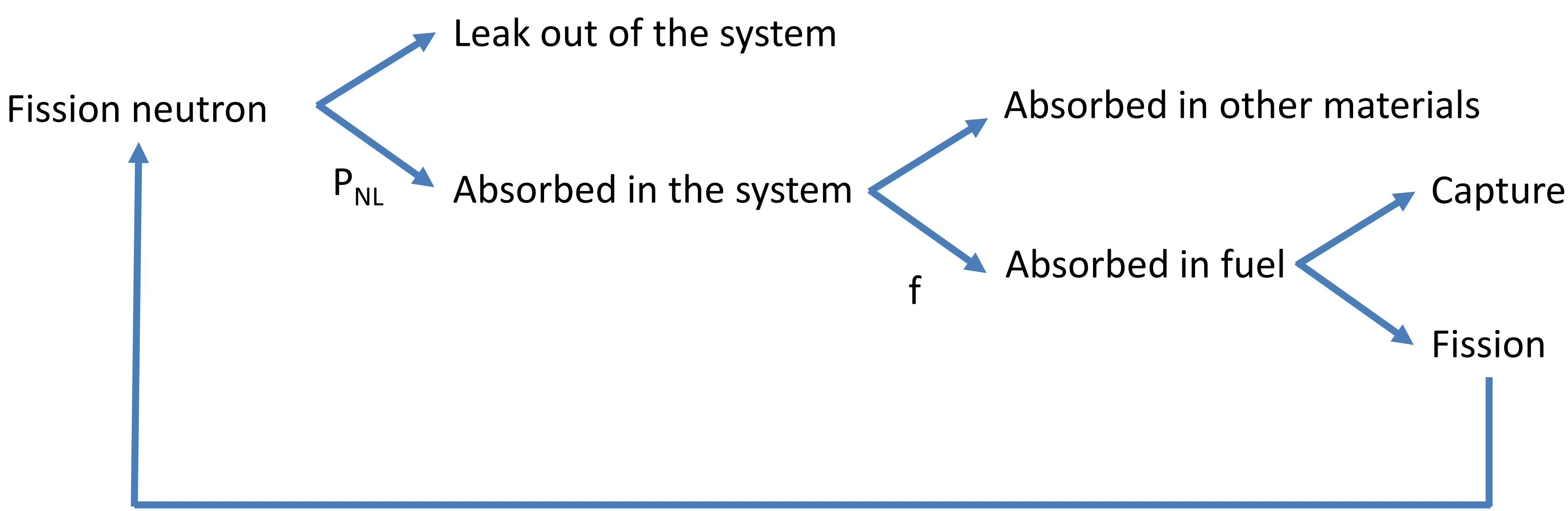
Emitted by fragments after fission on **time scale from ms to sec**

The trick is to **make the reactor critical thanks to that small fraction of neutrons**

→ Delayed neutrons **dominate the reactor response time** making it much longer

➡ Reactor control manageable by absorbers: "control rods"

Physics of multiplication: path representation



η = average number of neutrons produced per neutron absorbed in the fuel

P_{NL}= probability of non-leakage (for a **finite system**)
f = conditional probability that, if neutron will be absorbed, it will be absorbed in fuel

Physics of multiplication

Multiplication can be written as

$$k = \frac{N_2}{N_1} = \eta \ f \ P_{NL}$$

N_1, N_2 = number of neutrons in two subsequent generations

η = average number of neutrons produced per neutron absorbed in the fuel

where $$\eta = \nu \frac{\sigma_f^F}{\sigma_a^F}$$

$\sigma_f^F =$ Fission cross section in the fuel

$\sigma_a^F =$ Absorption cross section in the fuel

$\nu =$ Average number of emitted neutrons

f = conditional probability that, if neutron will be absorbed, it will be absorbed in fuel

P_{NL}= probability of non-leakage

Infinite reactor → P_{NL}= 1 ⟹ $$k_\infty = \eta \ f$$

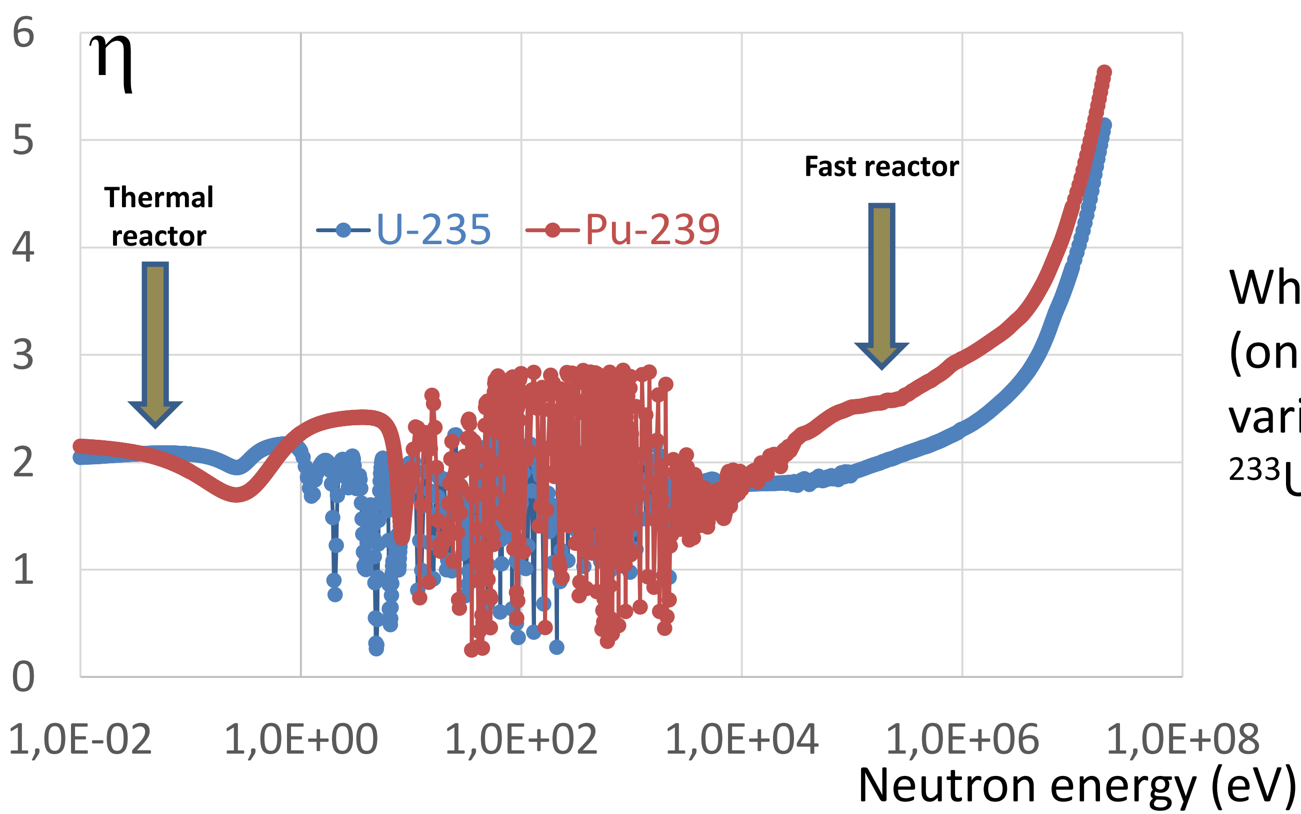
- ✓ This is a property of the material, not of the geometry
- ✓ For a finite, non-homogenous reactor → **effective k, or k_{eff}**

Simple considerations

$$k = \frac{N_2}{N_1} = \eta f P_{NL}$$

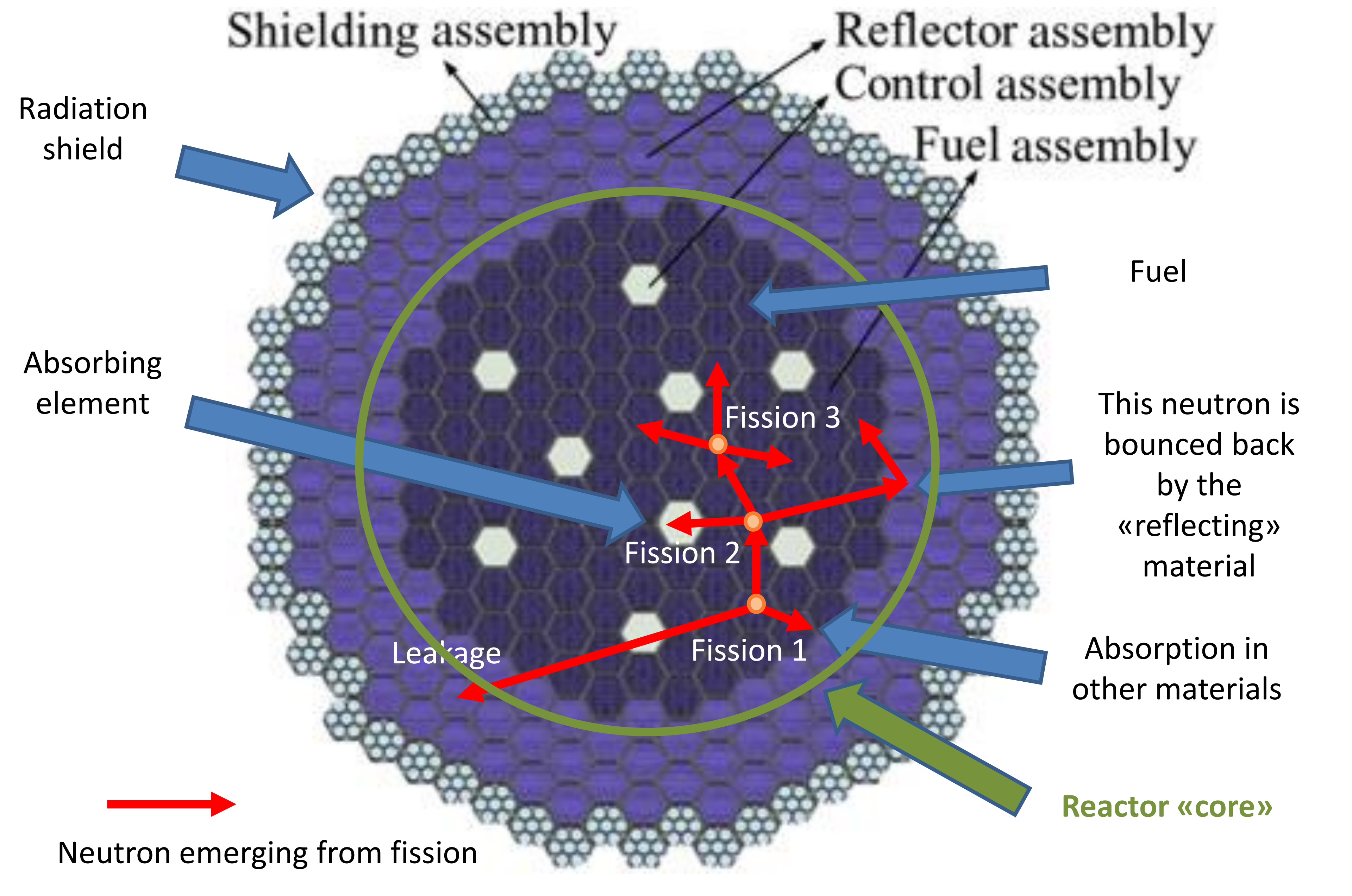
If n is absorbed, it is absorbed in the fuel

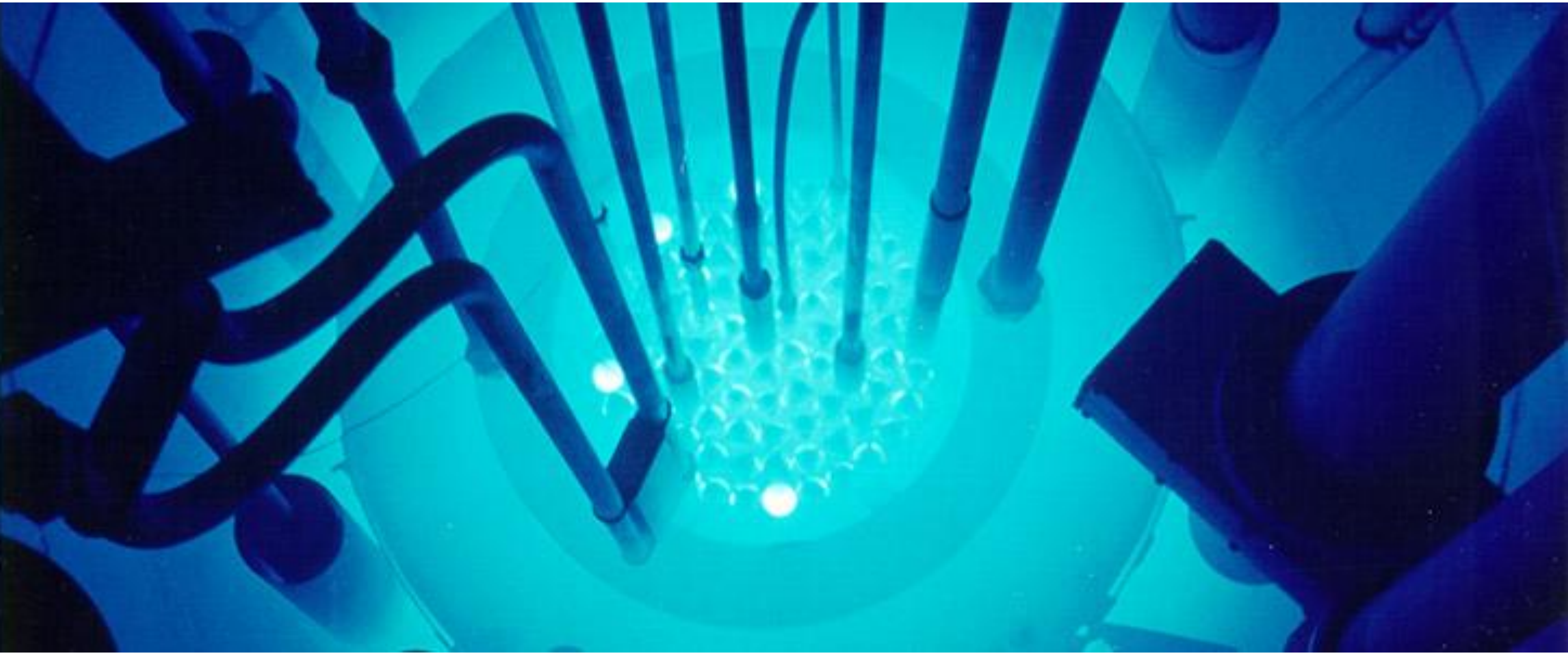
$f < 1$, $P_{NL} < 1$ → To have k~ 1 ➔ η significantly > 1



Which is indeed the case (on average):
variation of η with energy for ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu

Physics of multiplication: visual representation





Neutron population and reactor classes

➔ it is easiest to maintain a fission chain reaction using slow neutrons

➔ Hence **most nuclear reactors until now (Gen. I to III+) use low mass number materials such as water or graphite to slow down or moderate the fast fission neutrons**

➔ neutrons slow down to energies comparable to the thermal energies of the nuclei in the reactor core

➔ **Thermal reactor:** average neutron energy comparable to thermal energies

➔ It requires the **minimum amount of fissile material** for fueling

- ✓ As an example, a **Light Water Reactor (LWR)** can start with 3 % ^{235}U + 97 % ^{238}U
- ✓ **Burn-up** of ^{235}U is compensated by **breeding** of ^{239}Pu
- ✓ After 1 year, the core may contain 1 % ^{235}U + 1 % ^{239}Pu

Neutron population and reactor classes

However

the number of neutrons emitted per neutron absorbed in the fuel is largest for fast neutrons

→but σ_f **is smaller**

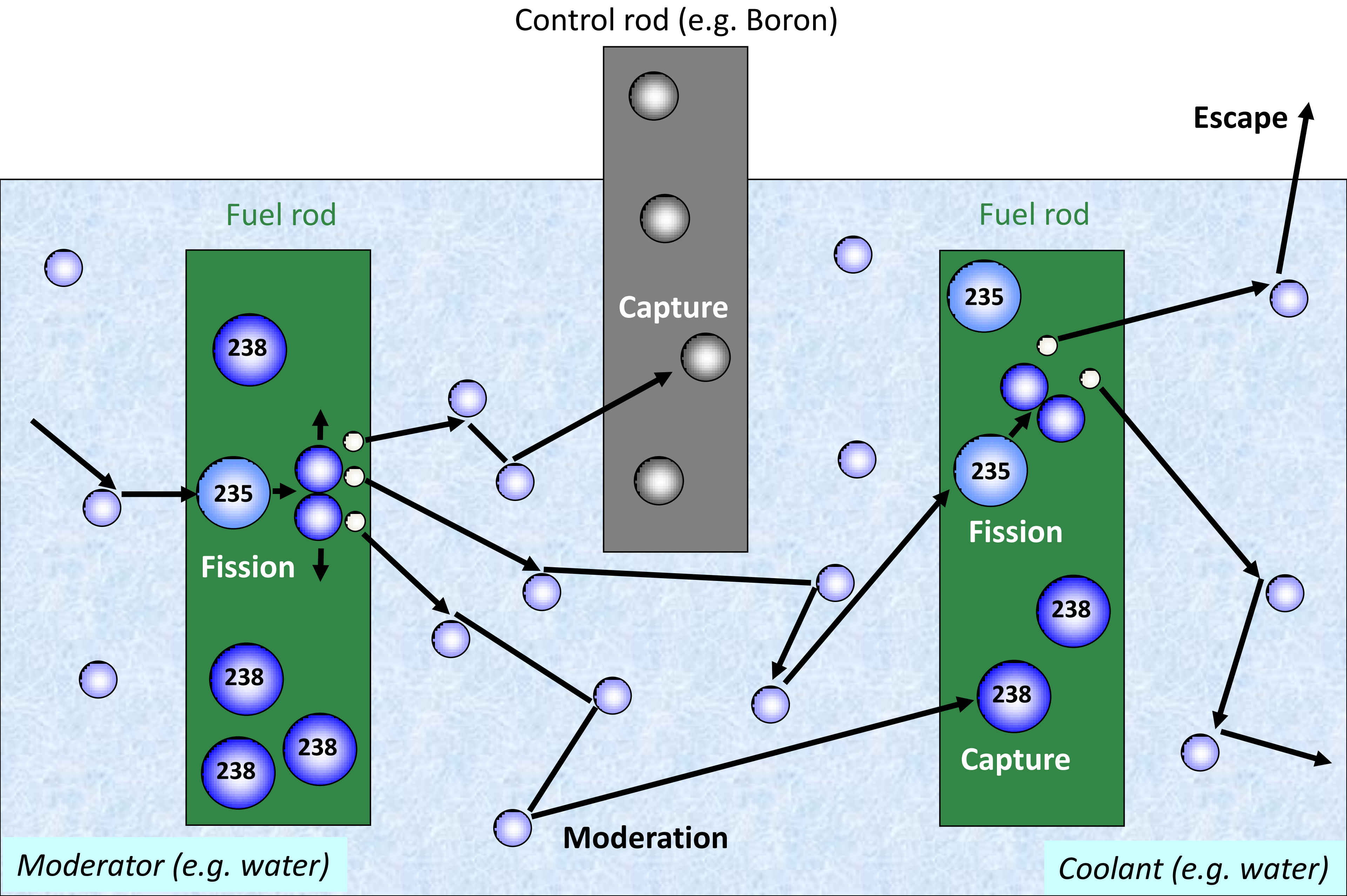
→ **need much more fissile content and higher neutron fluxes** to reach comparable power

→ to keep the neutron energy high, **only high mass-number materials in the core**

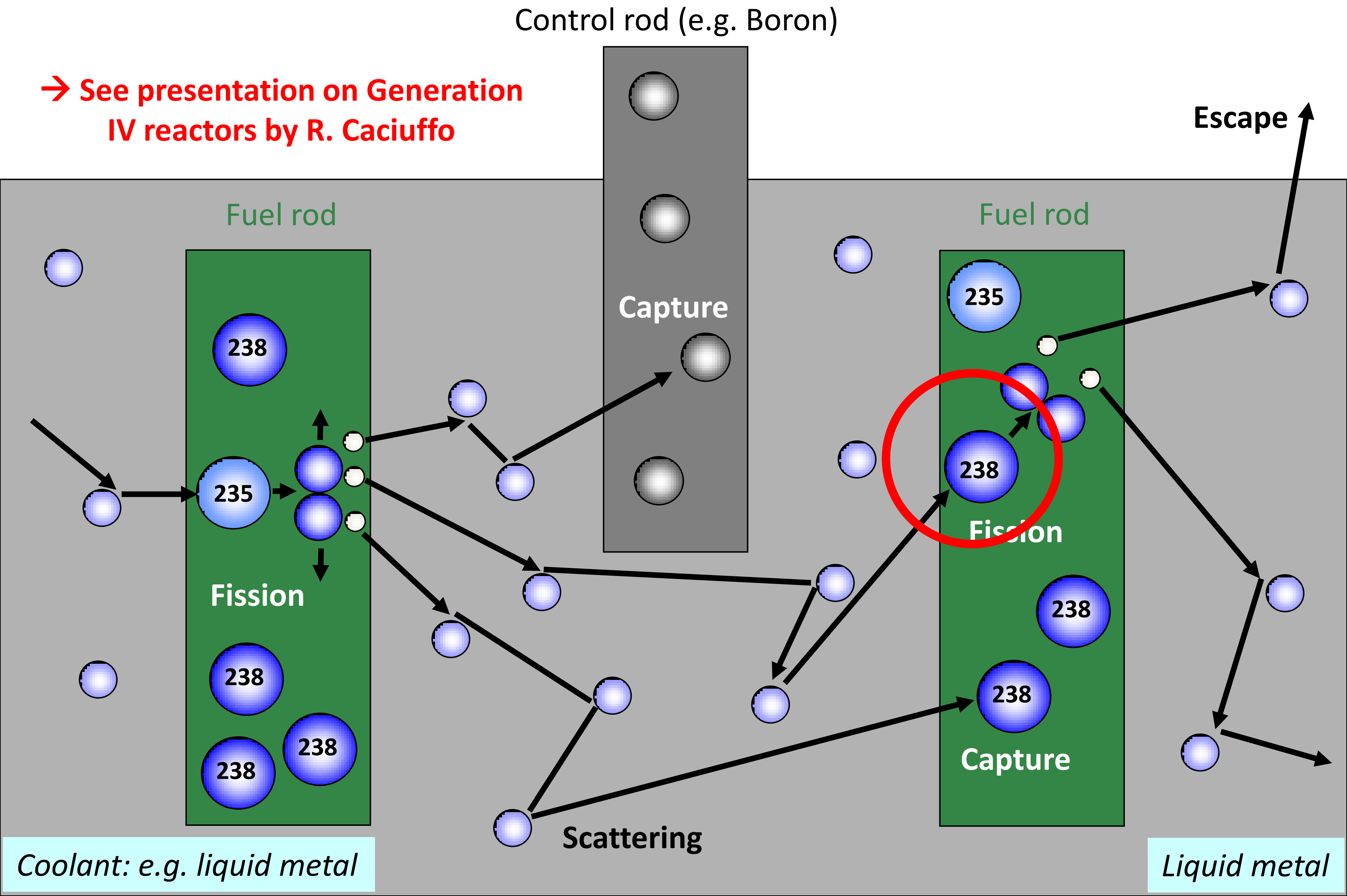
→ **Fast reactor:** average neutron energies above 100 keV

→ one can use the "extra" neutrons to **convert or breed new fuel** → "Fast Breeder"

The thermal reactor



The fast reactor



Nuclear reactor zoo

Most current reactors
→ ordinary water serves as both coolant and moderating material in the reactor

There are two major types of Light Water Reactors (LWR):

1) pressurized water reactors (PWR)
2) boiling water reactors (BWR)

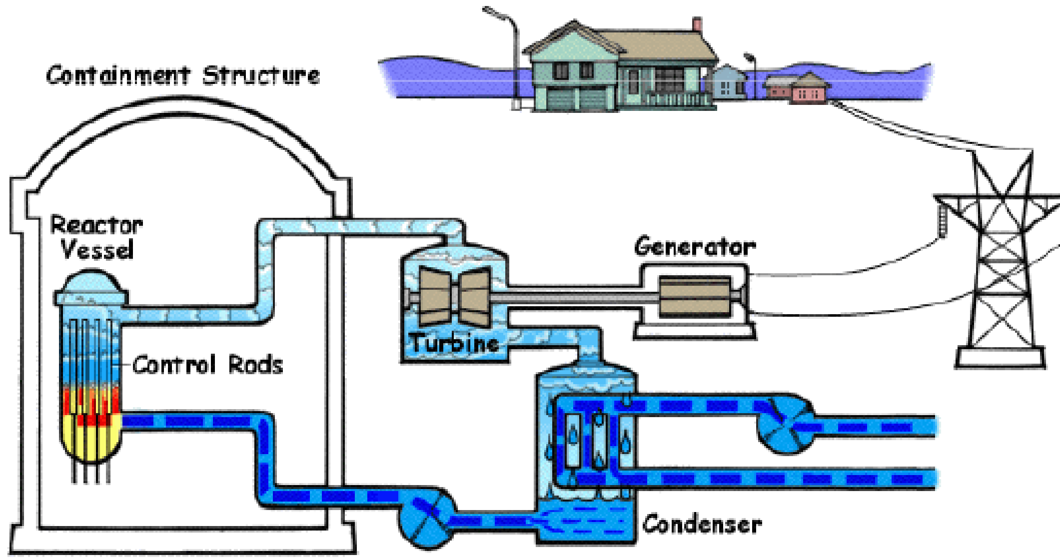
In a **PWR** the primary coolant is water maintained under very high pressure (~160 bar)
→ high coolant temperatures (> 300°) without steam formation within the reactor

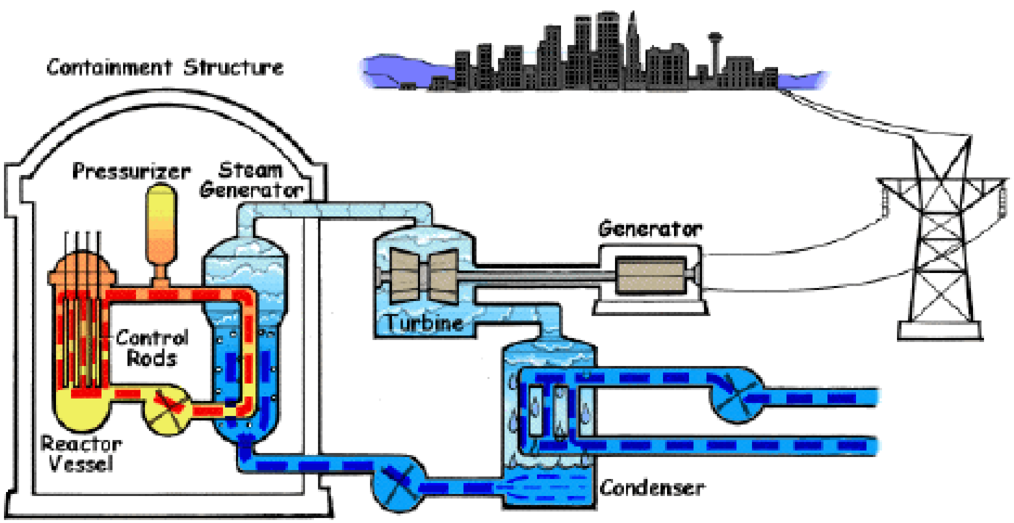
In a **BWR**, the primary coolant water is maintained at lower pressure (~ 70 bar)
→ appreciable boiling (at ~ 285°) and steam within the reactor core itself
→ the reactor itself serves as the steam generator → no secondary loop and heat exchanger

In both PWR and BWR, the nuclear reactor itself and the primary coolant are contained in a **large steel pressure vessel** designed to accomodate the high pressures and temperatures

BWR and PWR

BWR





PWR

Nuclear reactor zoo

Heavy water (D_2O) reactor
→ deuteron has lower neutron capture capture cross section with respect to hydrogen
→ low-enrichment uranium fuels (including natural uranium)
→ Developed in Canada in the CANDU (CANadian Deuterium Uranium) series of power reactors and in the UK as Steam Generating Heavy Water Reactors (SGHWR).

Gas-based reactors
→ the early MAGNOX reactors developed in the UK: low-pressure CO_2 as coolant
→ High-Temperature Gas-cooled Reactor (HTGR, USA): high-pressure helium as coolant
→ Pebble-bed concept
→ Advanced Gas Reactors (AGR, Germany and UK)

Decay heat

Decay heat is the heat released as a result of radioactive decay: the energy of the alpha, beta or gamma radiation is converted into atomic motion

In nuclear reactors **decay of the short-lived radioisotopes created in fission continues at high power**, for a time after shut down

Heat production comes **mostly from β decay** of fission products

A practical approximation is given by the formula

$$\frac{P}{P_0} = 6.6 \cdot 10^{-2} \left[\frac{1}{(\tau - \tau_s)^{0.2}} - \frac{1}{\tau^{0.2}} \right]$$

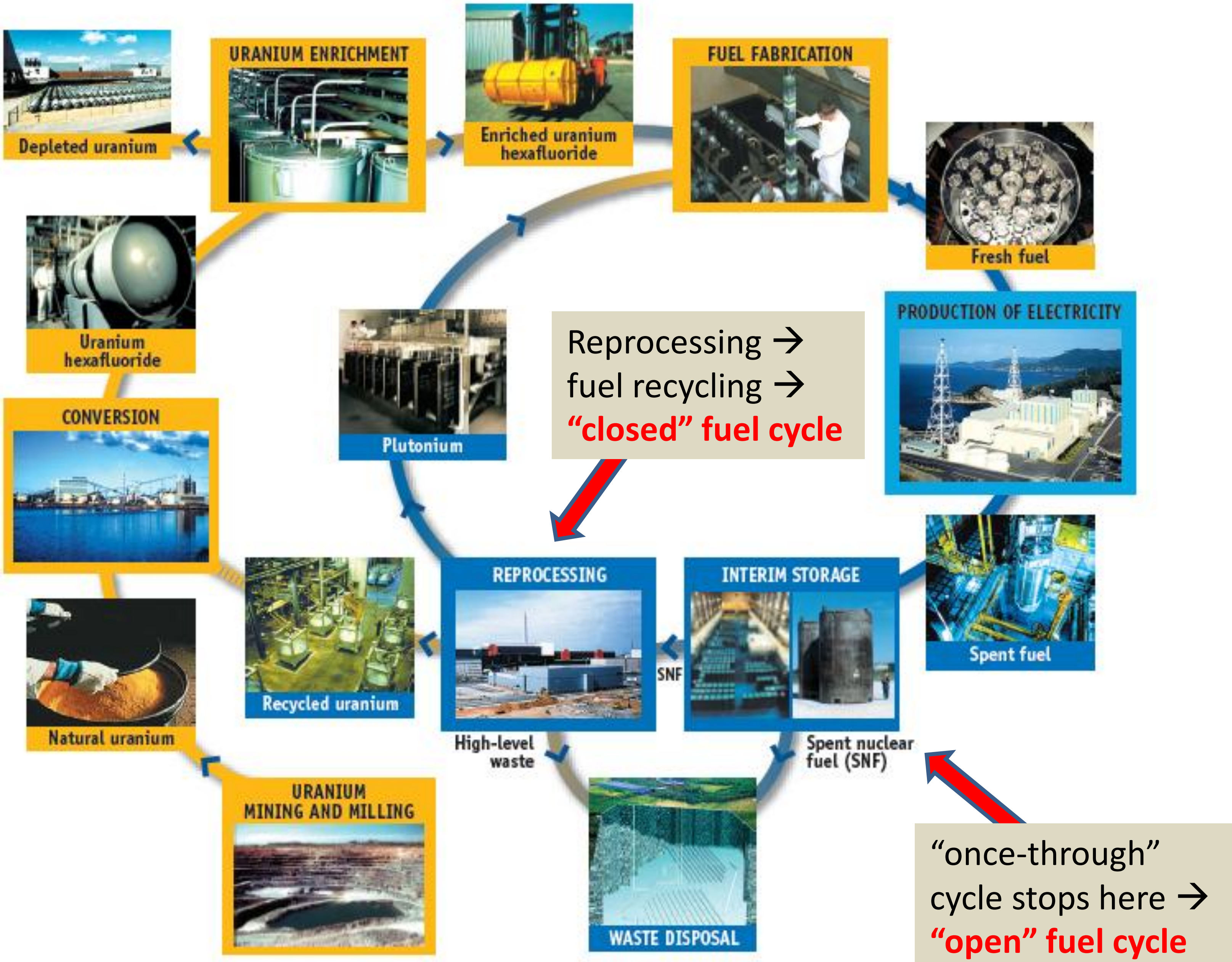
Where P is the decay power, P_0 is the reactor power before shutdown, τ is the time since reactor startup and τ_s is the time of reactor shutdown measured from the time of startup (in seconds)

➡ **At shutdown, the heat power is about 6.5 % (~200 MWth for a 1 GWe reactor)**
Sufficient to melt the core….

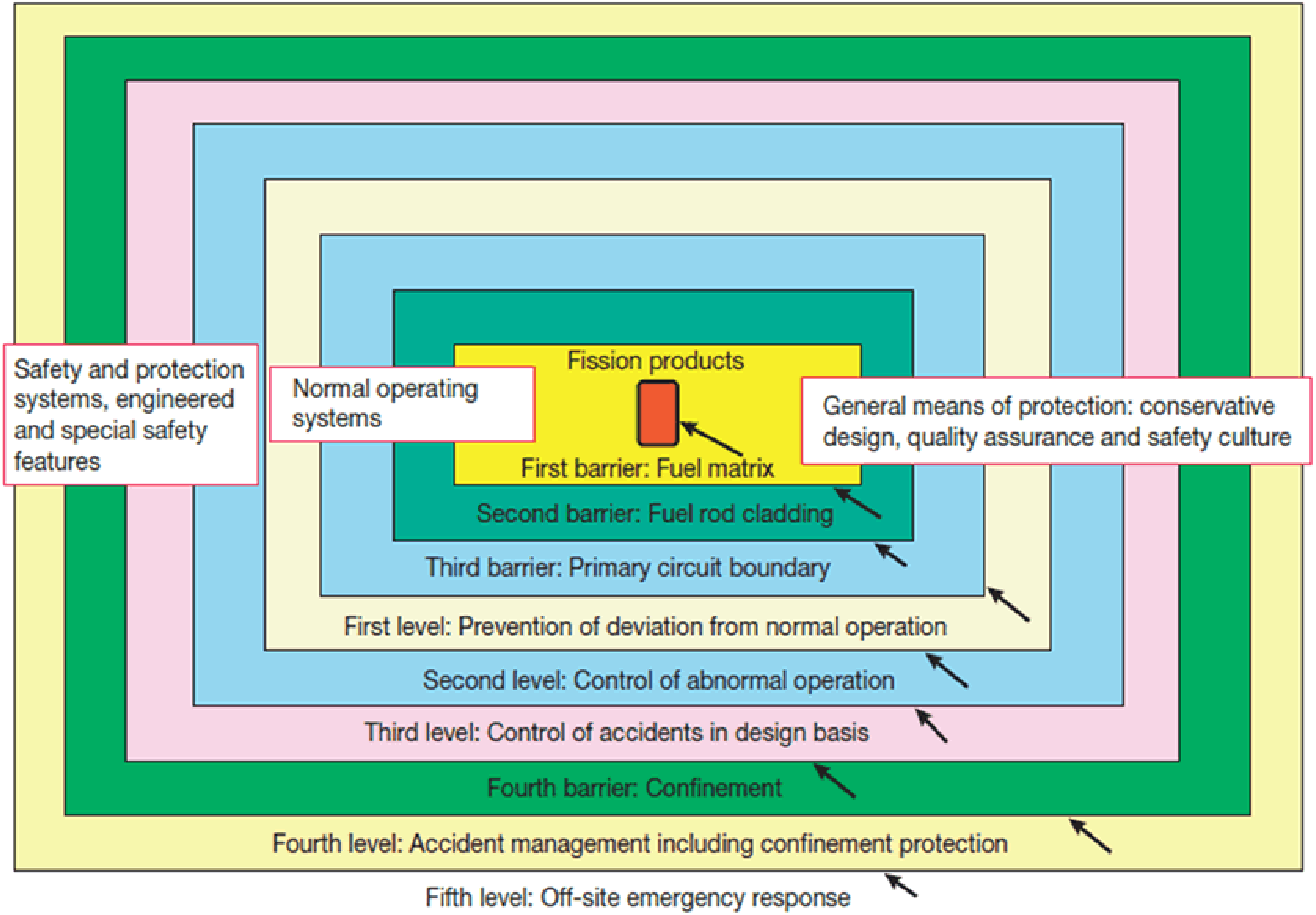
About 1 hour after shutdown, the decay heat will be about 1.5% of the previous core power. After a day, the decay heat falls to 0.4%, and after a week it will be only 0.2%
Spent fuel rods are kept for long time in water pool, before storage or reprocessing.

Removal of decay heat very important → Fukushima…
"Heat sink" must not be compromised

The nuclear fuel cycle



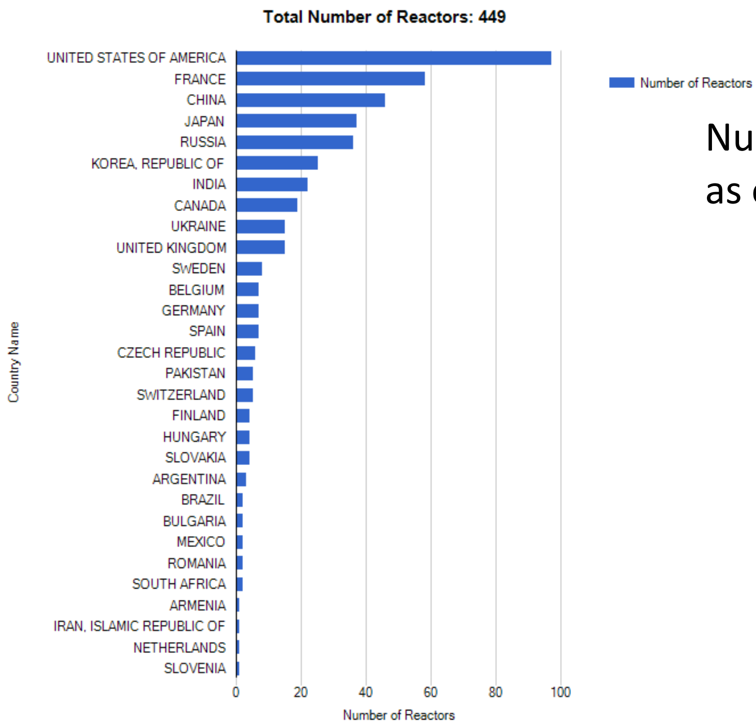
Safety: defence in depth



Control of abnormal operation should include some (negative) feedback mechanisms: e.g. if temperature (power) goes up, reaction cross section goes down

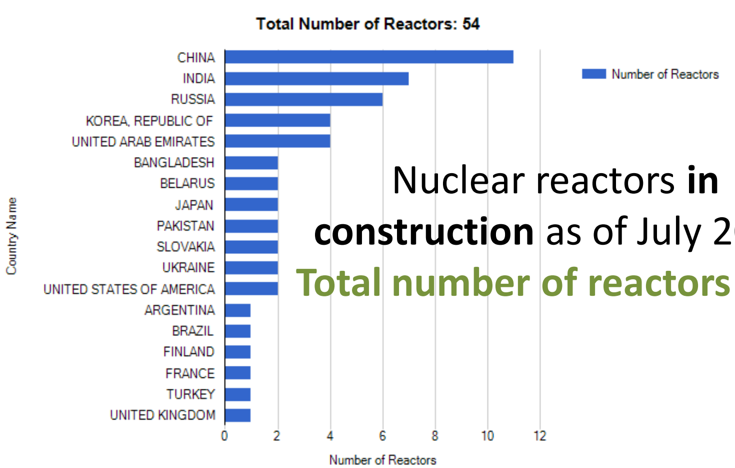
Courtesy of IAEA

Nuclear energy today in the world



Nuclear reactors **in operation or in long-term shutdown** as of July 2019

Total number of reactors = 449

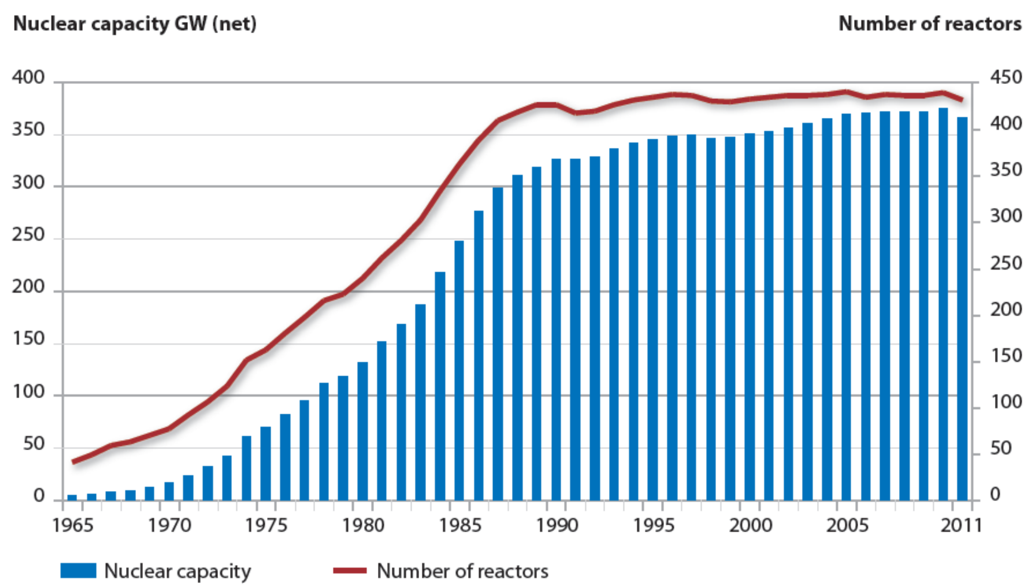


Nuclear reactors **in construction** as of July 2019

Total number of reactors = 61

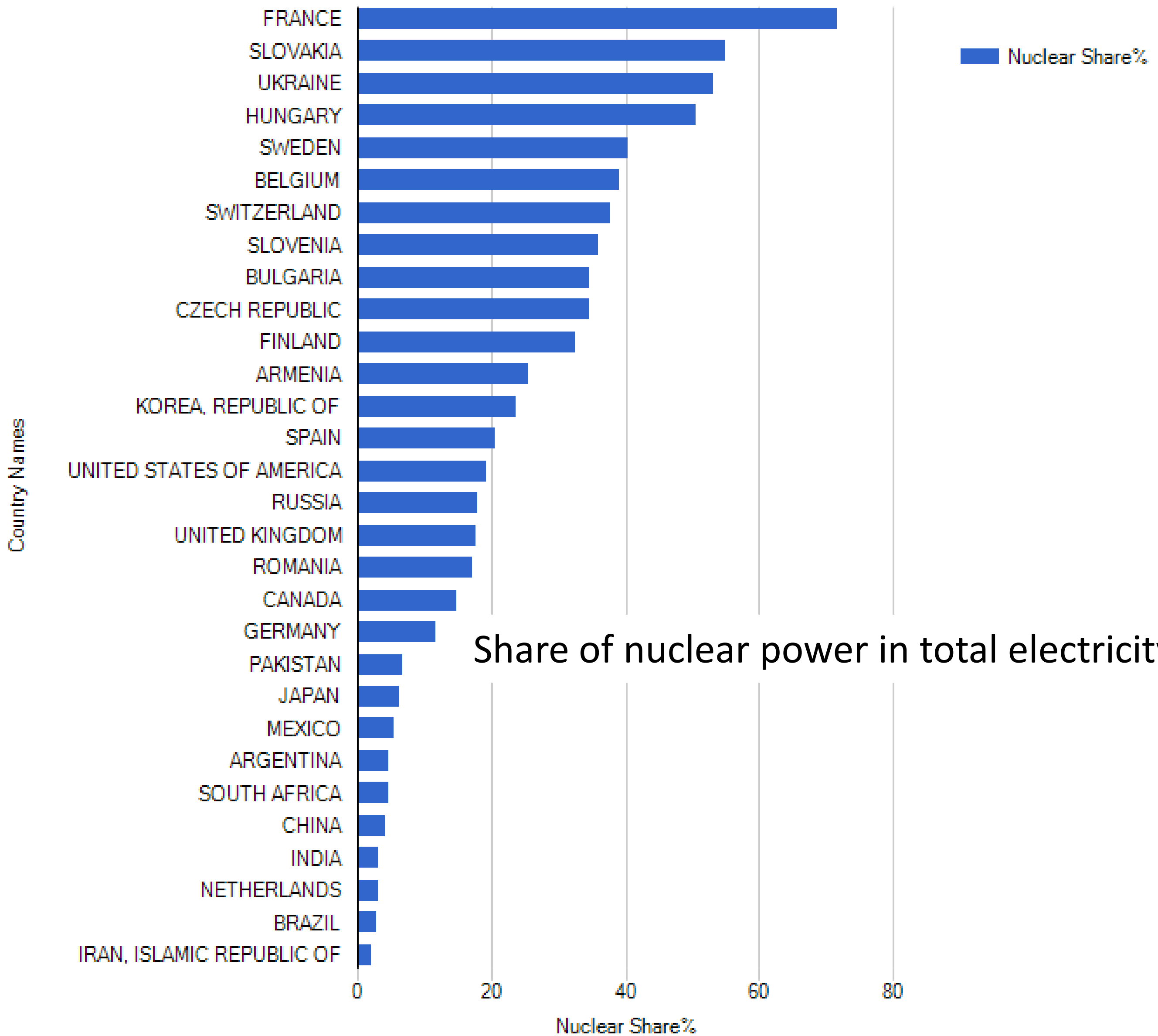
Source: IAEA Power Reactor Information System (PRIS)

Worldwide nuclear generating capacity and number of operating reactors (1965-2011)



Source: OECD/NEA – Nuclear Energy Today 2012

Share of electricity

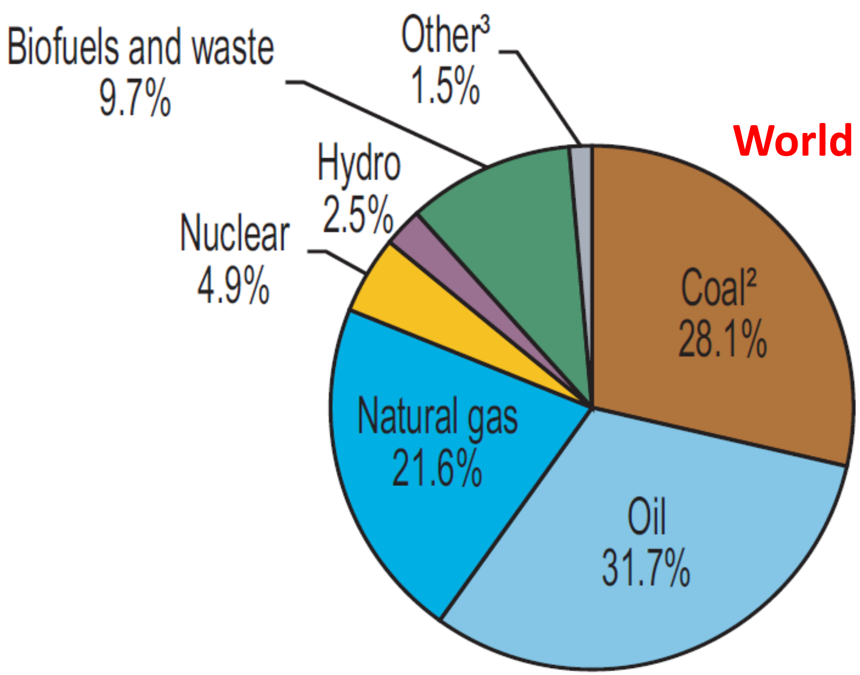


Share of nuclear power in total electricity (July 2019)

Source: IAEA Power Reactor Information System (PRIS)

Nuclear energy in the worldwide perspective

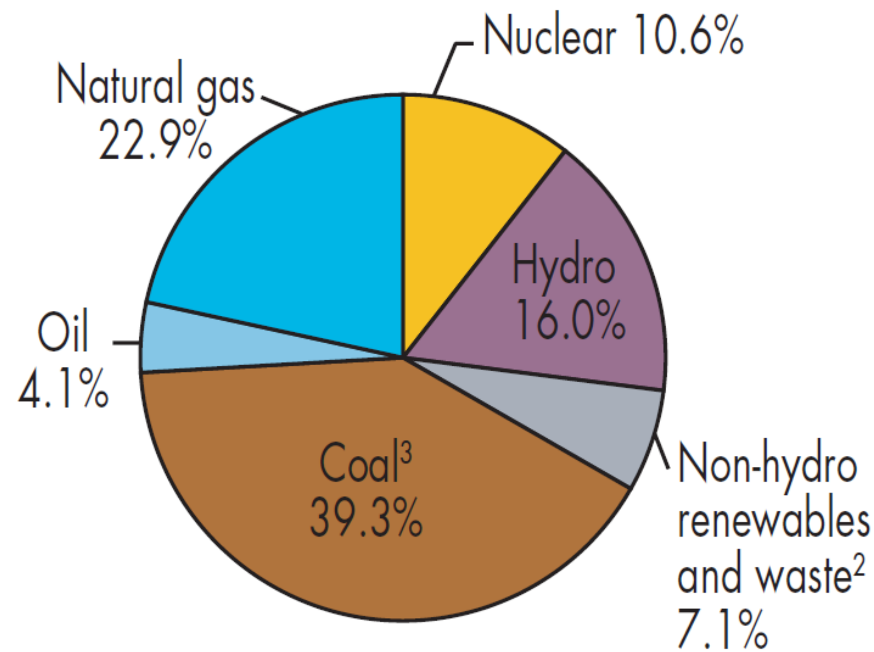
World Total Primary Energy Supply (TPES, 2015)



13 647 Mtoe (*)

1. World includes international aviation and international marine bunkers.
2. In these graphs, peat and oil shale are aggregated with coal.
3. Includes geothermal, solar, wind, tide/wave/ocean, heat and other.

World electricity generation (2015)



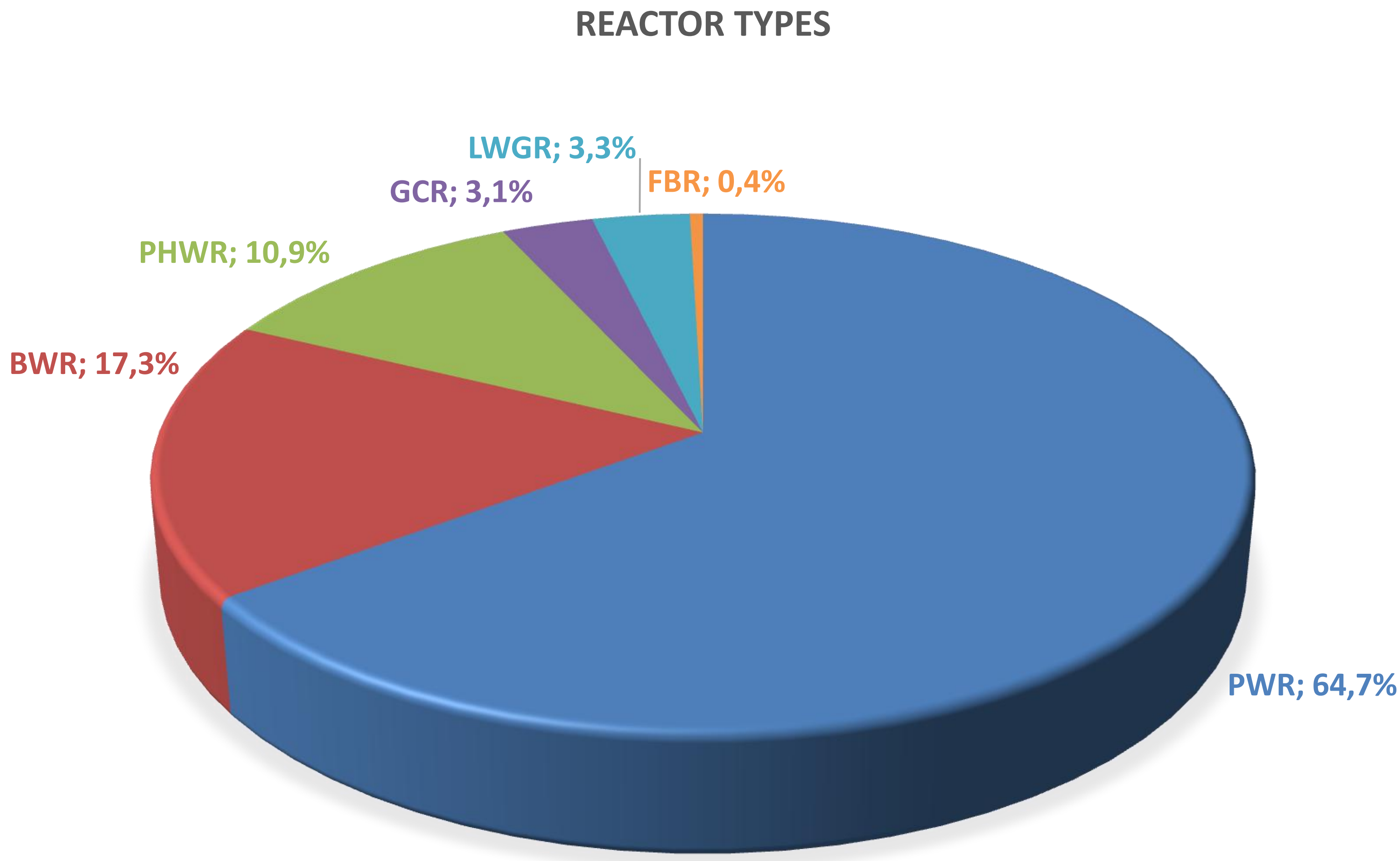
24 255 TWh (**)

1. Excludes electricity generation from pumped storage.
2. Includes geothermal, solar, wind, tide/wave/ocean, biofuels, waste, heat and other.
3. In these graphs, peat and oil shale are aggregated with coal.

Source: [IEA, Key World Energy Statistics, 2017]

(*) 1 tonne oil equivalent (toe) = 41.868 GJ = 10 Gcal = 11.63 MWh
(**) 1 TW = 10^{12} Joule/s, 1 TWh = $3.6 \cdot 10^{15}$ J

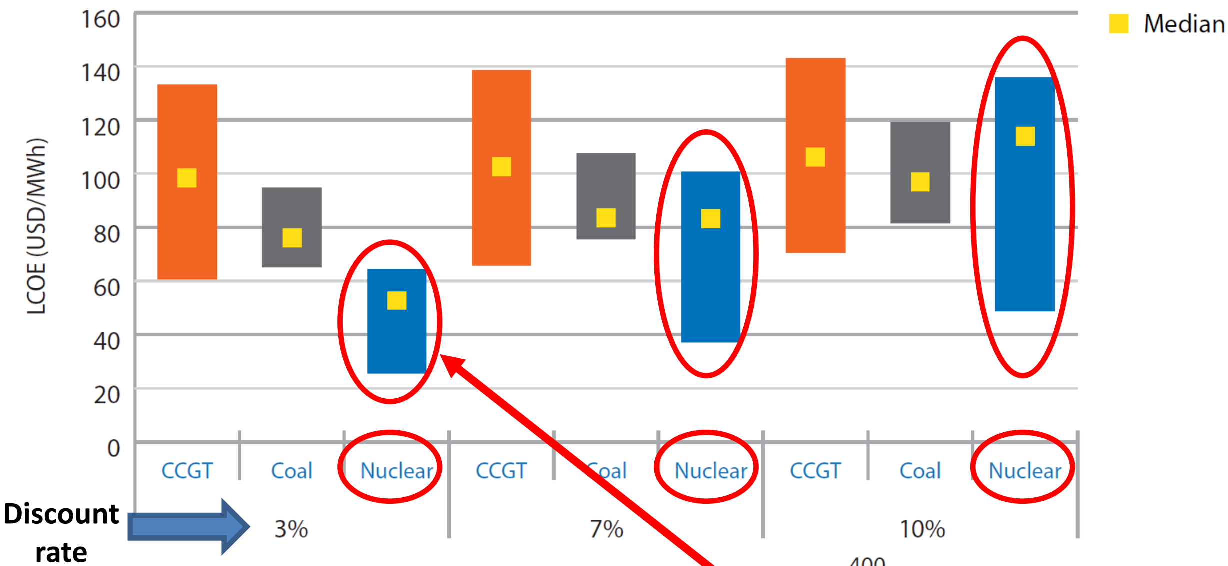
Reactor types in use worldwide (end of 2016)

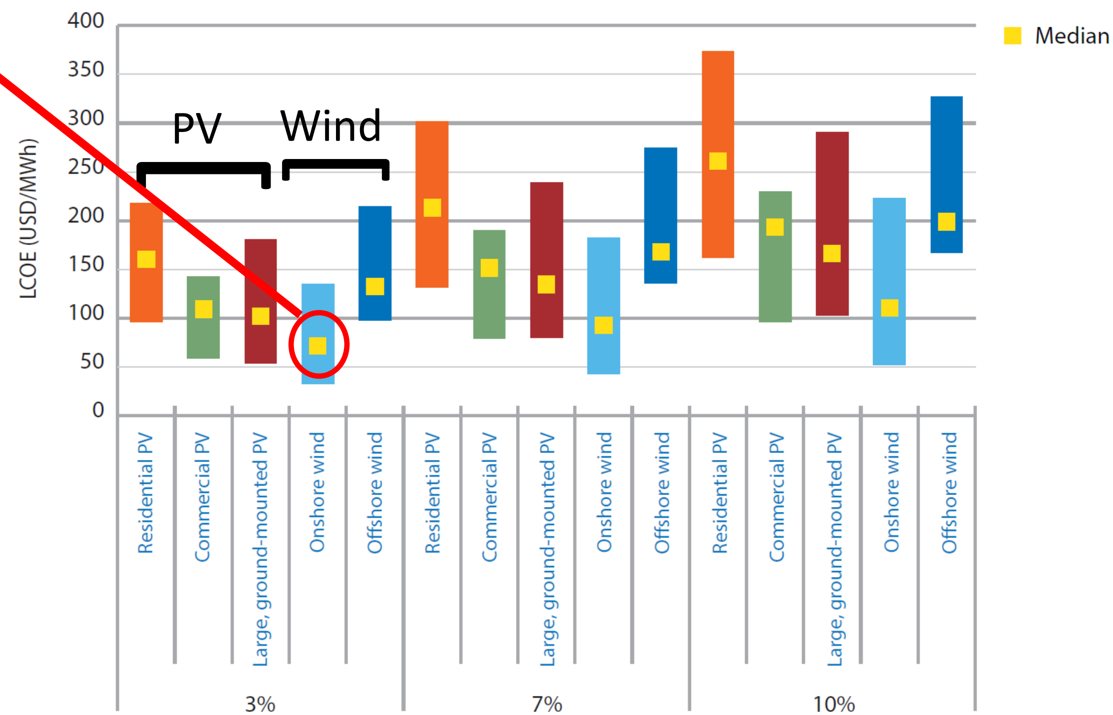


PWR = Pressurized Water Reactor
BWR = Boiling Water Reactor
PHWR = Pressurized Heavy Water Reactor
GCR = Gas-Cooled Reactor
LWGR = Light Water cooled, Graphite moderated Reactor
FBR = Fast Breeder Reactor

Source: European Nuclear Society

Cost of electricity



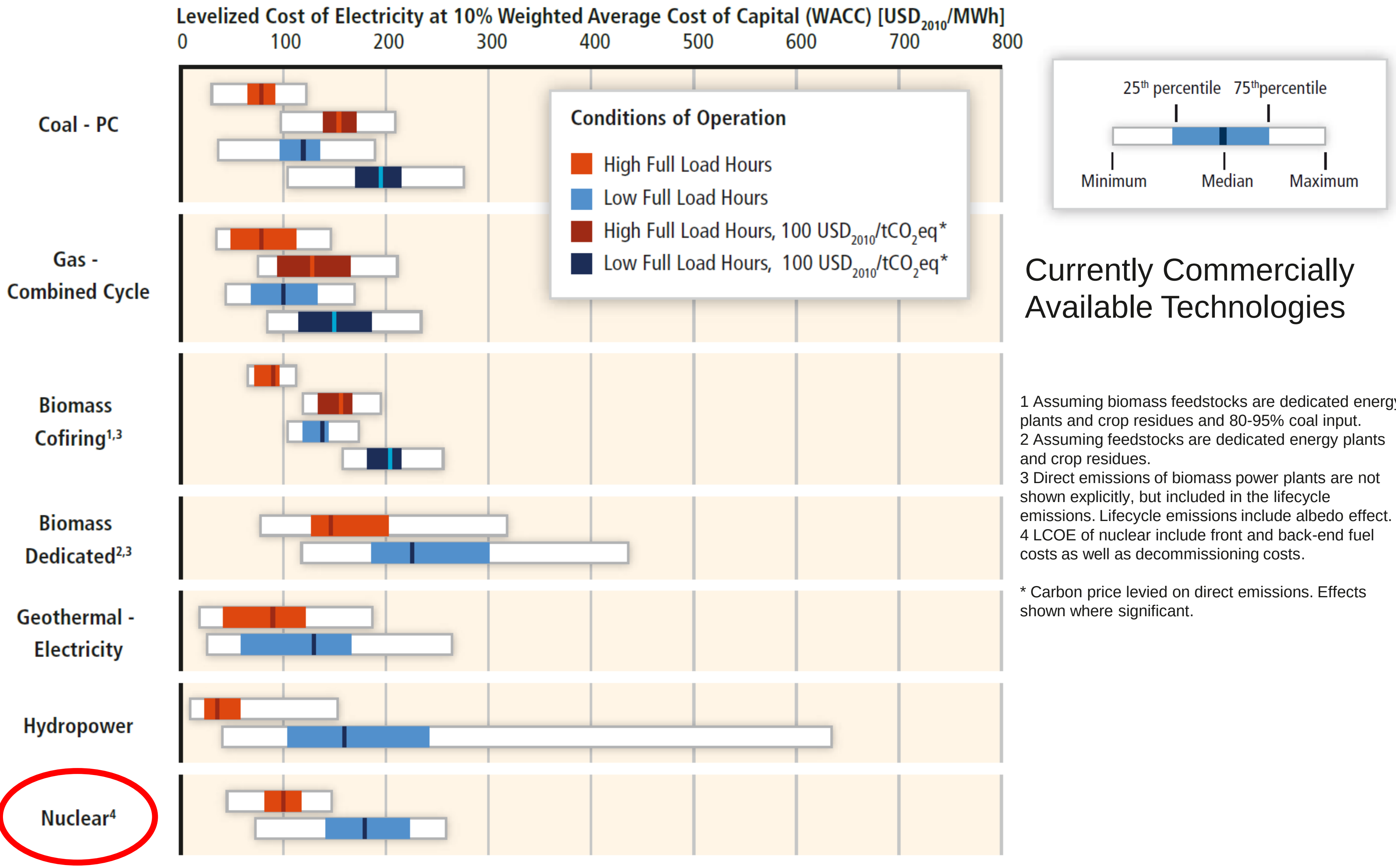


LCOE (Levelized Cost Of Electricity) for various technologies (USD/MWh)

- ✓ **Measures <u>lifetime costs</u> divided by energy production**
- ✓ **Calculates present value of the <u>total cost of building and operating a power plant</u> over an assumed lifetime**
- ✓ **Allows <u>comparison of different technologies</u> with unequal life spans, project size, different capital cost, risk, return, and capacities**

Source:
IEA/NEA, Projected Costs of Generating Electricity, 2015

Cost of electricity

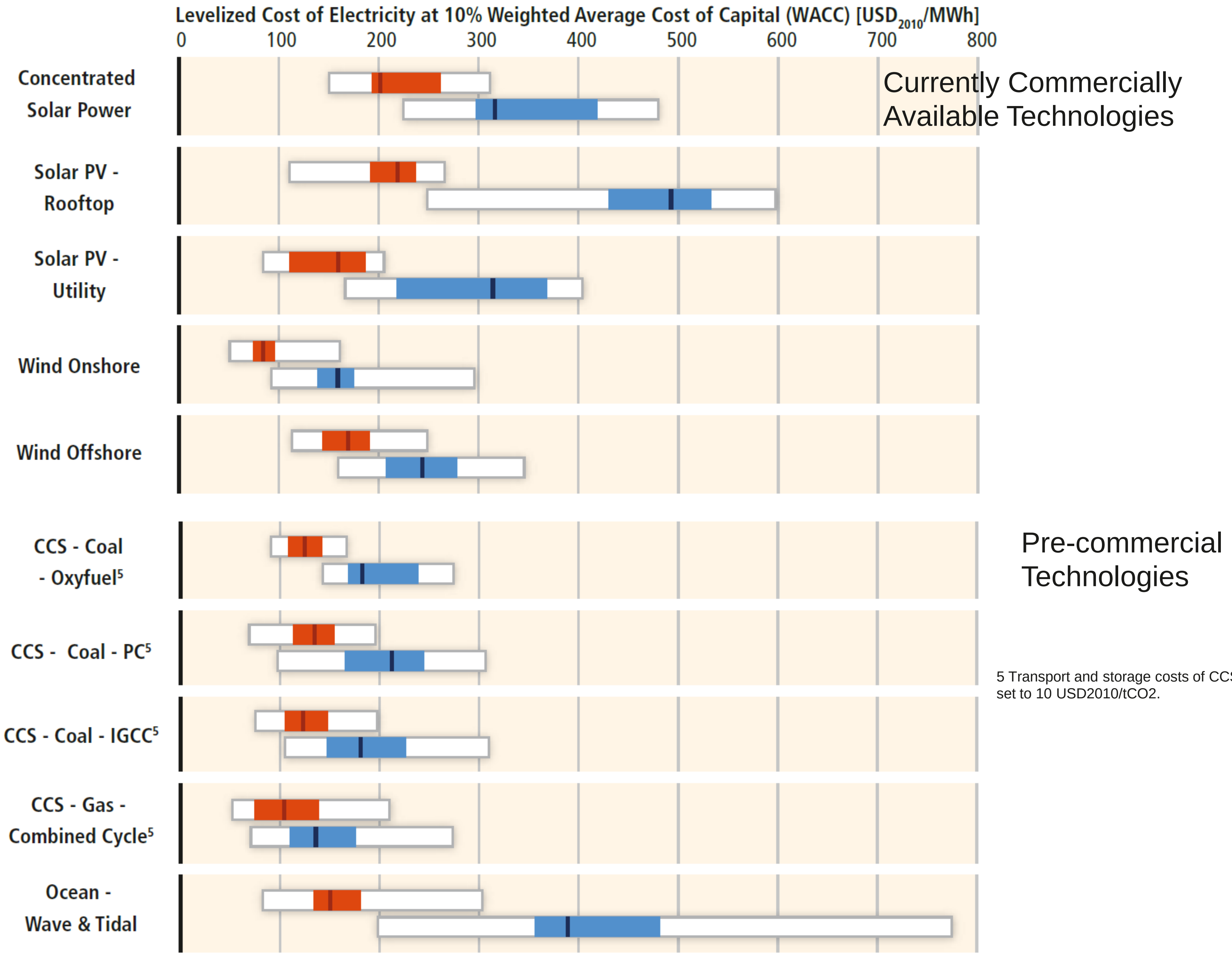


Currently Commercially Available Technologies

1 Assuming biomass feedstocks are dedicated energy plants and crop residues and 80-95% coal input.
2 Assuming feedstocks are dedicated energy plants and crop residues.
3 Direct emissions of biomass power plants are not shown explicitly, but included in the lifecycle emissions. Lifecycle emissions include albedo effect.
4 LCOE of nuclear include front and back-end fuel costs as well as decommissioning costs.

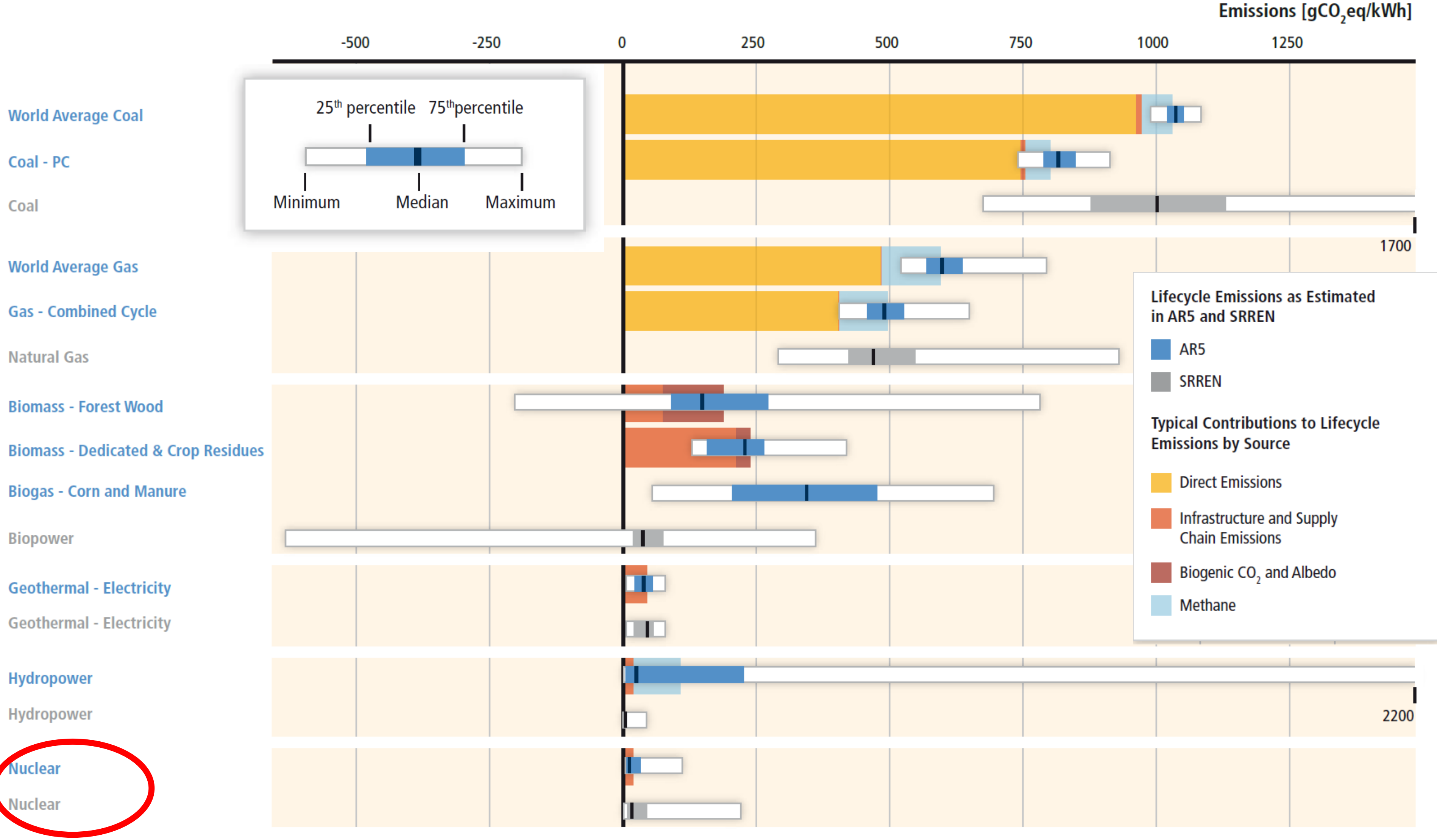
* Carbon price levied on direct emissions. Effects shown where significant.

Climate Change 2014 Mitigation of Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), p. 71 - Cambridge University Press

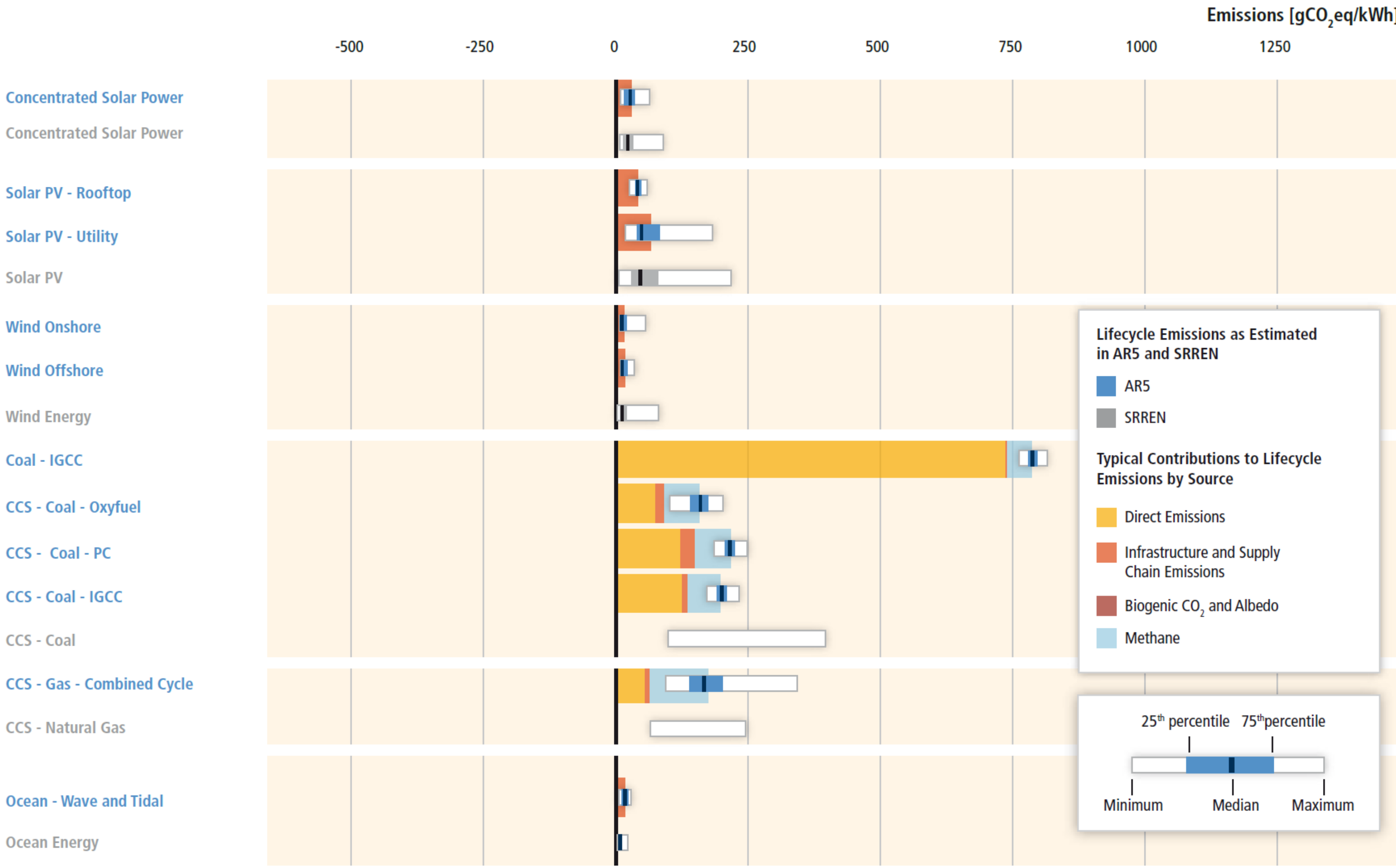


5 Transport and storage costs of CCS are set to 10 USD2010/tCO2.

Lifecycle emissions compared



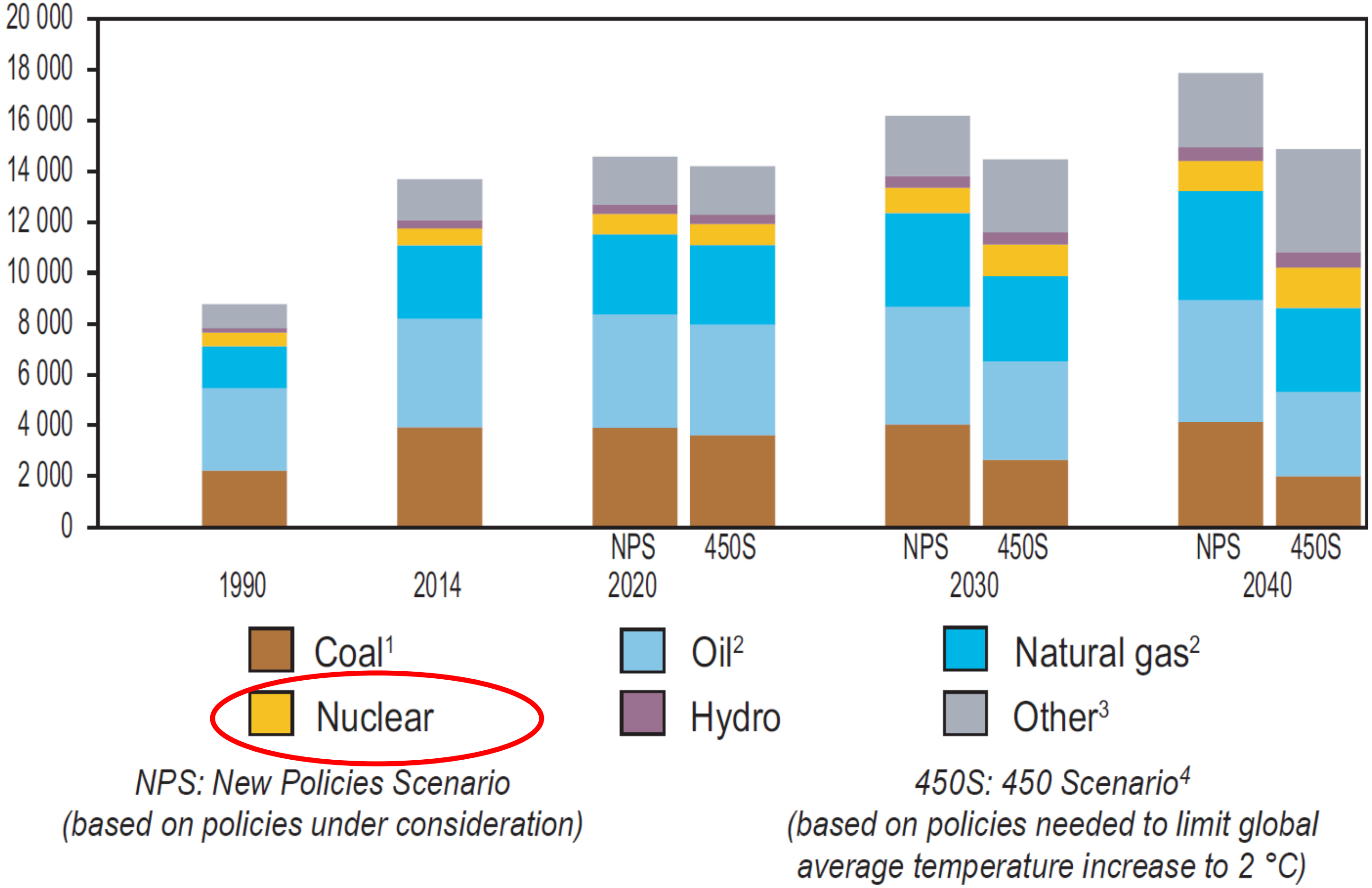
Climate Change 2014 Mitigation of Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), p. 71 - Cambridge University Press


Emissions [gCO_2eq/kWh]
-500
-250
0
250
500
750
1000
1250
Concentrated Solar Power
Concentrated Solar Power
Solar PV - Rooftop
Solar PV - Utility
Solar PV
Wind Onshore
Wind Offshore
Wind Energy
Coal - IGCC
CCS - Coal - Oxyfuel
CCS - Coal - PC
CCS - Coal - IGCC
CCS - Coal
CCS - Gas - Combined Cycle
CCS - Natural Gas
Ocean - Wave and Tidal
Ocean Energy
Lifecycle Emissions as Estimated in AR5 and SRREN
AR5
SRREN
Typical Contributions to Lifecycle Emissions by Source
Direct Emissions
Infrastructure and Supply Chain Emissions
Biogenic CO_2 and Albedo
Methane
25th percentile
75th percentile
Minimum
Median
Maximum

Perspectives and issues

Worldwide energy trends: projection on energy supply

Total primary energy supply by fuel type (in million tonnes oil equivalent)



1. In these graphs, peat and oil shale are aggregated with coal.
2. Includes international aviation and marine bunkers.
3. Includes biofuels and waste, geothermal, solar, wind, tide, etc.
4. Based on a plausible post-2016 climate-policy framework to stabilise the long-term concentration of global greenhouse gases at 450 ppm CO2-equivalent.

Source: IEA, Key World Energy Statistics, 2017

How long will U resources last ?

As an example, **fuel fabrication** for a big nuclear power plant with **1000 MWe production**, requires about **160 tons natural U per year**

→ In the **current scheme** with about 450 reactors and **369.000 MWe capacity**, "conventional" (cheap) **reserves would last for another 80 years** (maybe less if average reactor power will increase)

→ Should nuclear power increase as in some of the above scenarios, we should think about (more expensive) resources like phosphates (doable) or U from sea water (still under study)

→ Switching to fast reactors/Thorium cycle would increase availability to a few 100/few 1000 years

	million tons uranium
Australia	1.14
Kazakhstan	0.82
Canada	0.44
USA	0.34
South Africa	0.34
Namibia	0.28
Brazil	0.28
Russian Federation	0.17
Uzbekistan	0.12
World total (conventional reserves in the ground)	4.7
Phosphate deposits	22
Seawater	4 500

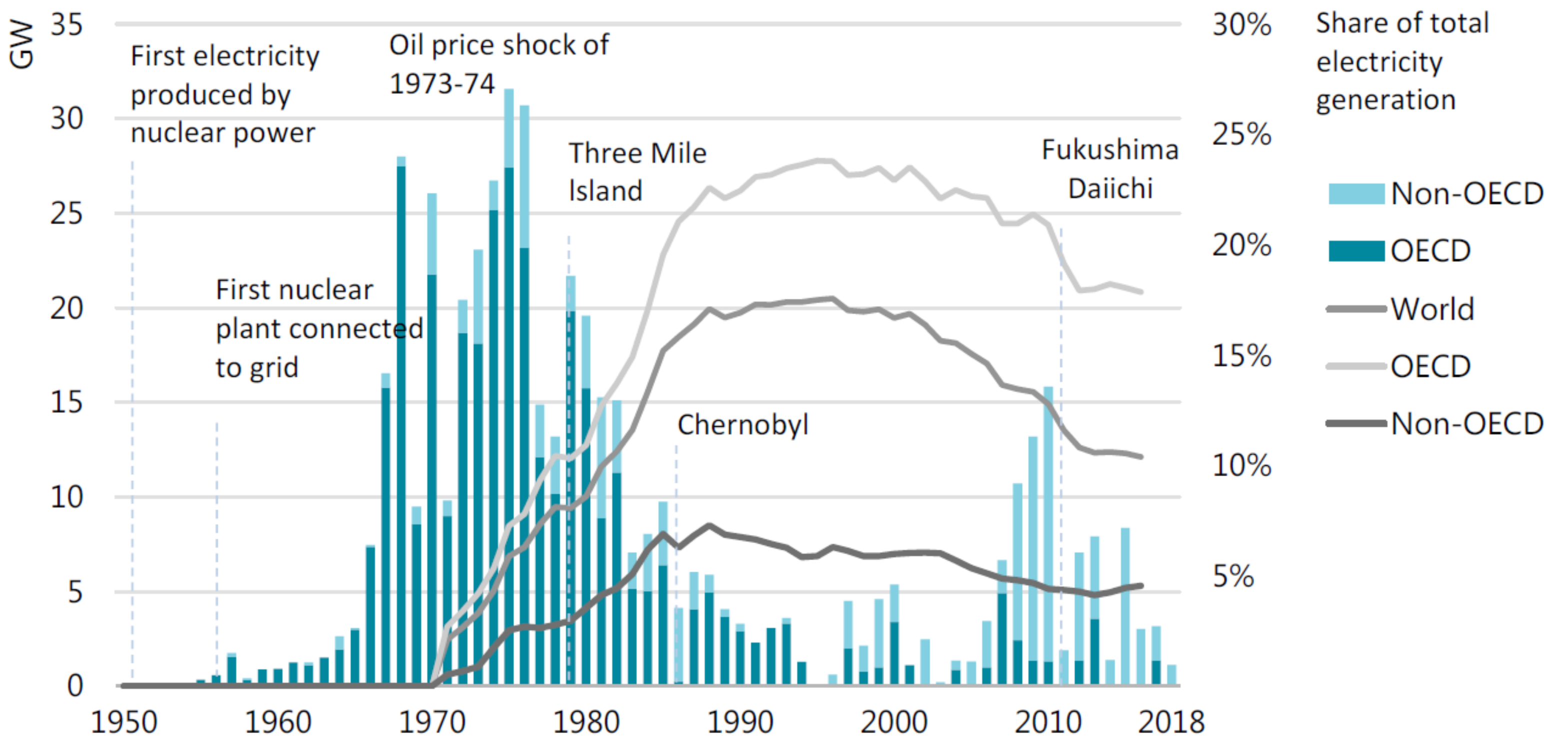
Lifetime of uranium resources (in years) for current reactor technology and future fast neutron systems (based on 2006 uranium reserves and nuclear electricity generation rate)

	Identified resources	Total conventional resources	Total conventional and unconventional resources
Present reactor technology	100	300	700
Fast neutron reactor systems	> 3 000	> 9 000	> 21 000

Source: OECD/NEA, Nuclear Energy Outlook, 2008

Reactor ageing

Reactor construction starts and share of nuclear power in total electricity generation

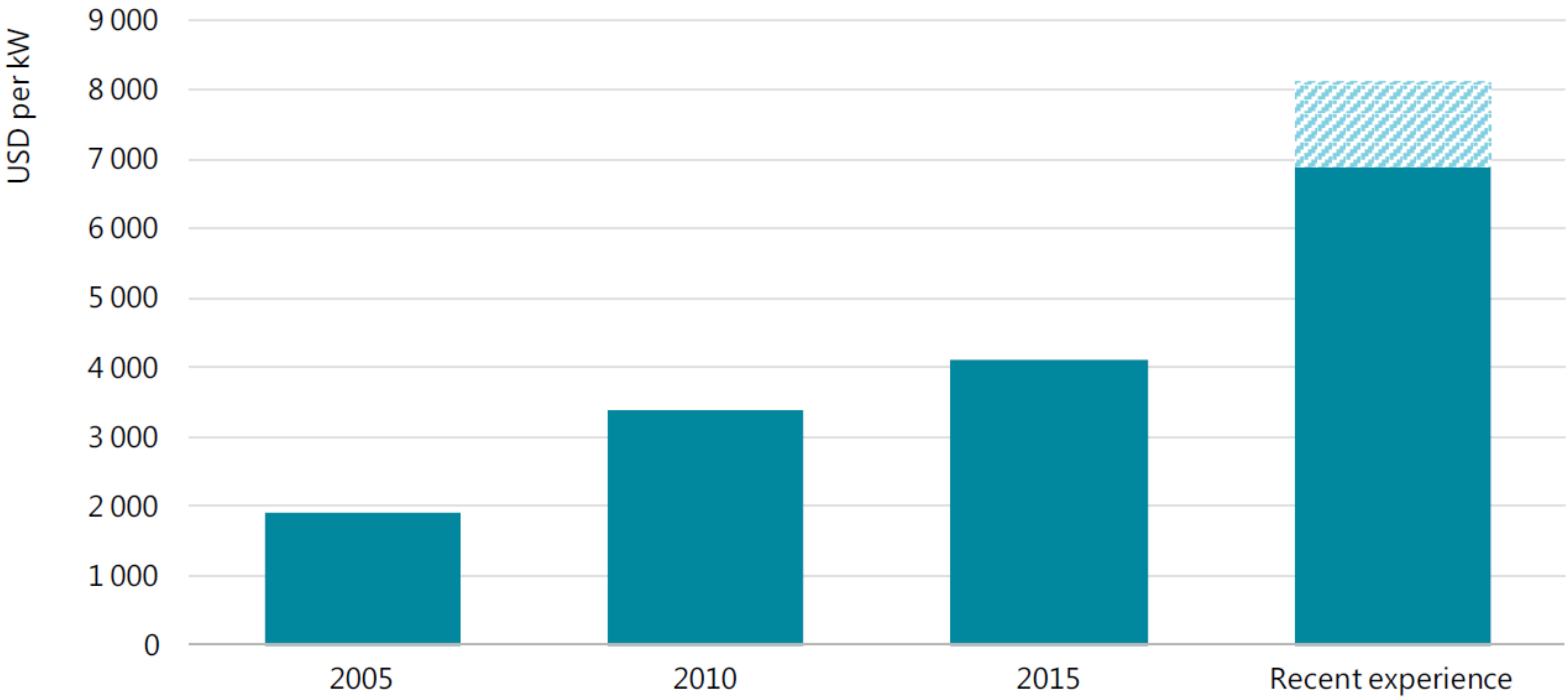


Typical lifetime of a plant is 40 to 60 years
→ many are being or are going to be decommissioned

Nuclear Power in a Clean Energy System, IEA 2019

Construction costs

Projected overnight construction cost[1] of nuclear power capacity and recent United States and Western European experience



Source: IEA analysis based on IEA/NEA (2005, 2010 and 2015 editions), Projected Costs of Generating Electricity.

Nuclear Power in a Clean Energy System, IEA 2019

[1]Cost of a construction project if no interest was incurred during construction, as if the project was completed "overnight."

Market pressure

NUCLEARENERGY INSIDER

Analysis for the nuclear energy community

Home | New Build | Supply Chain | Small Modular Reactors | Operations & Maintenance

Scientists warn 20% of US nuclear capacity at risk; Toshiba liquidates UK new build company

Nov 14, 2018

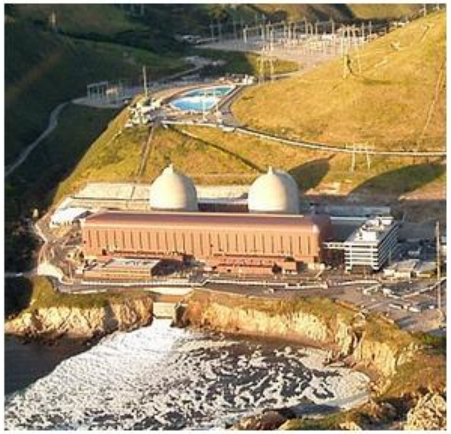
Our pick of the latest nuclear power news you need to know.

Scientists say 20% of US nuclear capacity unprofitable or set to close

More than one third of operational U.S. nuclear plants, representing 20% of nuclear capacity, are unprofitable or scheduled to close, the Union for Concerned Scientists (UCS) said in a report published November 8.

Nuclear operators face continuing pressure from low wholesale electricity prices, driven by low gas prices and rising renewable energy capacity. The states of New Jersey, New York and Illinois have introduced support mechanisms for nuclear plants but much wider support is required to prevent a hike in carbon emissions, UCS said.

In May, Bloomberg New Energy Finance (BNEF) said more than a quarter of U.S. nuclear power plants do not earn enough



The Diabolo Canyon reactors in California are among 13 U.S. reactors set to close in 2018-2025 and many more could follow. (Image credit: Wikimedia Commons)

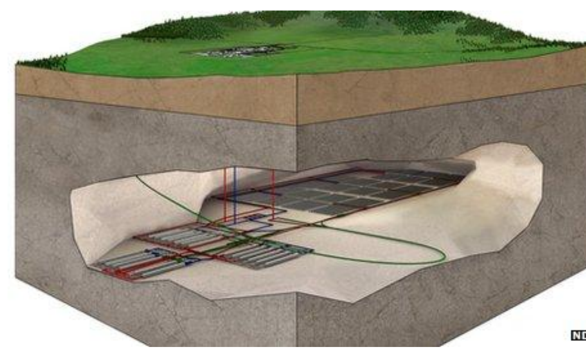
Nuclear waste – how much and what to do ?

In 1 year, a **typical** high power **reactor** produces about **1,200 Kg of radioactive material** in the fuel, of which **400 Kg** are long-lived, with half-lives from a few hundred to a few hundred thousand years → they **need to be segregated**

Spent fuel assemblies are put in **interim safe storage** for decades, but the same has to be done for the heavily activated structural materials when dismantling a decommissioned plant

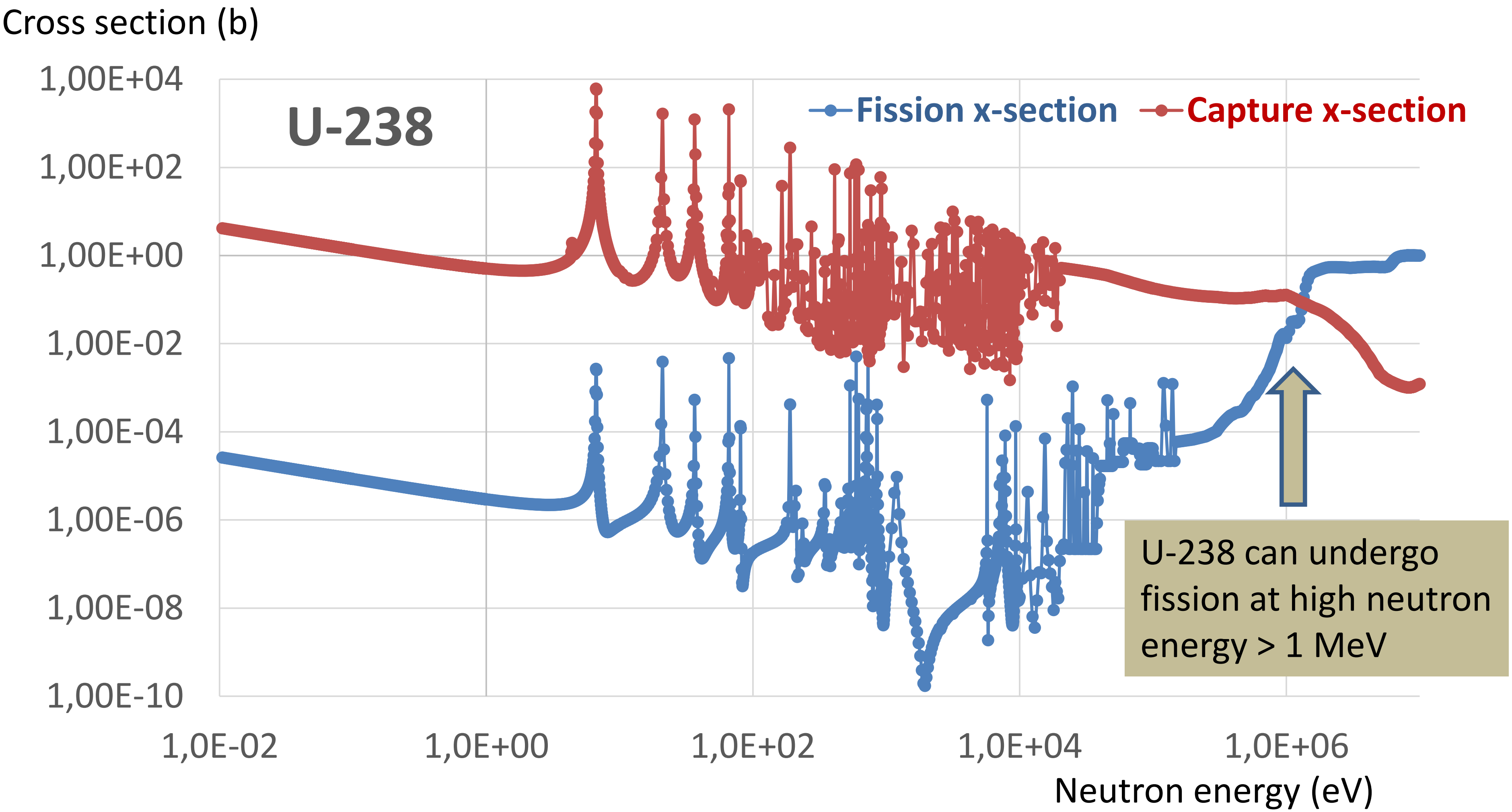

Example of spent fuel containers

Some countries (most advanced are Finland, Sweden and France) have plans to store spent fuel and other High Level and possibly Intermediate Level Waste in **underground repositories** at a few hundred meters depth: the so-called **geological repositories**
→ After a few 100,000 years radioactivity dropped to safe levels



Some countries (France, in particular) recycle the spent fuel by using specific processes to extract Uranium and Plutonium that can be used to produce fresh fuel (MOX, Mixed Oxide fuel)

Fast spectrum systems and waste incineration (transmutation)



Several **Minor Actinides** are characterized by a **fission threshold** around the **MeV**

➔ Such isotopes can be burnt in **fast reactors or in fast Accelerator Driven Systems (ADS)** (neutron spectrum from 10 keV to 10 MeV)

➔ See presentation on Generation IV reactors by R. Caciuffo and MYRRHA project by H. Abderrahim

Nuclear accidents

The fission process creates radioactive substances that can be dangerous for the environment and for human health→ they **must** be contained as much as possible

Chernobyl, Soviet Union, 1986

Fukushima, Japan, 2011

Safety measures are essential and are subject of continuous research and improvement

Accidents into perspective…

Train carrying liquid gas explodes in Italy killing 12

At least 50 injured as freight train derails in Viareggio and hits homes of sleeping families

▲ The aftermath of the explosion of gas tanks on a derailed train in the Italian town of Viareggio. Photograph: Olycom SPA /Rex Features

The Guardian, 30 June 2009

africanews. EN NEWS

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Mozambique fuel truck explosion: 73 dead, 100s injured

with AFP 17/11/2016

Los Angeles Times

CALIFORNIA

'Avian incident' knocks out 84% of massive California solar farm

A solar power facility in Borrego Springs, Calif., on Feb. 11. (Al Seib / Los Angeles Times)

By BLOOMBERG JUNE 20, 2019 | 8:05 AM

An "avian incident" sparked a fire at one of California's biggest solar farms, affecting 1,200 acres and knocking out 84% of the California Valley Solar Ranch's generating capacity.

The June 5 incident didn't damage solar panels at the 250-megawatt power plant, but distribution poles and cables need to be replaced, according to a regulatory filing Wednesday from owner Clearway Energy Inc. The company didn't say exactly how the blaze was ignited. …

About 40 megawatts of the San Luis Obispo County facility are in operation, and it's expected to return to full service by July 1. Clearway expects the incident to cost $8 million to $9 million this year, after estimated insurance recovery.

LATEST CALIFORNIA ›

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July 22, 2019

CALIFORNIA
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Californians living in wildfire-prone areas losing homeowners insurance following historic blazes
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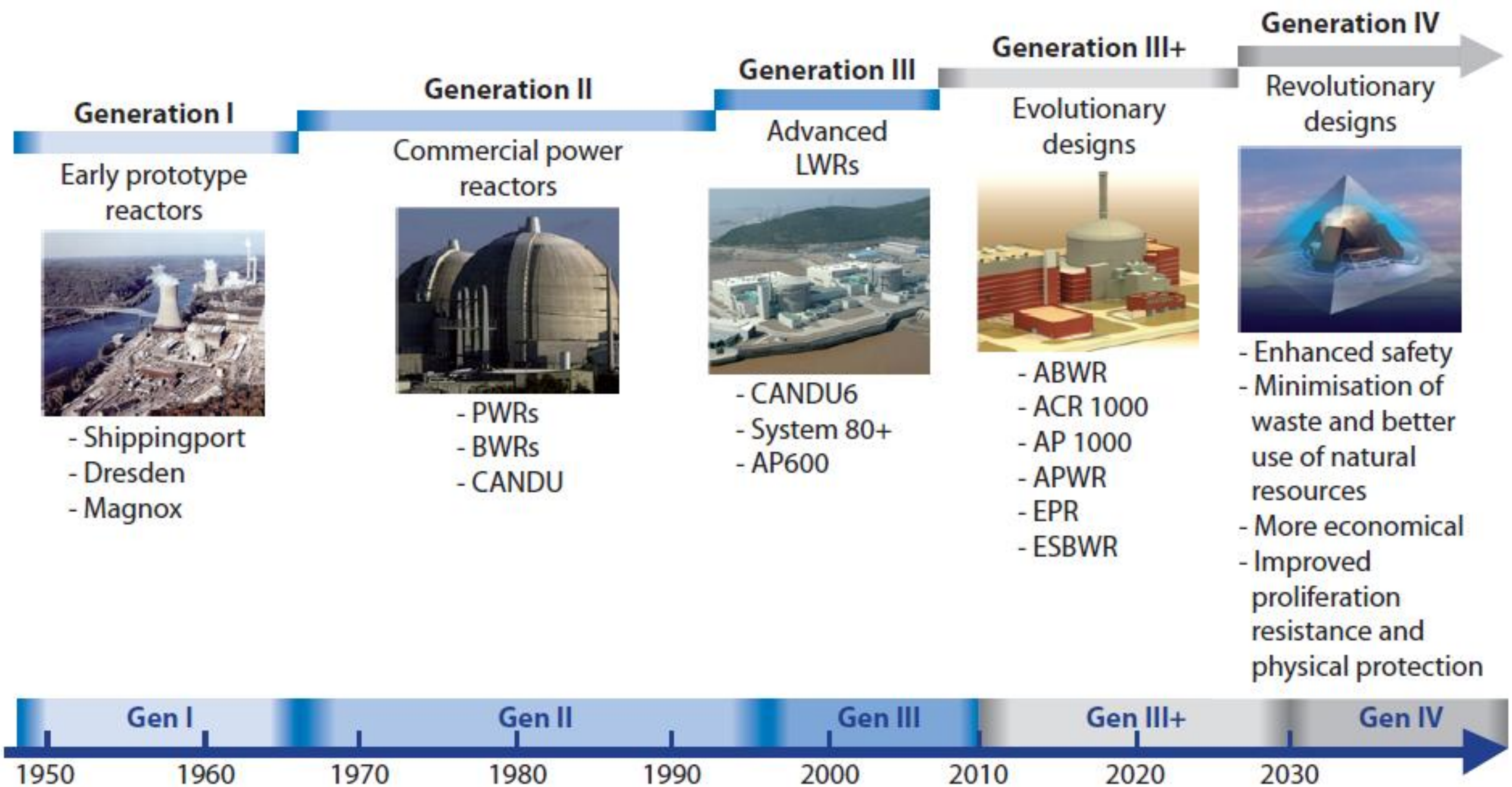
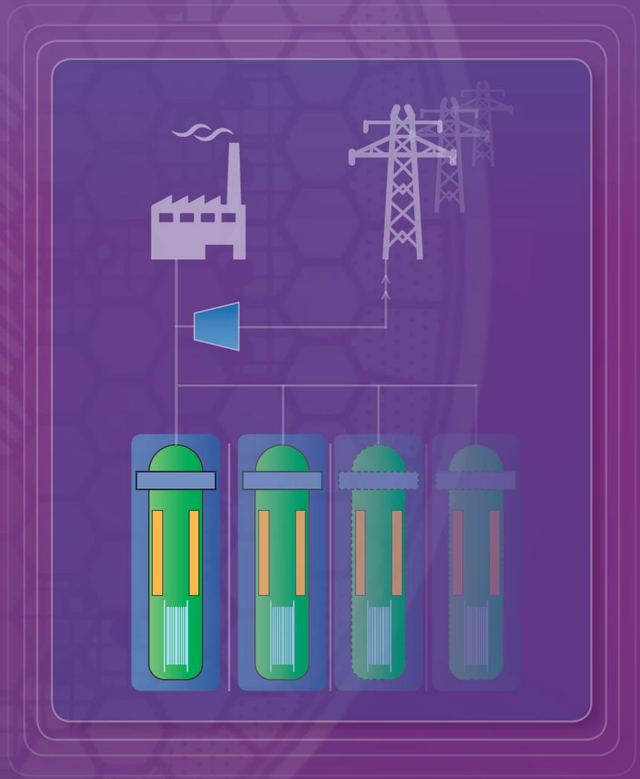
CALIFORNIA
Priest stole more than $95,000 from offerings in Northern California, diocese says
July 22, 2019

Past and future



Advances in Small Modular Reactor Technology Developments

A Supplement to:
IAEA Advanced Reactors Information System (ARIS)
2018 Edition



IAEA
International Atomic Energy Agency