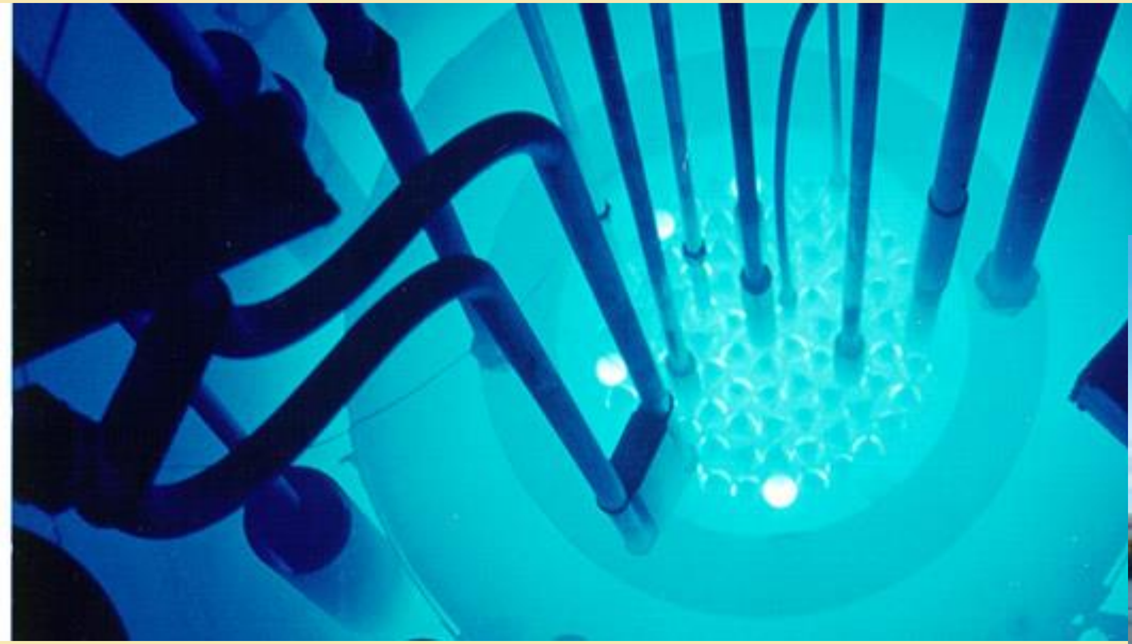
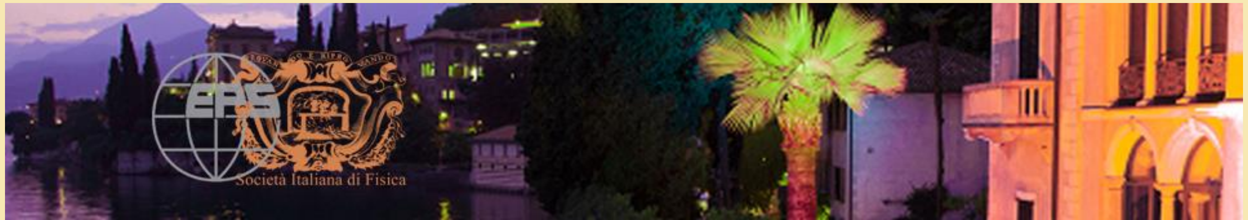
Fission safety and risks



M. Ripani
INFN Genova, Italy

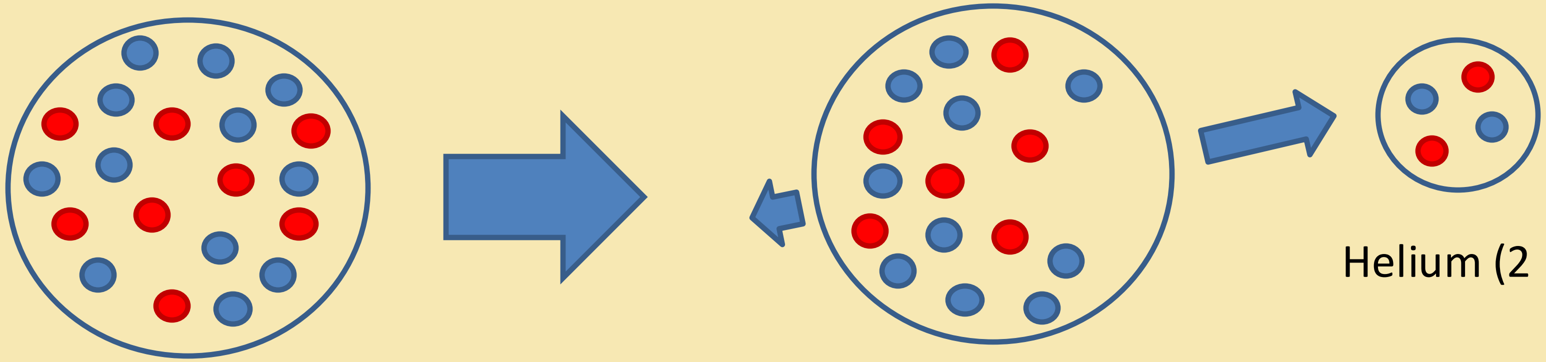
Joint EPS-SIF International School on Energy 2025



Radioactivity

Certain atomic nuclei are «unstable», that is, they tend to break up, releasing energy

Alpha (α) decay



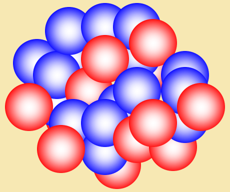
Helium (2 p, 2 n)

Uranium 238 (92 protons, 146 neutrons)

Thorium 234 (90 protons, 144 neutrons)

Elements and isotopes

There are many nuclear species



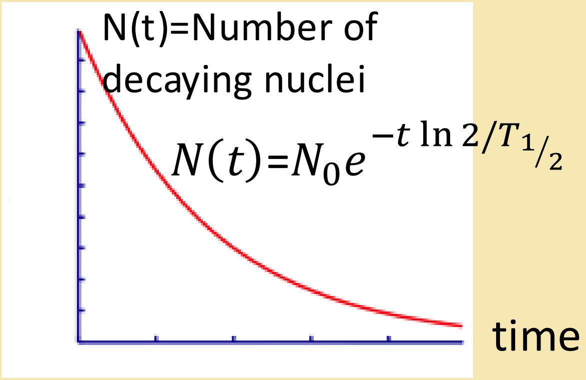
They are classified with two numbers:

Z = number of protons, which determines the chemistry

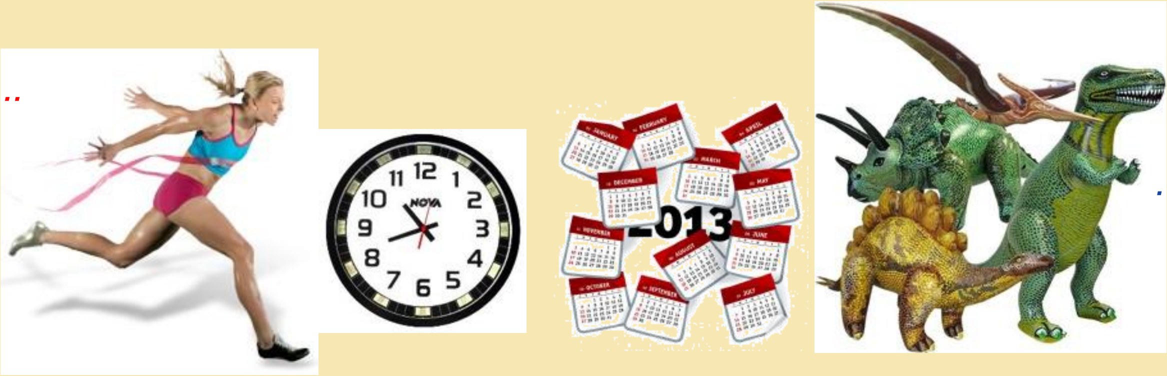
A = total number of nucleons (protons + neutrons)

- *each nuclear species is uniquely determined by its A and Z*
- *about 4400 known (A,Z) combinations (species)*
- *about 250 stable (minimum energy: equilibrium)*
- *the rest: radioactive (unstable)*

Each radioactive substance has a *characteristic time $T_{1/2}$* in which its radioactivity is halved.



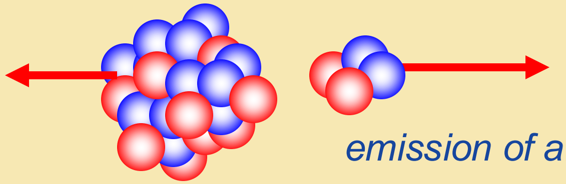
Some species decay in seconds...



...others in million (or even billion) years

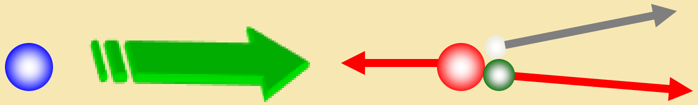
The three main types of radioactivity

alpha



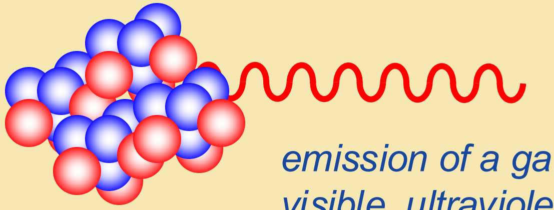
emission of an alpha particle (= helium nucleus)

beta(+)



a neutron transforms into a proton (or a nucleus with N neutrons and Z protons transforms into a nucleus with N-1 (N+1) neutrons and Z+1 (Z-1) protons, emitting an electron (positron, or beta/+ particle) and an antineutrino(neutrino)

gamma

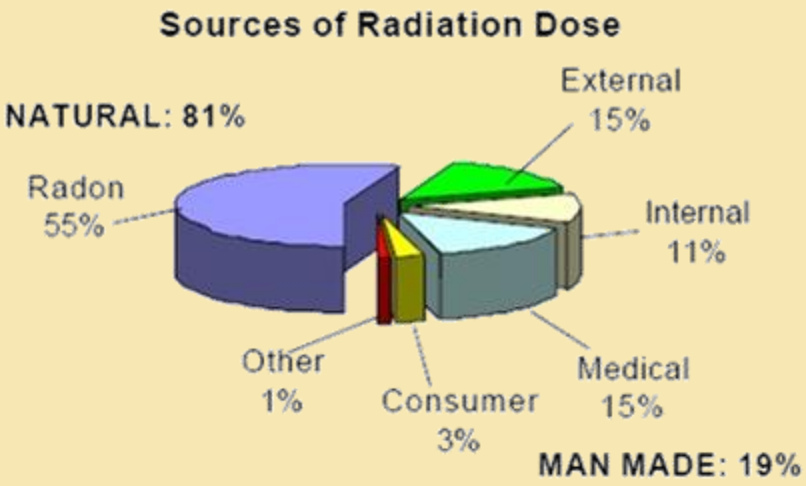


emission of a gamma ray (=photon, such as radio waves, microwaves, infrared, visible, ultraviolet, X-rays:
the only difference is the wavelength or, if you prefer, the energy)

Very often, alpha and beta radiation lead to the formation of nuclei in excited states which decay by gamma radiation

Radiation is part of our everyday life on earth

Radiation around us



From the sky: about 30 neutrons and 120 cosmic rays pass through our body per second

From air: about 10 atoms per second (Radon, Polonium, Bismuth, Lead) disintegrate in the lungs releasing alpha, beta, gamma

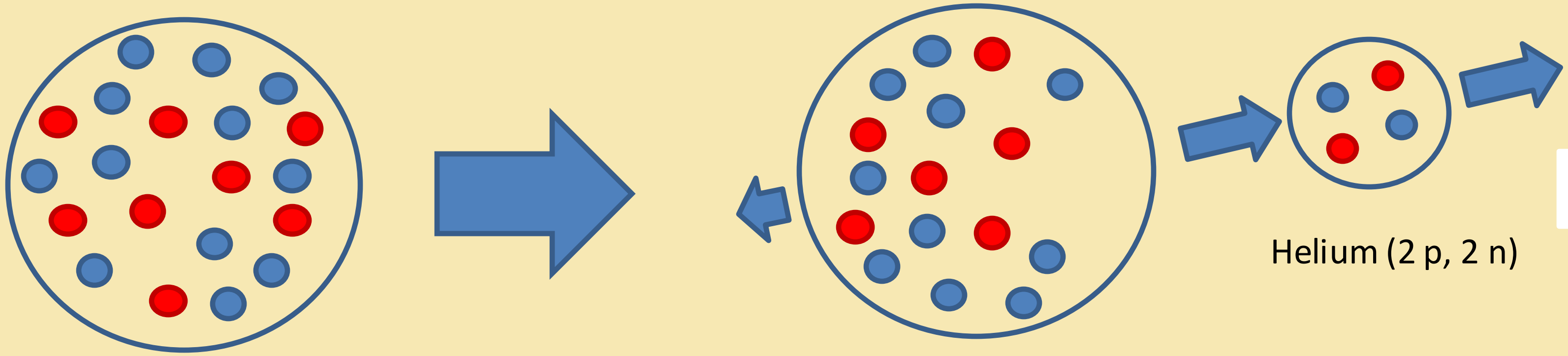
From diet: about 4500 atoms per second (Potassium-40) disintegrate in our body, releasing beta and gamma; also, about 2 atoms per second of natural uranium release alpha

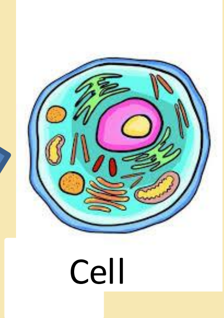
From the ground and buildings: about 56,000 gamma per second pass through our body

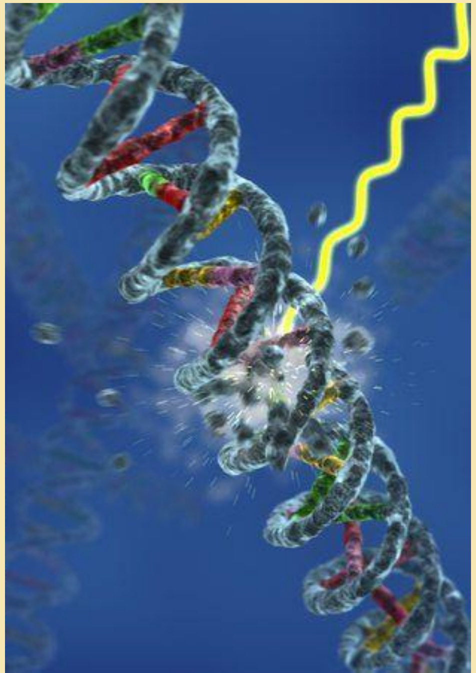
≈ 6000 decays per second of Potassium-40 (^{40}K) per m^3 of sea water

Biological effects of radioactivity

Radioactivity can be dangerous to the environment and humans due to cell damage (by *direct exposure* or by *inhalation or ingestion*)

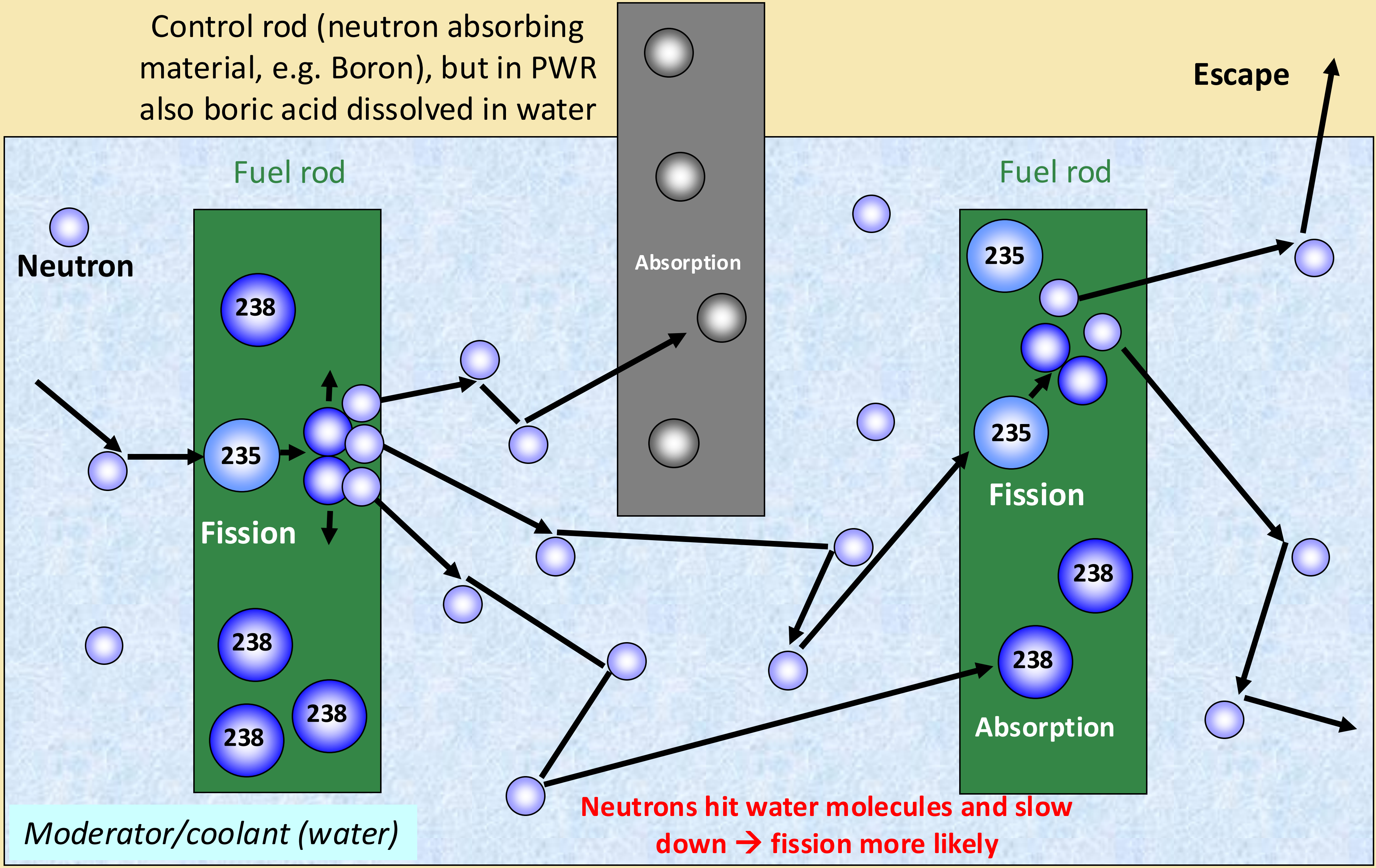






radiation can break DNA and cause mutations probably plays a role in evolution

The “thermal” reactor



Control rod (neutron absorbing material, e.g. Boron), but in PWR also boric acid dissolved in water

Uranium 238 practically does not produce fission but captures neutrons forming heavier elements that do not exist in nature, including Plutonium, which is a fuel

Neutrons hit water molecules and slow down → fission more likely

Operation of a reactor

Three key concepts to understanding the operation of a reactor:

- ✓ **Reactivity** → how the fission chain reaction changes over time (i.e., how k_{eff} changes)
- ✓ **Reactor stability**, the feedback mechanisms that hold it steady
- ✓ **Plant stability**, what happens when you connect your reactor to the rest of the plant (and beyond)

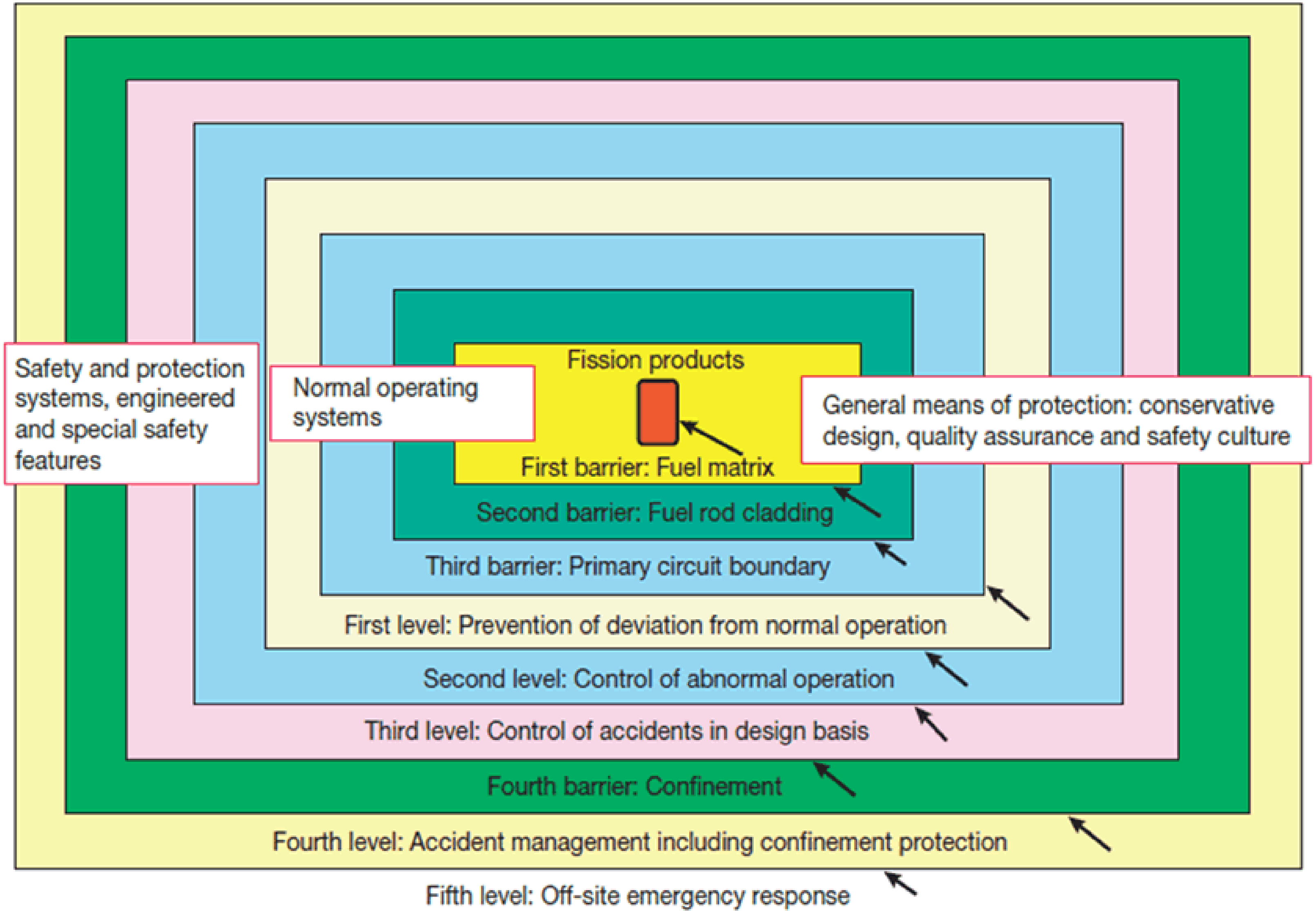
- ☐ Reactivity oscillates around zero, and, generally speaking, reactivity insertions must be below 1 $ < 1 %
- ☐ Otherwise, the reactor will become prompt-critical, with kinetics dominated by prompt neutrons and non-controllable
- ☐ In day-to-day operation, reactivity will typically change by a few pcm (a few 10^{-5})

Basic safety functions

Nuclear safety → avoiding the release of radioactive fission products to the environment, amounts to 3 things:

- ✓ **Criticality (reactivity)**→ chain reaction shut down in case of problems !
- ✓ **Cooling** → removing the decay heat to avoid core damage
- ✓ **Containment** → maintaining the integrity of fuel, primary circuit and reactor building → three barriers to fission product release **→"Defence in depth"**

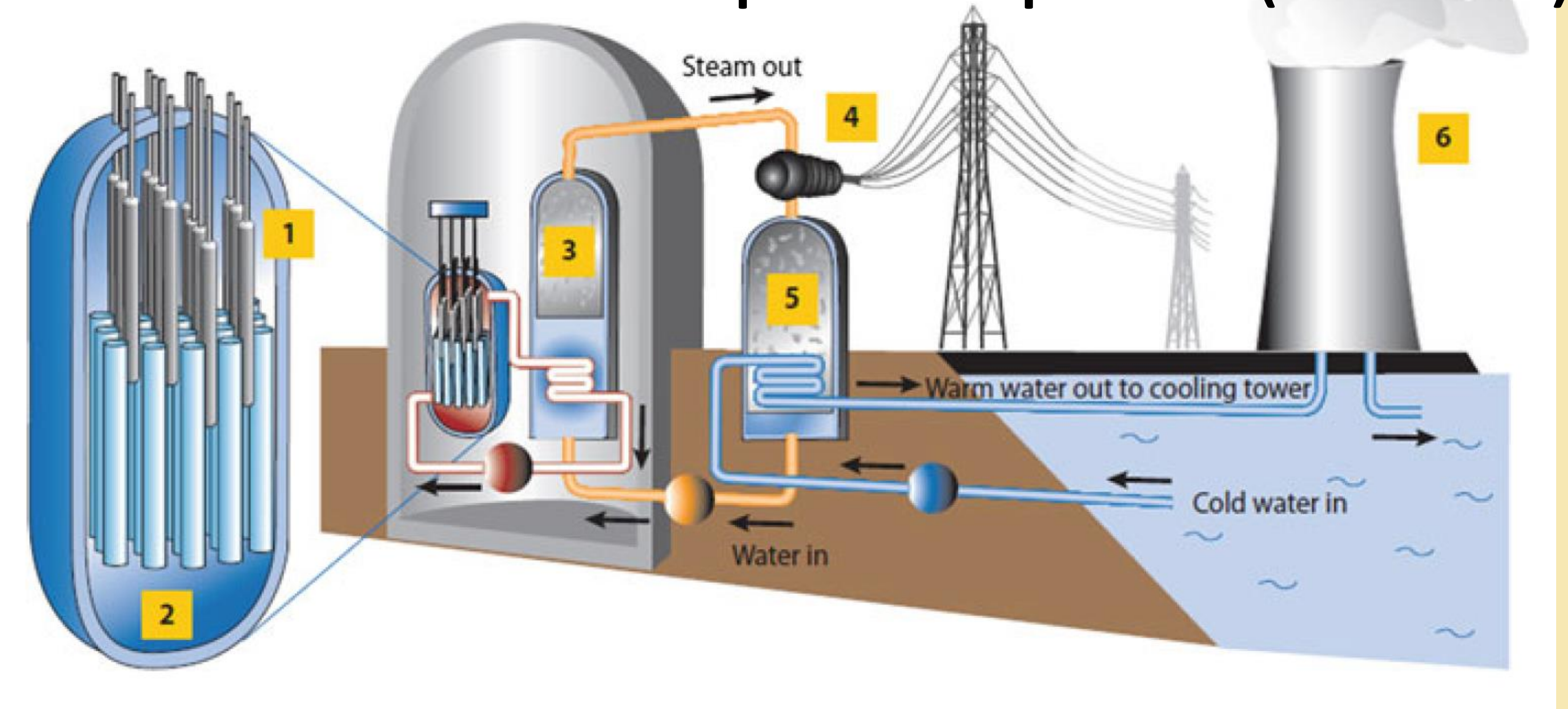
Defence in depth



© IAEA

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

The nuclear power plant (a PWR)



Basic components of a thermal nuclear power reactor (**Pressurised Water Reactor, PWR**):

1-Reactor: fuel rods (light blue) heats up pressurised water. **Water temperature is around 300 ^{o}C at a pressure of 155 bar**. Control rods (grey) absorb neutrons to control or halt the fission process.

2-Coolant and moderator: fuel and control rods are surrounded by water (primary circuit) that serves as coolant and moderator

3-Steam generator: water heated by the nuclear reactor transfers thermal energy through thousands of pipes to a secondary circuit of water to create high-pressure steam

➔ **the reactor core with its pressure vessel (1,2) and the steam generator (3) are protected by a containment building**

4-Turbo-generator set: steam drives the turbine, which spins the generator to produce electricity just like in a fossil-fuel plant

5-Condenser: removes heat to convert steam back to water, which is pumped back to the steam generator

6-Cooling tower: removes heat from the cooling water that circulates through the condenser, before returning it to the source at near-ambient temperature

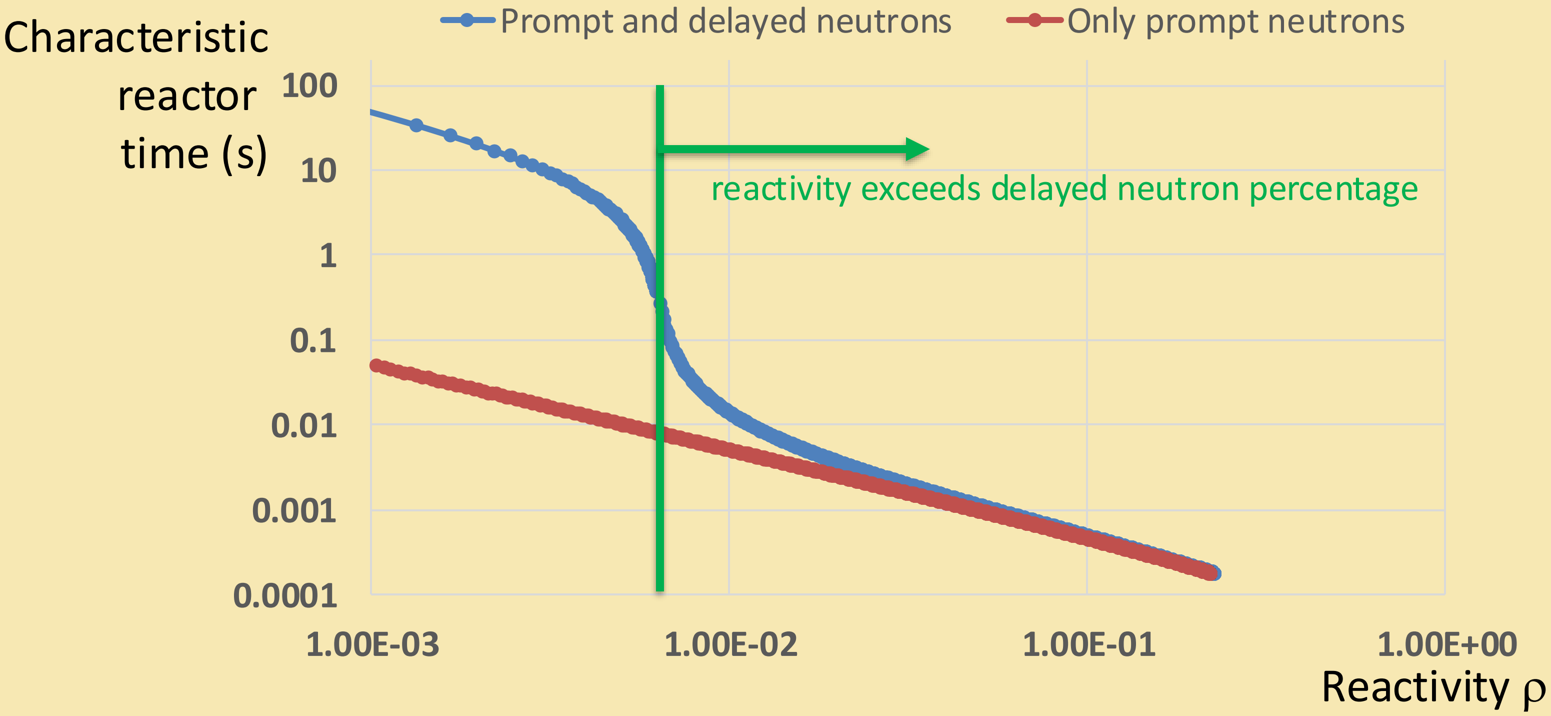
Source: OECD-NEA Nuclear Energy Today, 2nd edn. (2012), ISBN 978-92-64-99204-7. NEA Report No. 6885

Critical reactor control

After including delayed neutrons, kinetics equation admit solutions of the type $n(t) = n(0)e^{t/\tau_{ch}}$

With τ_{ch} = **characteristic reactor evolution time**

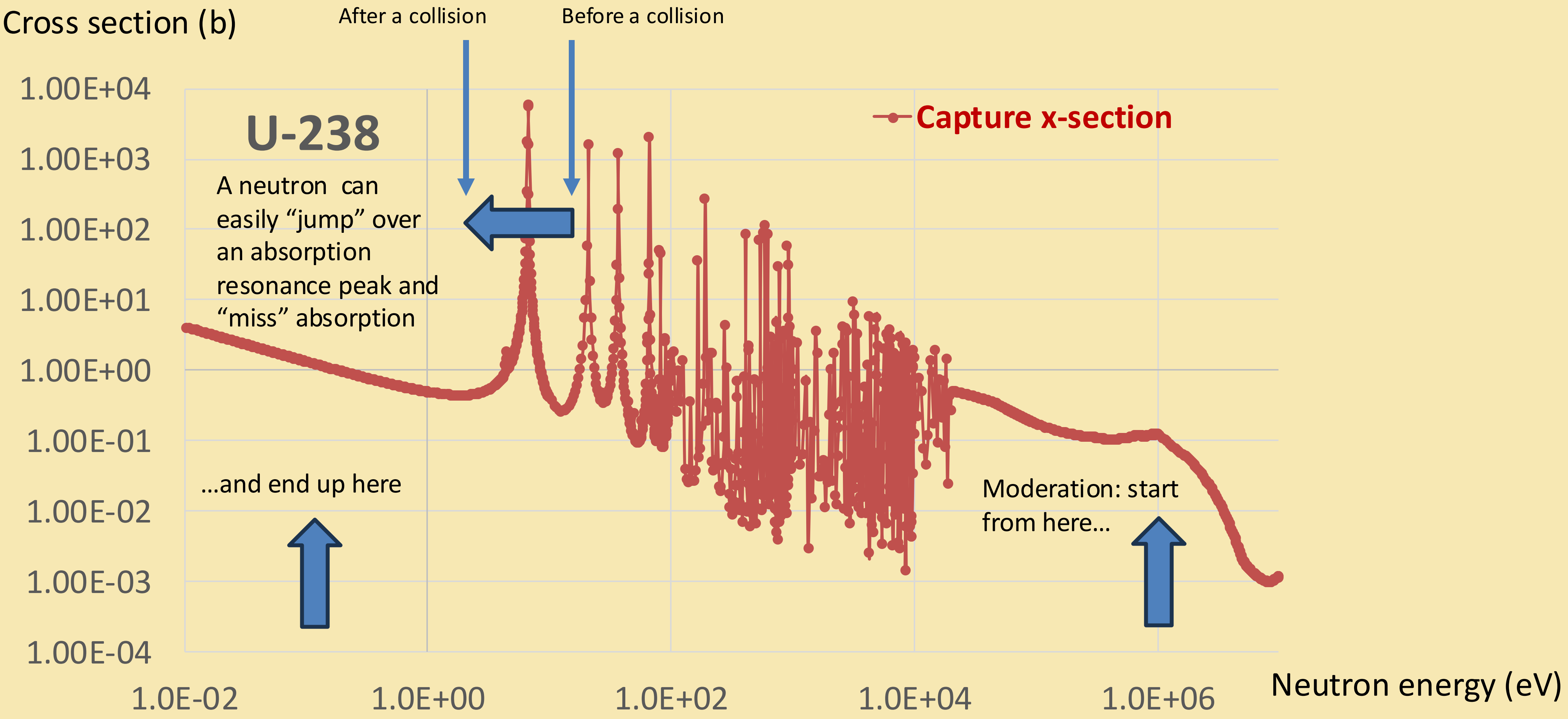
Example with for ^{235}U, β = 0.64 %, T_d=8.8 sec



- ✓ **If reactivity ρ < delayed neutron percentage β, τ_{ch} is above 250 ms ➔ safe**
- ✓ **ρ = 0 → τ_{ch} = ∞ ➔ critical, stable reactor**

An example of feedback mechanism: the Fuel Temperature Coefficient

- ✓ Fission occurs on U-235, while U-238 scatters or absorbs neutrons
- ✓ Absorption can be particularly strong if a neutron ends up colliding with U-238 on a resonance



A neutron can easily “jump” over an absorption resonance peak and “miss” absorption

…and end up here

Moderation: start from here…

An example of feedback mechanism: the PWR Fuel Temperature Coefficient

Temperature increases

↓

Atoms move faster

↓

Resonances are broadened (Doppler broadening)

↓

Probability of capture increases

↓

Probability to survive absorption decreases

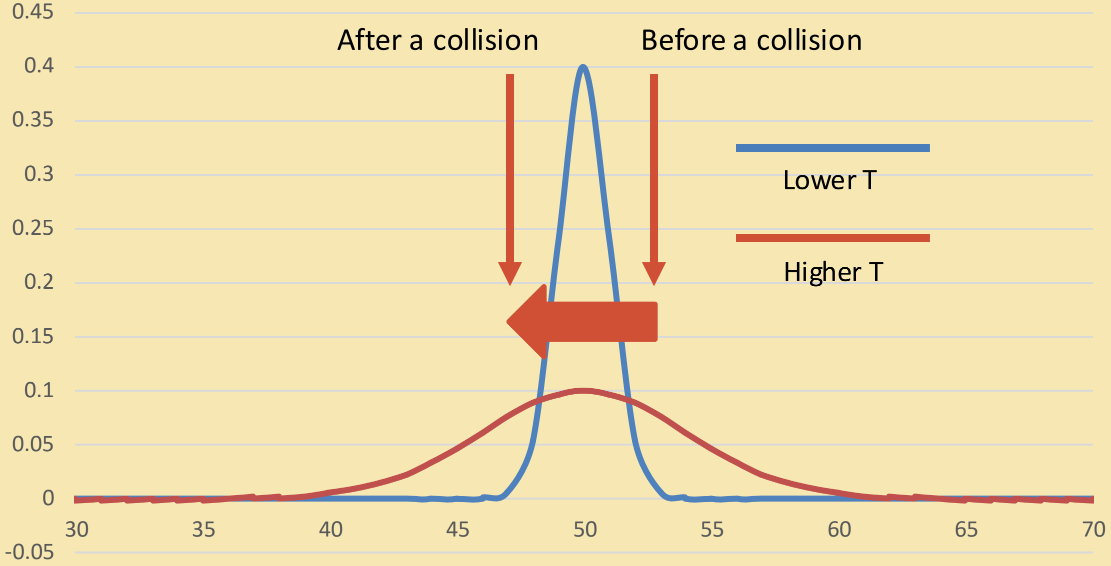
↓

K_{eff} and reactivity ρ go down

↓

Negative FTC

Doppler broadening



$$k_{eff} = \eta \, f \, \boxed{p} \, \varepsilon \, P_{NL}$$

- ✓ It's **a natural feedback mechanism that tends the control the power → good for safety**
- ✓ However, **if I want to increase the power**, I need to counteract this mechanism adding more neutrons, essentially by decreasing additional neutron absorption in the system

An example of feedback mechanism: the PWR (moderator) Void Coefficient

Temperature increases a lot

↓

Water (moderator) boils and steam bubbles are formed

↓

Neutrons are less slowed down

↓

Probability of fission decreases (η decreases)

↓

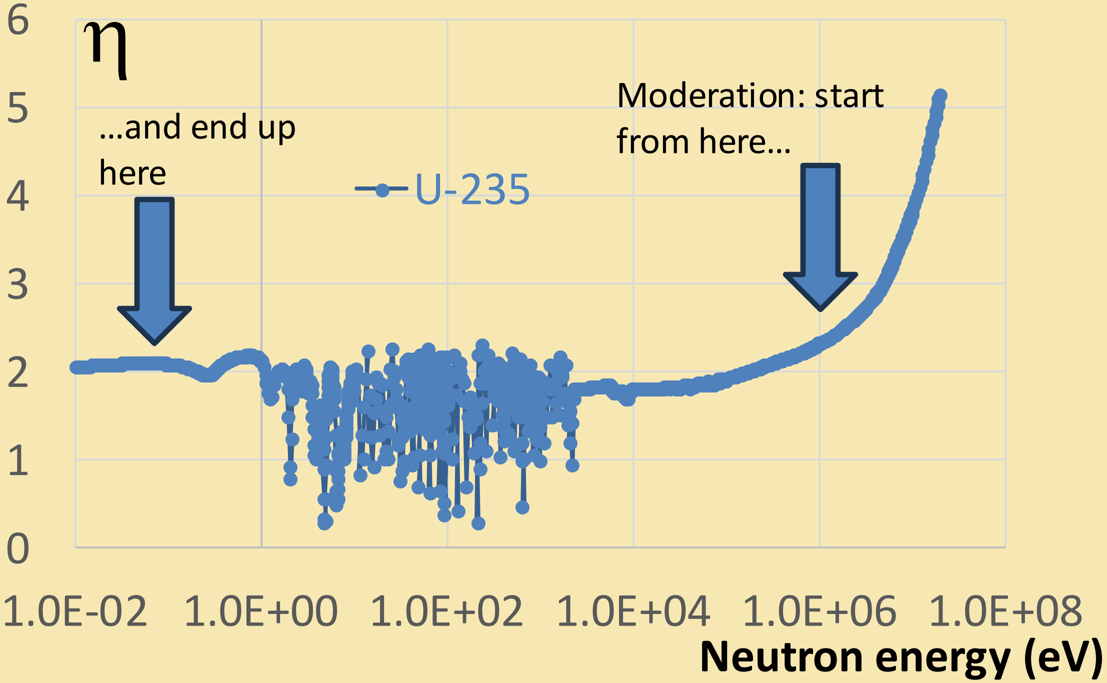
Reactivity goes down

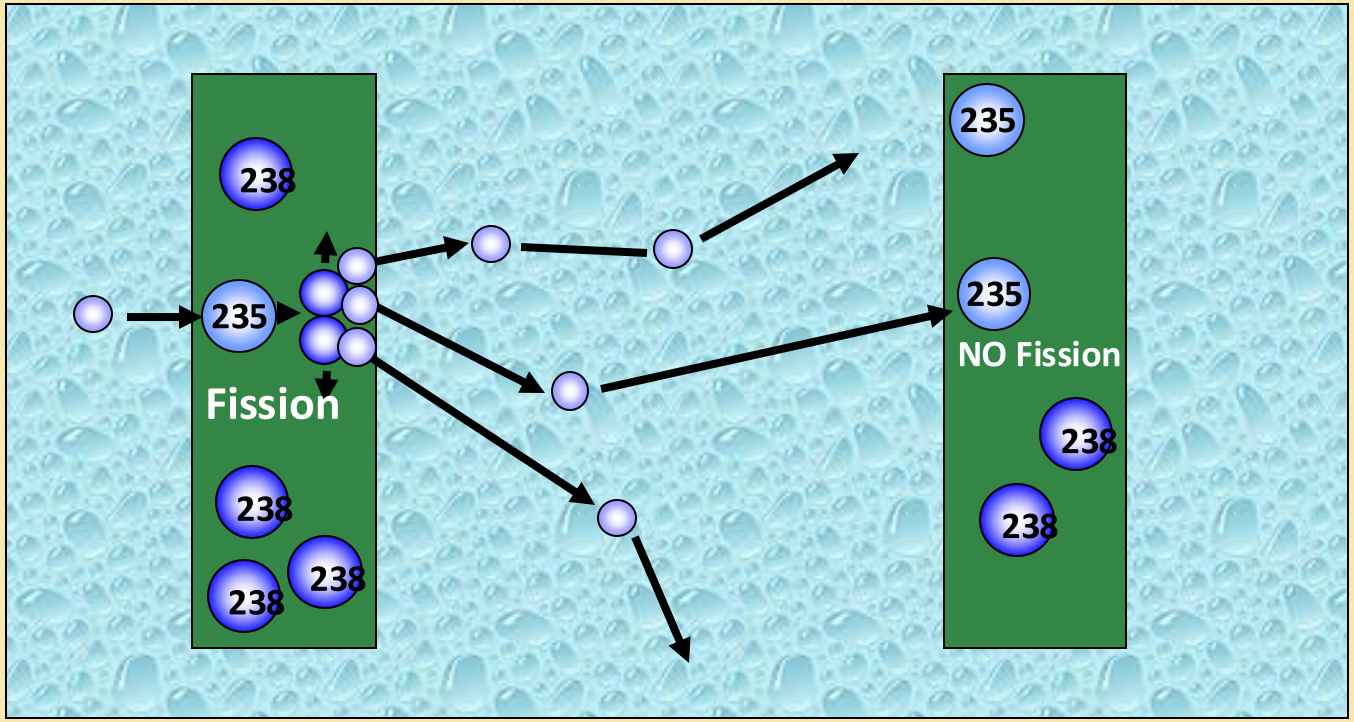
↓

Negative Void Coefficient

$$k_{eff} = \boxed{\eta}\, f\, p\, \varepsilon\, P_{NL}$$

- ✓ It's **a natural feedback mechanism that tends to correct an anomalous reactor state (boiling moderator) → good for safety**





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 radioisotopes created in fission continues for a long time after shut down**

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%, which still requires cooling, though…
Spent fuel rods are kept for long time in water pools, before storage or reprocessing.

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

The design basis

For a nuclear power station, **the main risk is an uncontrolled release of radioactive fission products to the environment** (a «radiological release»).

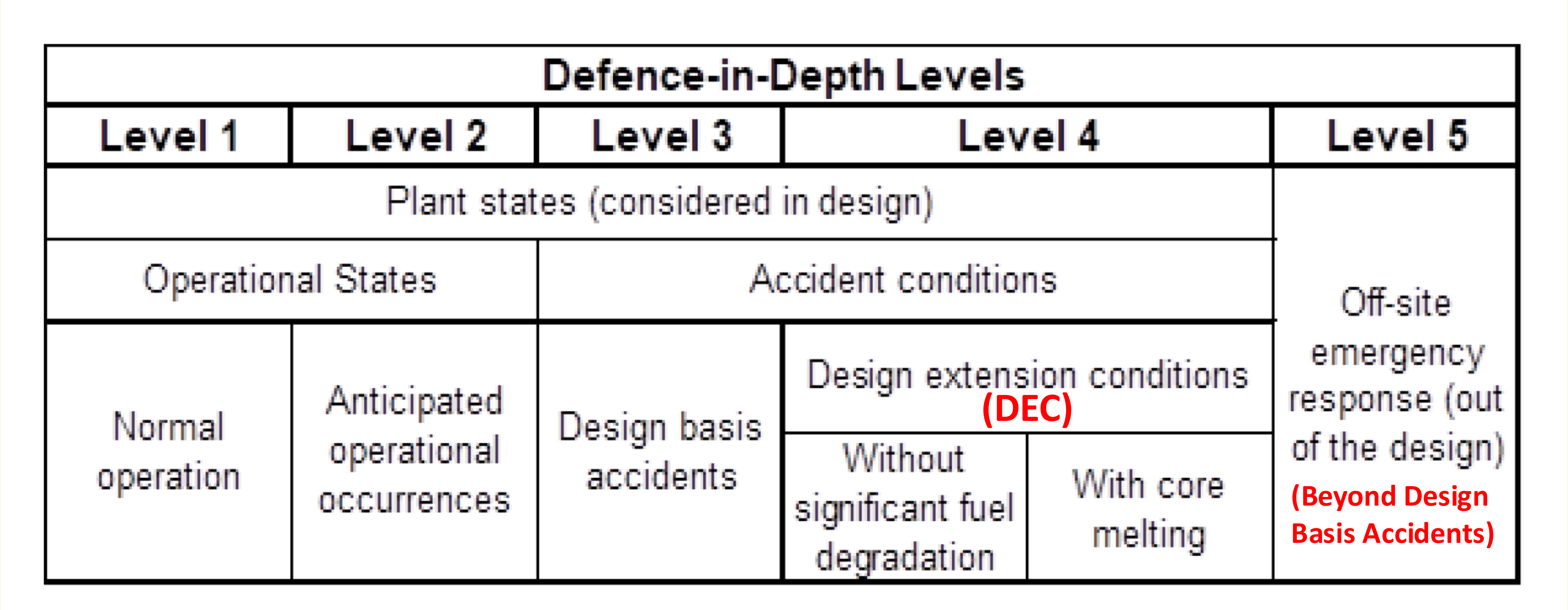
The **Safety Case** is based on a set of “Operating Rules” that must be always followed, to **avoid harm to people, environment, or damage to property**

- Nuclear Power Station are built based on established **“Design Codes”**
- A **Regulator** (an independent safety body) approves a generic design
- The Regulator also issues a particular **Site License** for building, operating and eventually decommissioning a specific plant

The **safety case** of a nuclear power station comprises **very many different documents**, each covering just one aspect of the design, as a result of a multiyear work by several people designing the plant and developing its safety case in parallel

A **site licence** will include **a list of conditions** that must be met for the plant to be operated: safety case, training of operators, emergency planning in case there is a release of radioactivity offsite, operating rules, etc.

The Design Basis



Defence-in-Depth Levels					
Level 1	**Level 2**	**Level 3**	**Level 4**		**Level 5**
Plant states (considered in design)					Off-site emergency response (out of the design) **(Beyond Design Basis Accidents)**
Operational States		Accident conditions			
Normal operation	Anticipated operational occurrences	Design basis accidents	Design extension conditions **(DEC)**		
			Without significant fuel degradation	With core melting	

Probability

International supervision

Two organisations provide help with supervising safety:

- ✓ The **International Atomic Energy Agency (IAEA),** a United Nations body, has the mission to promote the safe, secure and peaceful use of nuclear technology
  - → The IAEA publishes Standards and Guides, allowing operating companies and regulators to align with an internationally recognized expert base to make reference to

- ✓ The **World Association of Nuclear Operators (WANO),** set-up after the Chernobyl disaster, focuses on "best practices" collected from operating companies around the world
  - → WANO can perform visits to nuclear plant sites, indicate "Gaps to Excellence", and discuss with the staff how to address them

How to implement Defence-in-Depth: the Reactor Protection System (RPS) and the Engineered Safety Features (ESF)

- ✓ The RPS is an **engineered system that monitors the status of a reactor** and its associated equipment, e.g.:
  - ☐ Reactor power
  - ☐ Reactor temperature
  - ☐ Reactor pressure
  - ☐ Neutron and gamma detectors counting in various positions
  - ☐ Etc.

- ✓ It uses signals coming from the reactor and associated equipment
- ✓ **When a signal moves outside of a predetermined setpoint, it will automatically shut down the reactor (reactor trip)**
- ✓ Operators cannot override the RPS
- ✓ It's not unusual for a modern PWR to run for 5–10 years without an automatic trip
- ✓ The **RPS performs a rapid intervention** in case of anomalies not spontaneously controlled
- ✓ The **EFS** performs interventions in a **longer time scale**
- ✓ The **EFS mitigates incorrect parameters by activating various systems:**
  - ▪ **Emergency Core Cooling System (ECCS)**
  - ▪ **Containment systems**
  - ▪ **Auxiliary Feedwater Systems → keep the water level in the Steam Generators**

- ✓ In most modern plants, **redundancy is heavily implemented** → safety systems are quadruplicated, i.e. four sets of pumps, SGs, power supplies etc.

What can go wrong in a PWR: a few examples

- Station black out (loss of electrical grid)
- **Large break LOss of Coolant Accident (LOCA)**
- Steam Generator Tube Leak (SGTL)
- Main Steam Line Break (MSLB)
- …
- Severe Accidents → **By definition, a Severe Accident is one in which you've failed to adequately cool the core → some degree of core damage will occur**

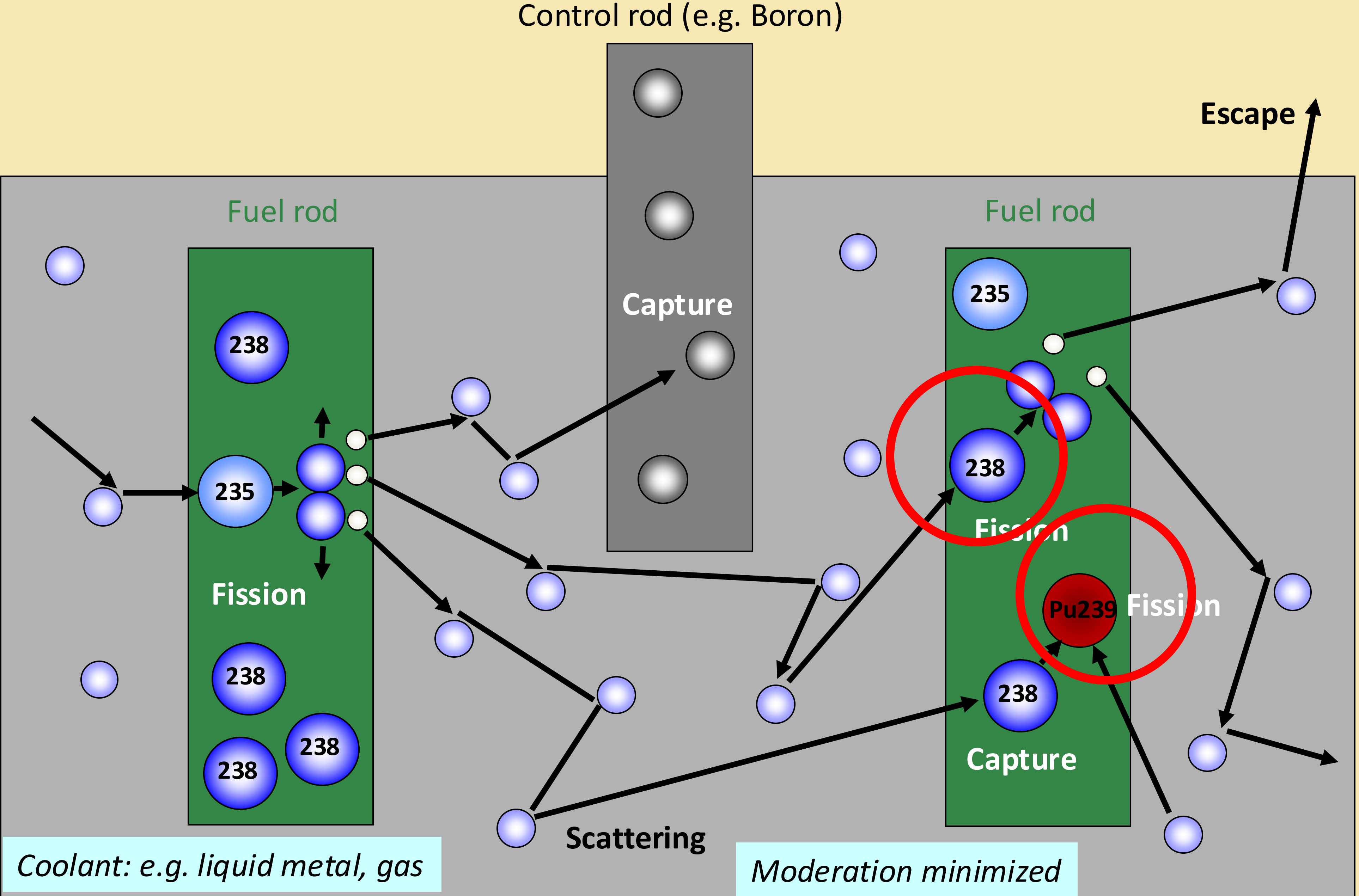
Large break LOss of Coolant Accident (LOCA)

The **primary cooling circuit is operated at very large pressure, 155 bars**…

Suppose there is a **large break in the primary cooling circuit piping**; then:

- ✓ **Pressure within the system** will fall very quickly
- ✓ Loss of moderator
- ✓ **Water starts to boil**
- ✓ **Fuel temperature will rise**
- ✓ The **pressure** outside of the reactor vessel, **within the reactor containment building**, will start to rise
- ✓ Thanks to the negative Fuel Temperature Coefficient and Void Coefficient, **power** will go down
- ✓ The **RPS** detects a problem and drops the control rods → reactor trip → the **reactor is shut down**…
- ✓ …But the fuel is not adequately cooled (decay heat), so I need emergency cooling…
- ✓ **Safety Injection Tanks** start to pour water just due to their high pressure →no electricity needed, just physics
- ✓ All **Emergency Core Cooling System** pumps are started to provide a long-term Safety Injection of water
- ✓ **In case of concurrent Station Blackout**, the ECCS will start on Diesel Generators
- ✓ **Reactor Building Spray System** to lower the pressure in the reactor building, if needed
- ✓ The **Reactor Building is isolated** as the steam from the primary circuit may contain some radioactivity (e.g. from radioactive gases released by failed fuel pins)

The fast reactor



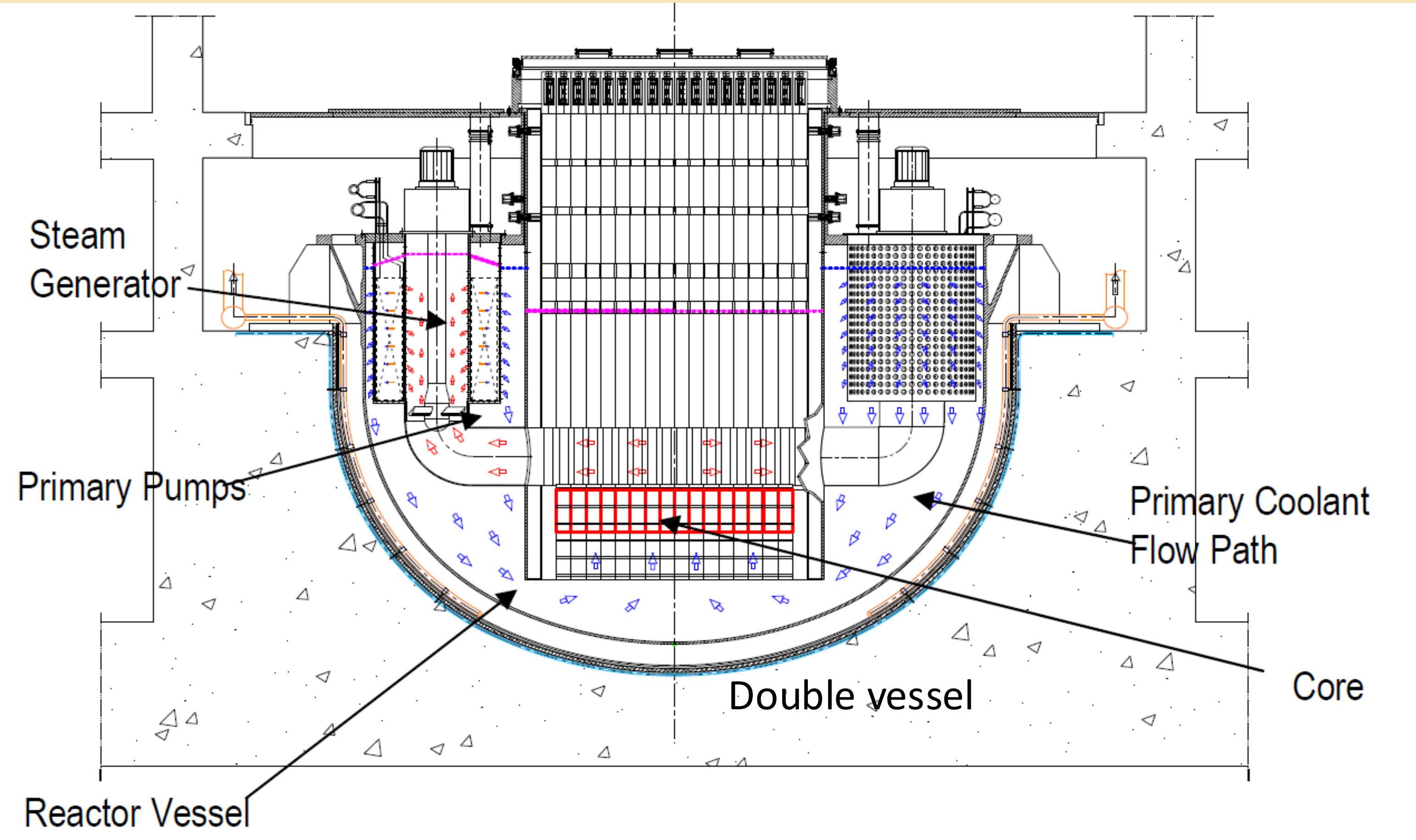
Coolant: e.g. liquid metal, gas

Moderation minimized

Fast reactors have several advantages:

- **Better utilization of uranium resources**
- **Less production of long-lived waste**
- **Higher temperature → better thermodynamic efficiency and possibility to use for industrial heat**
- **....**
- **But what about safety ?**

Example: the Lead Fast Reactor



As one of the key design features, **LFR designs aim at practical elimination of severe accident situations with large core melting**, based on:

i. utilization of the **intrinsic features of lead as a coolant** (high boiling point, relative inertness in contact with air and water, natural convection capability, and high thermal inertia)

ii. comprehensive understanding of the fuel degradation phenomena (including phenomena such as fuel dispersion/ dissolution/segregation vs. aggregation)

iii. the application of the fundamental principles of **redundancy, independence as well as diversity**

Some safety aspects

- Lead has **very high boiling point**
  - The margin to coolant boiling is very high for lead-cooled systems ➔ coolant boiling rather hypothetical (system structures would melt well before the onset of boiling)
  - **This allows operating the primary system close to atmospheric pressure** ➔ accident scenarios with boiling Lead in the core are therefore considered to be highly unlikely

- **BUT, the freezing temperature of Lead is 327°C**
  - **Coolant solidification has to be prevented**
  - **Necessary features for heating of the coolant need to be foreseen** to keep lead at the required temperature in both planned shutdown (including reactor commissioning) and **during emergency conditions**.
  - More of a problem for the equipment, rather than for safety itself

- Lead **does not react with water or air** (at variance with sodium)
  - Steam Generator installed inside the Reactor Vessel → better efficiency, better leak tightness also in terms of radioactive dispersion out of the core vessel, better decay heat removal
  - Less stringent requirements on reactor leak tightness

Some safety aspects

- Lead has **very high thermal inertia**
  - ❑ The high volumetric heat capacity combined with the inventory of the coolant present in the primary circuit provides high thermal inertia, which **contributes to the slowing of any transient related to loss of forced coolant mass flow or loss of heat sink**
  - Lead has **Natural convection capability**
    - ❑ **Natural circulation is predicted to be well established** in LFR primary systems, due to the simple flow path design and due to neutronic characteristics of lead that allow larger fuel pin pitches and lower coolant velocities, together resulting in low pressure drops ➔ **passive safety**
    - ❑ **If passive cooling fails, as ECCS e.g. dedicated air-cooled heat exchangers can be used, water injection between reactor and safety vessel,…**
- **Retention of volatile fission products**
  - ❑ Lead provides a relatively good capacity for retention of important volatile fission products as well as activation products

However…

Interaction with Oxygen and Water

- **Lead coolants are relatively chemically inert in contact with water or air**
- However, in case of a **steam generator tube rupture** (SGTR) event, **water interaction with lead needs to be considered and adequately prevented and/or mitigated**
- Potential for over-pressurization of the primary circuit, sloshing and steam/water entrainment, which might result in a positive reactivity insertion
- Potential formation of solid PbO possibly causing flow blockages

Operation in Lead coolant environment

- **Flowing heavy liquid metals are corrosive** and can induce or accelerate a material failure under static (brittle fracture) or time-dependent loading (fatigue and creep)
- **A preventive measure** to limit the corrosion risks is to design LFRs to operate within a relatively low temperature range while maintaining a controlled concentration of dissolved oxygen in the coolant, which must be high enough to support the formation of protective oxide layers on surfaces of
- For conventional materials, **at temperatures around 500°C** the corrosion protection through the oxide barrier seems to fail and the **application of functional surface coatings** (for example Al_2O_3, SiO_2 or aluminium alloy) or the **use of steels with addition of silicon or aluminium** is therefore considered.
- As an LFR operates at a relatively **high temperature compared and in high fast neutron fluence conditions, due consideration of creep and radiation effects on fuel and structural materials is necessary**

A very bad accident

- ✓ On 3 December 1984, over 500,000 people were exposed to highly dangerous substances, in what is considered the world's worst industrial disaster
- ✓ A government affidavit in 2006 stated that the leak caused 558,125 injuries, including 38,478 temporary partial injuries and approximately 3,900 severely and permanently disabling injuries.
- ✓ Estimates vary on the death toll, with the official number of immediate deaths being 2,259. Others estimate that 8,000 died within two weeks, and another 8,000 or more have since died from related diseases.
- ✓ In 2008, the Government paid compensation to the family members of 3,787 victims killed in the release, and to 574,366 injured victims.

What accident is it ?

- ✓ It's the **Bhopal disaster**, in the vicinity of the Union Carbide India Limited pesticide plant in Bhopal, Madhya Pradesh**, India**
- ✓ Over 500,000 **people were exposed to the highly toxic gas methyl isocyanate → a chemical accident !**

Source: Wikipedia

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 in 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

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. …

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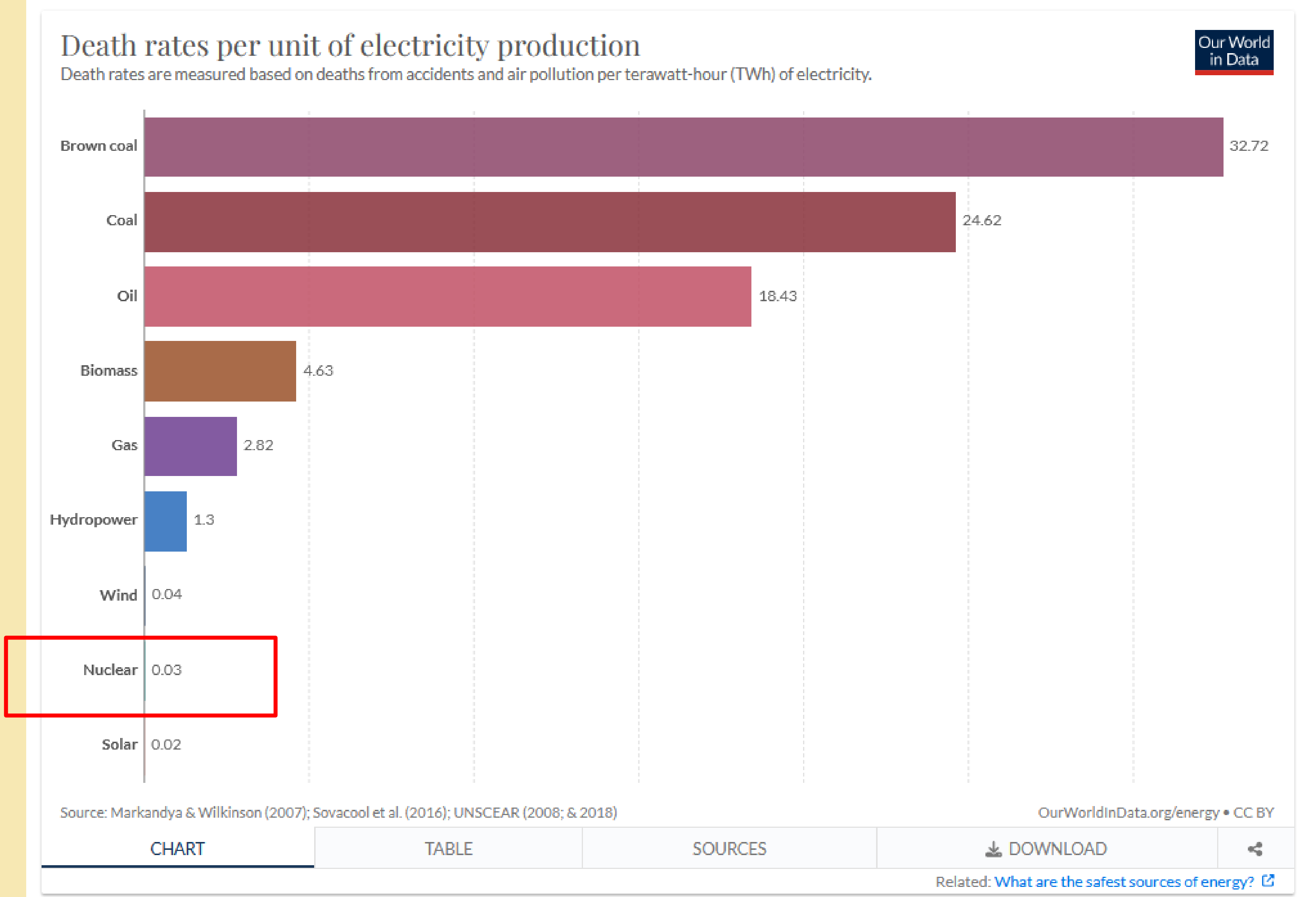
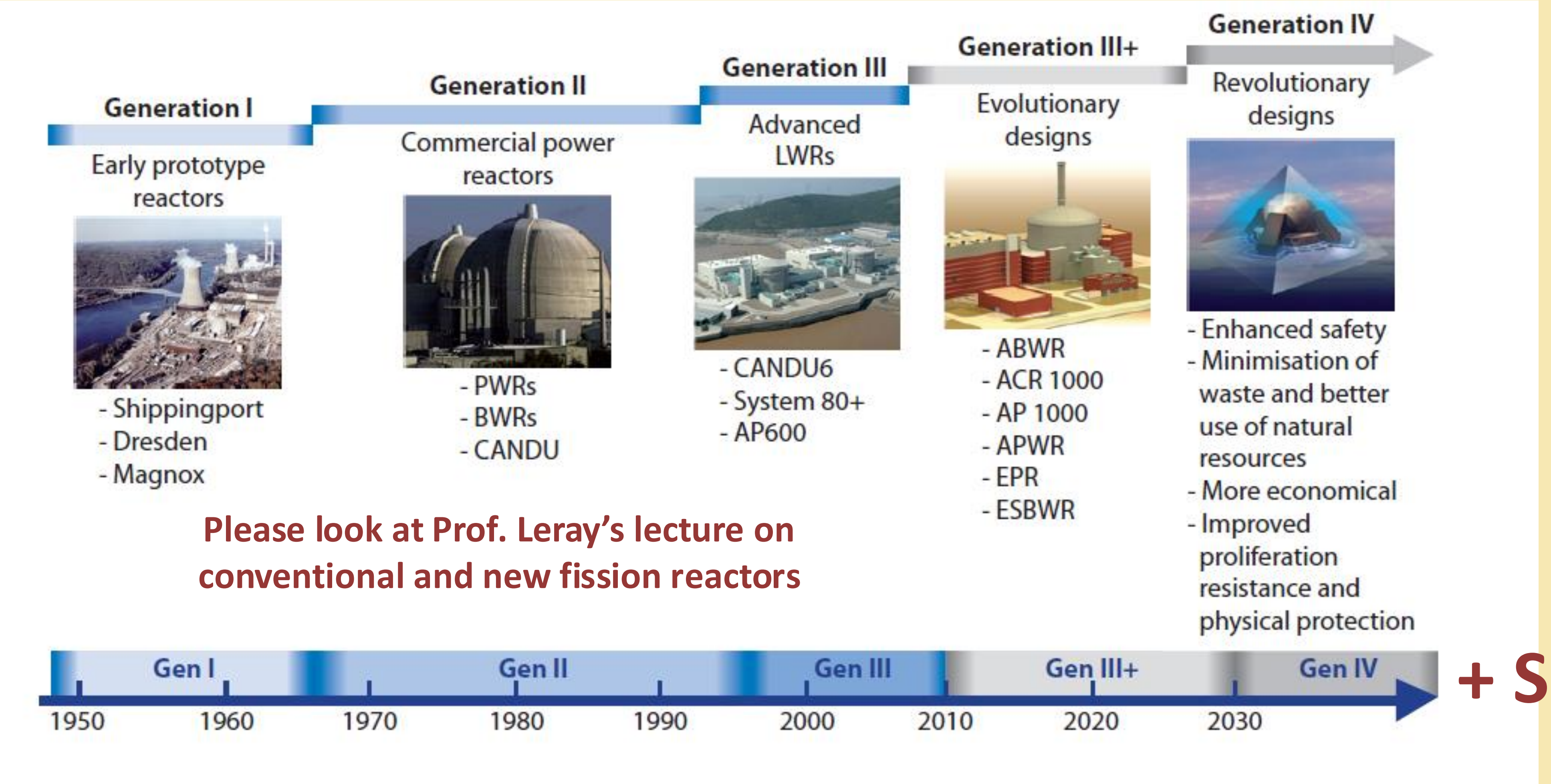
About 40 megawatts of the San Luis Obispo County facility are in operation, and it’s expected to return to full service by July 1. Clearway expects the incident to cost $8 million to $9 million this year, after estimated insurance recovery.

How dangerous is nuclear energy ?



From: https://ourworldindata.org/grapher/death-rates-from-energy-production-per-twh

Conclusions: past and future



Please look at Prof. Leray's lecture on conventional and new fission reactors

+ SMR

Safety