Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

Nuclear Technologies 1

n_TOF Nuclear Physics Winter School 2024
Saint-Gervais Mont-Blanc, January 21-26, 2024

Giacomo Grasso – ENEA, NUC-ENER-PRO

Nuclear Energy in Context

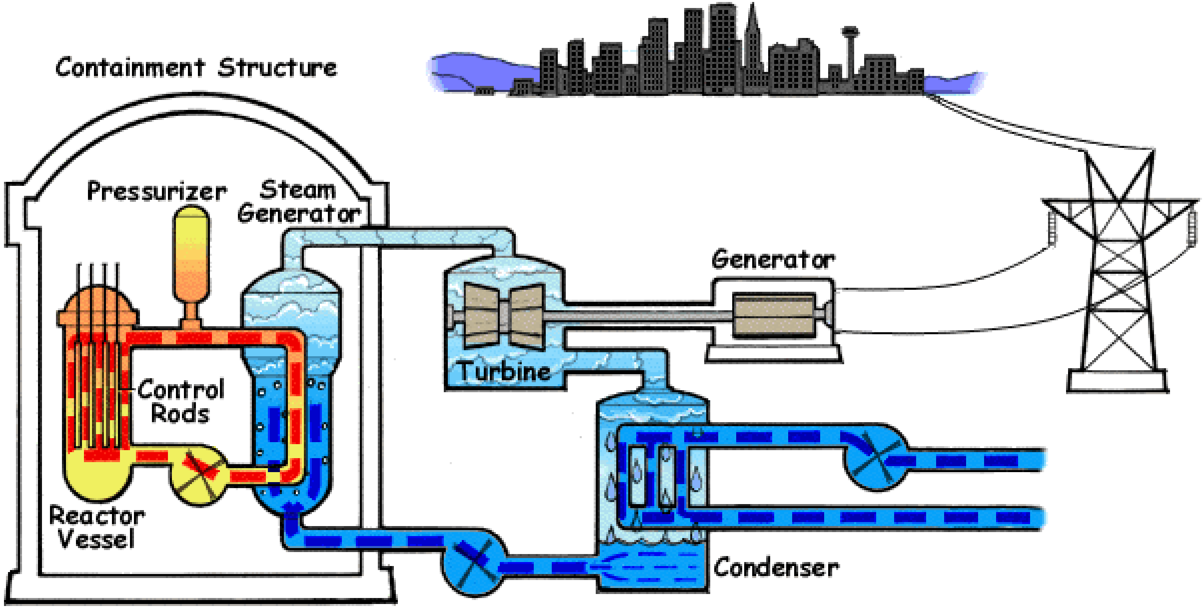
Principles and applications

Nuclear energy

Working principle of a power plant

Nuclear energy

Working principle of a power plant



Nuclear energy

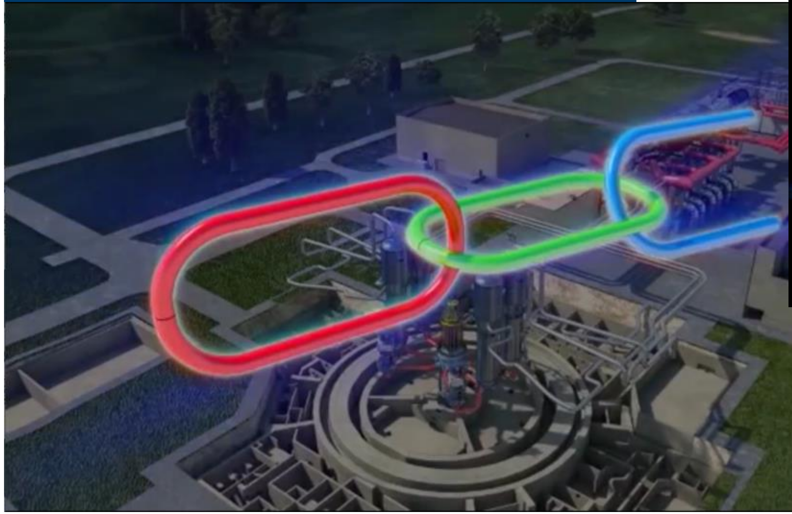
Attributes

No GHG emission

- No combustion for operation

No combustion for operation

Dispelling a myth (or two)



Nuclear energy

Attributes

No GHG emission

High energy concentration

- 200 MeV per fission, vs few eV per oxidation

200 MeV per fission, vs few eV per oxidation

Exploiting the nuclear forces rather than electrostatic ones, the theoretical energy density can be up to 3 900 000 MJ/kg, vs

coal	24 ÷ 30 MJ/kg
oil	42 ÷ 44 MJ/kg
gas	53 ÷ 55 MJ/kg

5 g of fuel (1 pellet)
(5% burnup)

655 kg of coal
(100% burnup)

480 l of oil
(100% burnup)

500 m^3 of gas
(100% burnup)

Nuclear energy

Attributes

No GHG emission

High energy concentration

Low cost

- Fuel very cheap

Fuel very cheap

The incidence of fuel cost on the energy cost is minimized because of the high energy density.

* And the nuclear fuel cost is the only one also including costs for final waste management!

0.56 ¢/kWh*
(9 $ per pellet)

5.16 ¢/kWh
(85 $ for 655 kg)

10.90 ¢/kWh
(212 $ for 480 l)

1.64 ÷ 2.28 ¢/kWh
(48 $ for 500 m^3)

Nuclear energy

Attributes

No GHG emission

High energy concentration

Low cost

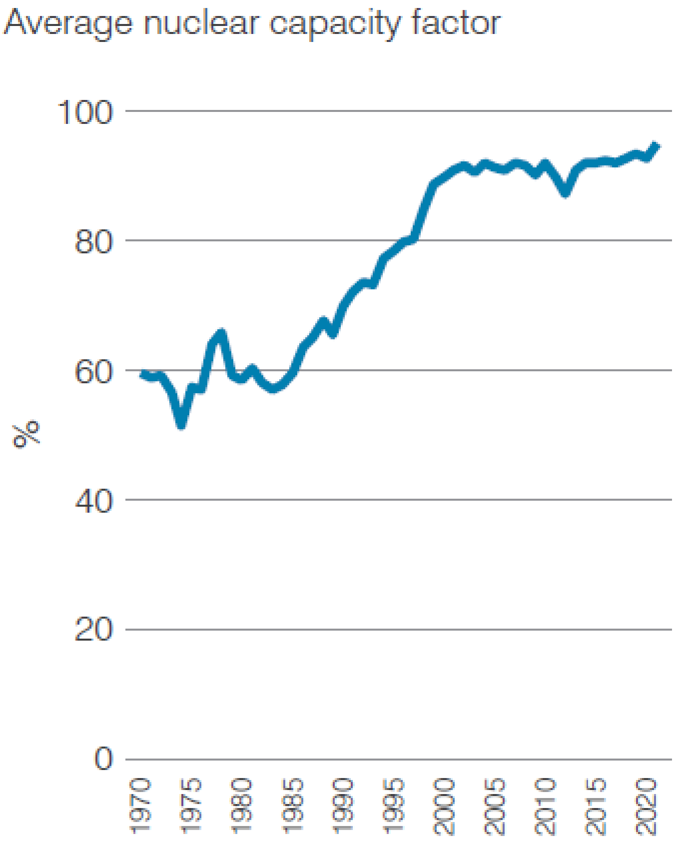
High reliability

- Simple operating process

Simple operating process

After startup, a nuclear power plant operates almost autonomously, with minimal needs for control, for 12 ÷ 18 months before being shut down for refueling.

Overall, it can achieve load factors as high as 92%.



Source: World Nuclear Association, IAEA PRIS

Nuclear energy

Attributes

No GHG emission

High energy concentration

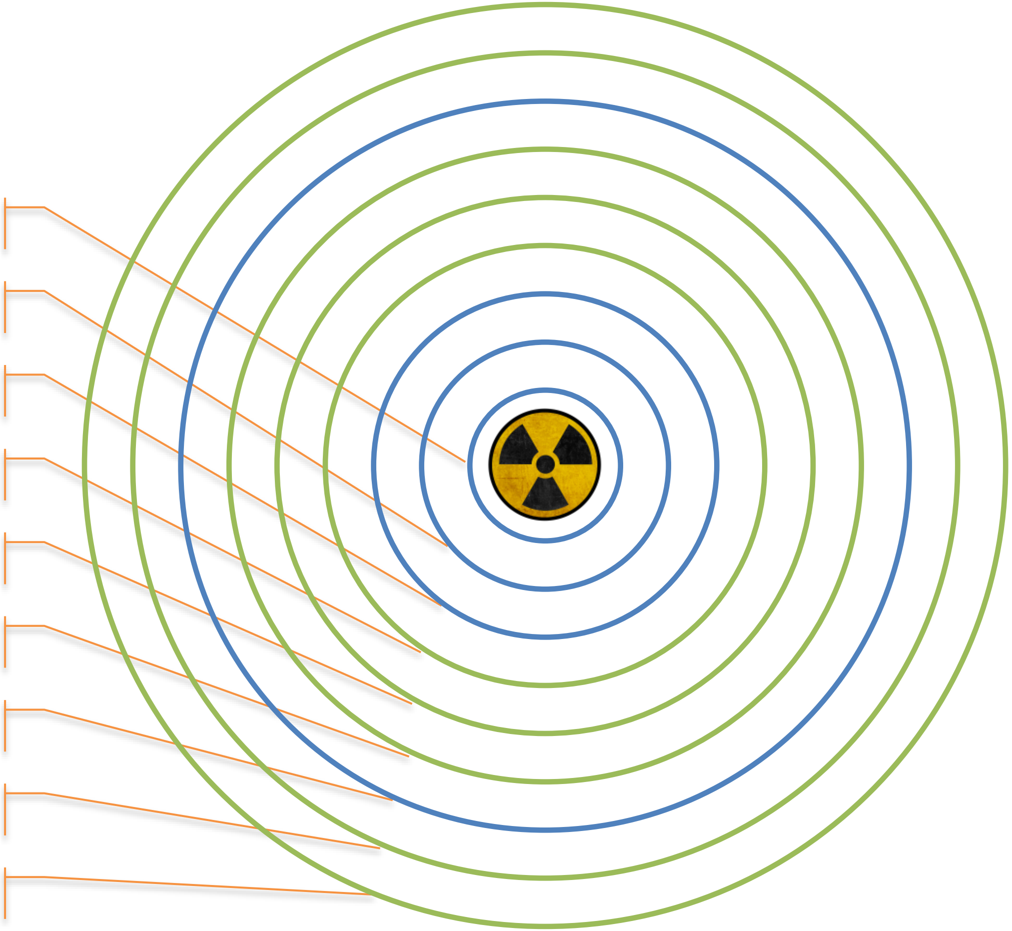
Low cost

High reliability

High safety

- Multiple independent lines of defence

Multiple independent lines of defence



B1: fuel matrix

B2: fuel rod cladding

B3: primary circuit boundary

L1: prevention of deviations

L2: control of abnormal states

L3: control of accidents in DB

B4: confinement building

L4: accident management

L5: off-site response

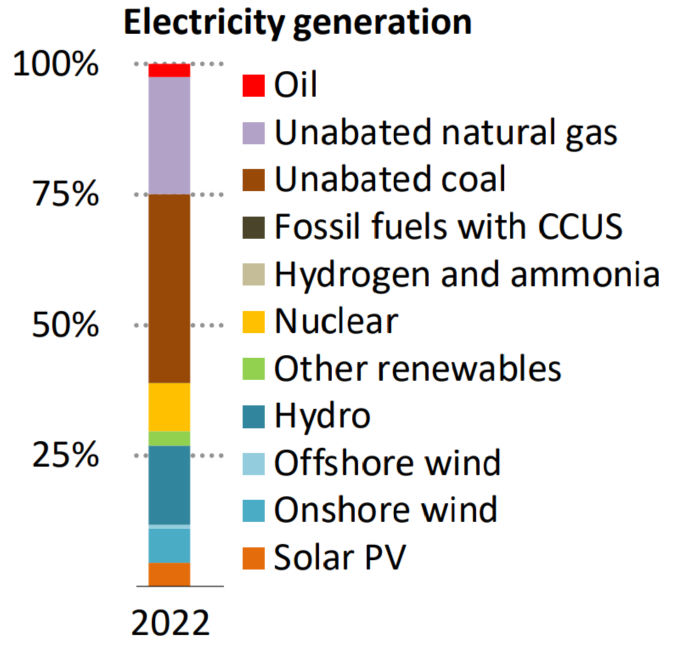
International context

Nuclear today

IEA World Energy Outlook 2023

After hydropower, nuclear is the first source for low-carbon electricity generation.

However, all low-carbon sources together still total only about 40% of the total electricity generation. Which is only about 1/3 of the total energy generation…

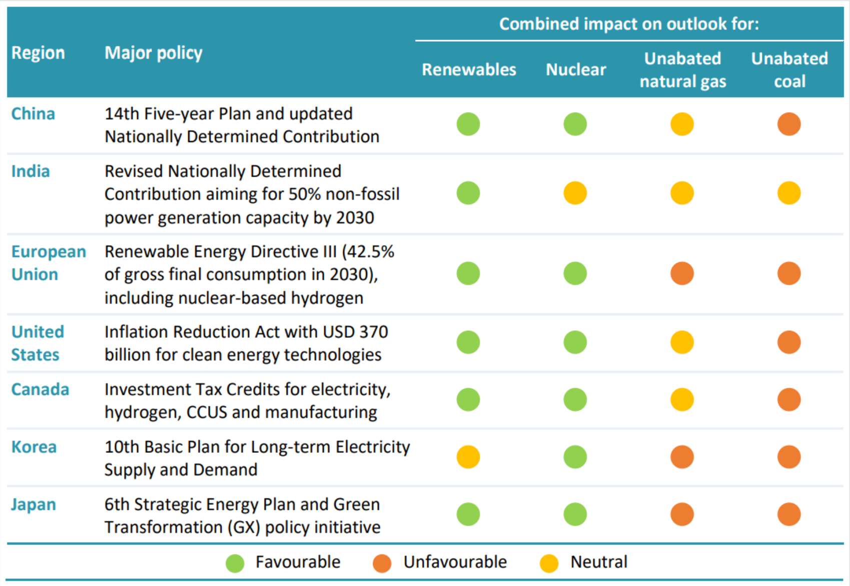


International context

Nuclear tomorrow

IEA World Energy Outlook 2023

Nuclear capacity additions grew by 40% in 2022, with 8 GW coming online, mostly in China, Finland, Korea and Pakistan. Moreover, many governments are taking a fresh look at how nuclear might contribute to their energy futures.



Region	Major policy	Combined impact on outlook for:			
		Renewables	Nuclear	Unabated natural gas	Unabated coal
China	14th Five-year Plan and updated Nationally Determined Contribution	🟢	🟢	🟡	🟠
India	Revised Nationally Determined Contribution aiming for 50% non-fossil power generation capacity by 2030	🟢	🟡	🟡	🟡
European Union	Renewable Energy Directive III (42.5% of gross final consumption in 2030), including nuclear-based hydrogen	🟢	🟢	🟠	🟠
United States	Inflation Reduction Act with USD 370 billion for clean energy technologies	🟢	🟢	🟡	🟠
Canada	Investment Tax Credits for electricity, hydrogen, CCUS and manufacturing	🟢	🟢	🟡	🟠
Korea	10th Basic Plan for Long-term Electricity Supply and Demand	🟡	🟢	🟠	🟠
Japan	6th Strategic Energy Plan and Green Transformation (GX) policy initiative	🟢	🟢	🟠	🟠

🟢 Favourable 🟠 Unfavourable 🟡 Neutral

International context

Nuclear tomorrow

COP28

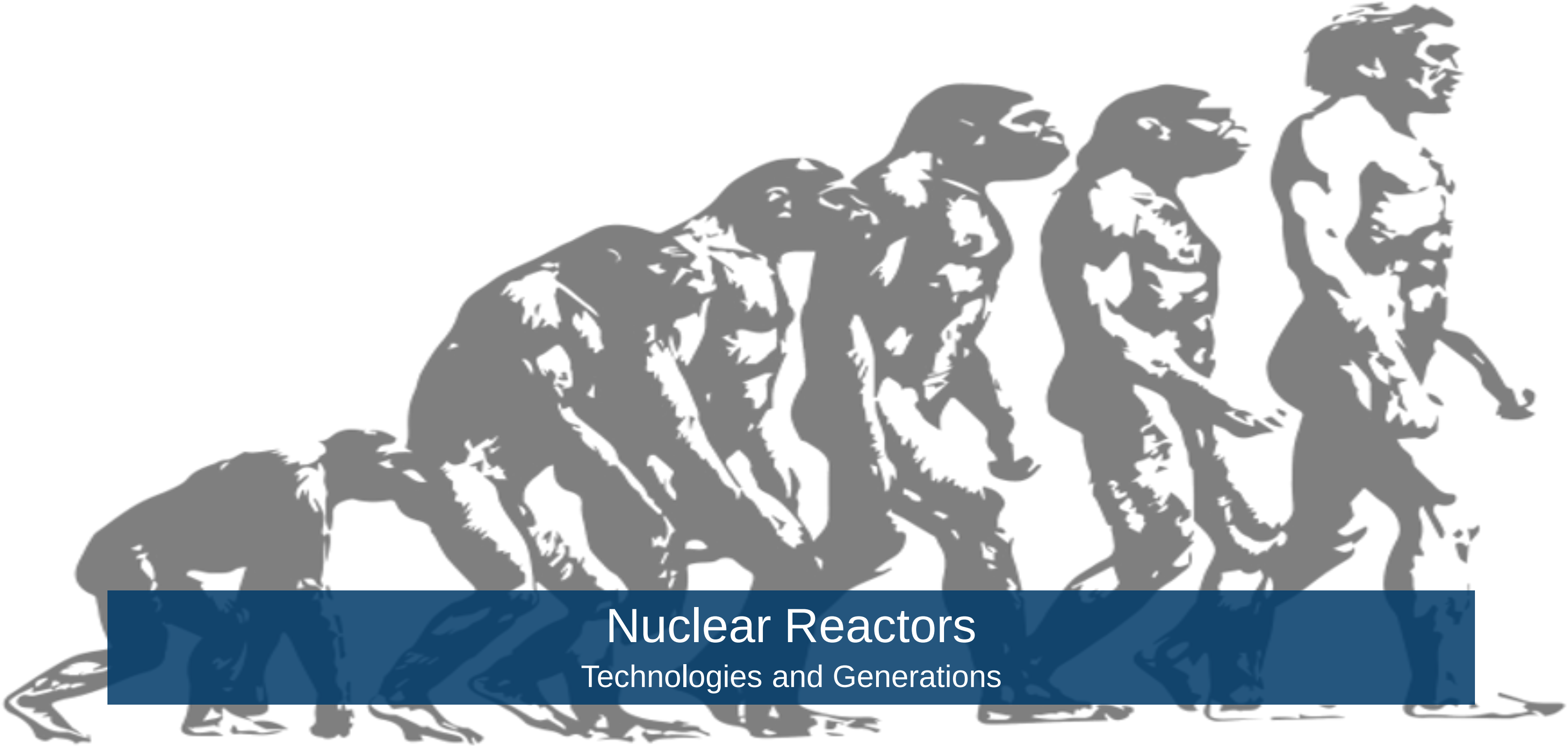
For the first time since the annual climate summits commenced, the 198 signatory countries to the UN Framework Convention on Climate Change officially called for accelerating the deployment of low-emission technologies including nuclear energy to help achieve deep and rapid decarbonization, particularly in hard-to-abate sectors such as industry and through the low carbon production of hydrogen.

Rafael MarianoGrossi
@rafaelmgrossi · Follow

#COP28's first Global Stocktake rightly places nuclear energy as part of the solution for deep decarbonization.

The @IAEAorg and I welcome this outcome. Onwards to scaling up this clean and reliable technology!

1:02 PM · Dec 13, 2023

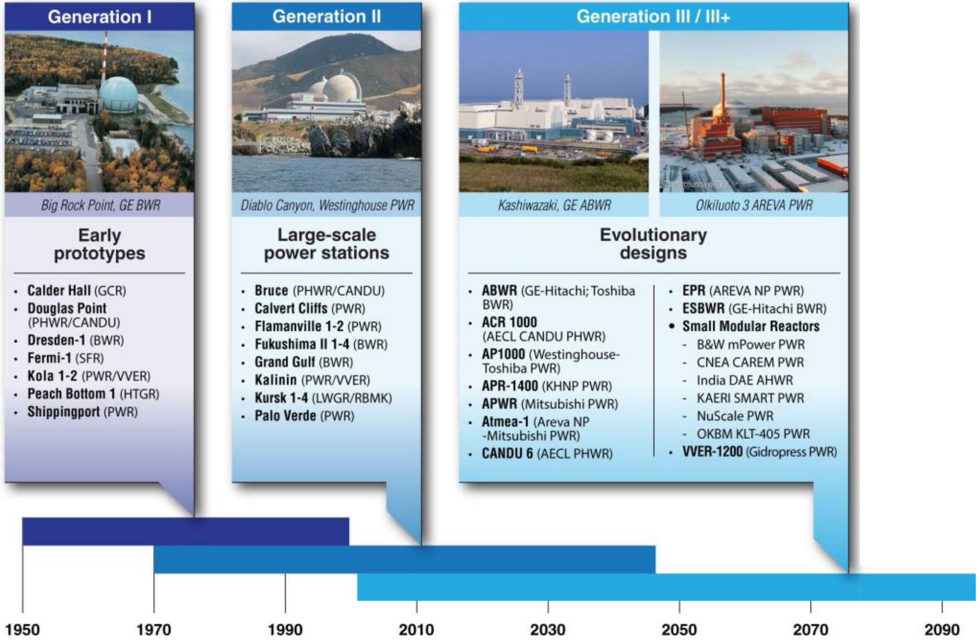


Nuclear Reactors

Technologies and Generations

A long way done…

Evolution of nuclear reactors



Generation I

Big Rock Point, GE BWR

Early prototypes

- **Calder Hall** (GCR)
- **Douglas Point** (PHWR/CANDU)
- **Dresden-1** (BWR)
- **Fermi-1** (SFR)
- **Kola 1-2** (PWR/VVER)
- **Peach Bottom 1** (HTGR)
- **Shippingport** (PWR)

Generation II

Diablo Canyon, Westinghouse PWR

Large-scale power stations

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Generation III / III+

Kashiwazaki, GE ABWR

Olkiluoto 3 AREVA PWR

Evolutionary designs

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  - KAERI SMART PWR
  - NuScale PWR
  - OKBM KLT-405 PWR
- **VVER-1200** (Gidropress PWR)

I

Generation I

Early, prototypical reactors

Generation I

What does it mean?

First reactors

- Are the first plants ever built with the specific objective of producing electric energy.

Prototypical

- Are characterized by unique projects, made each time for each new plant.

Generation I

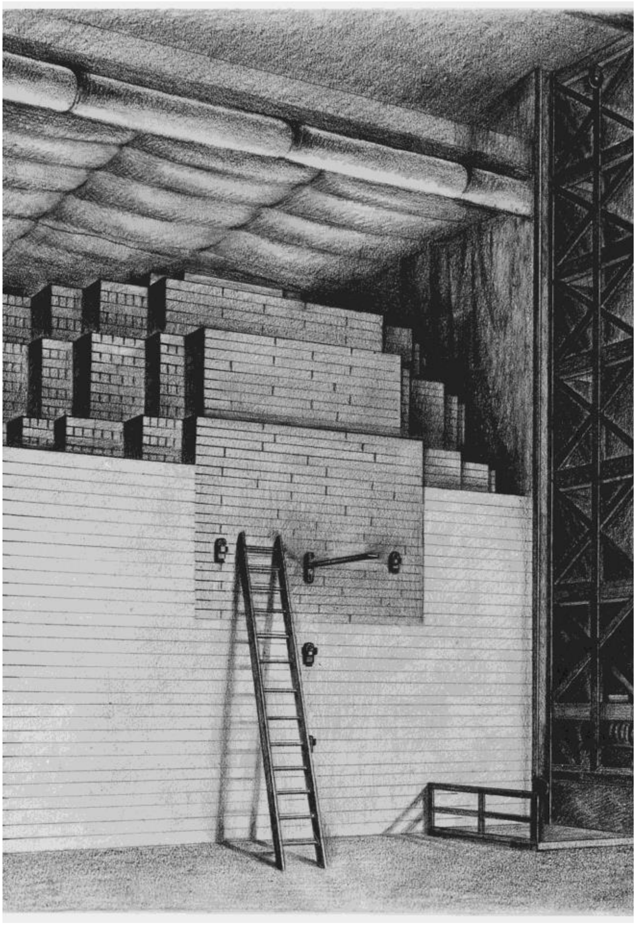
Which are?

- All plants made in the beginning
  (‘50s and ‘60s)
- Generally based on different reactor technologies
  (many investigated)
- Tipically of small size
  (< 300 MWe)

Obninskaja AES (Obnisk, Russia)

5 MWe

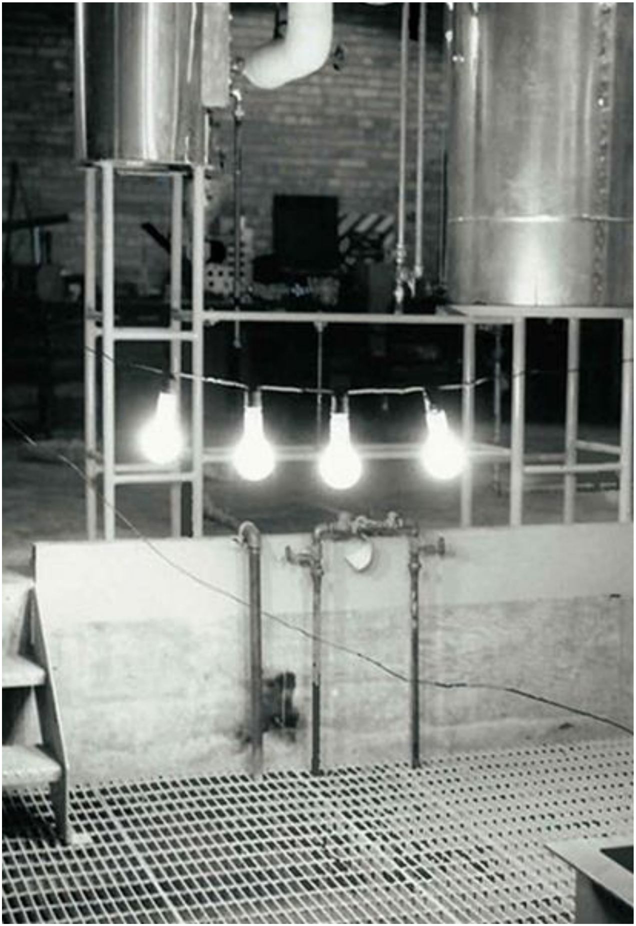
1st NPP in the world, was connected to the grid on June 27th 1954



It is worth recalling that…

…it was just a few years earlier – in 1942 – that Enrico Fermi built the first nuclear reactor in history: CP-1.

And it was far from producing energy…



It is worth recalling that…

…electricity was instead produced for the first time in 1951, by the EBR-1 reactor.

(yes: for lightning those 4 bulbs only!)

II

Generation II

Commercial power reactors

Generation II

What does it mean?

- Are the subsequent plants, which achieved the maturity of nuclear energy
- Are therefore characterized by:
  - affirmation of the most promising technologies (PWR, BWR, CANDU)
  - higher safety and reliability
  - higher generated power (up to 1000 MWe and more)

Generation II

What does it mean?

Affirmation of the most promising technologies

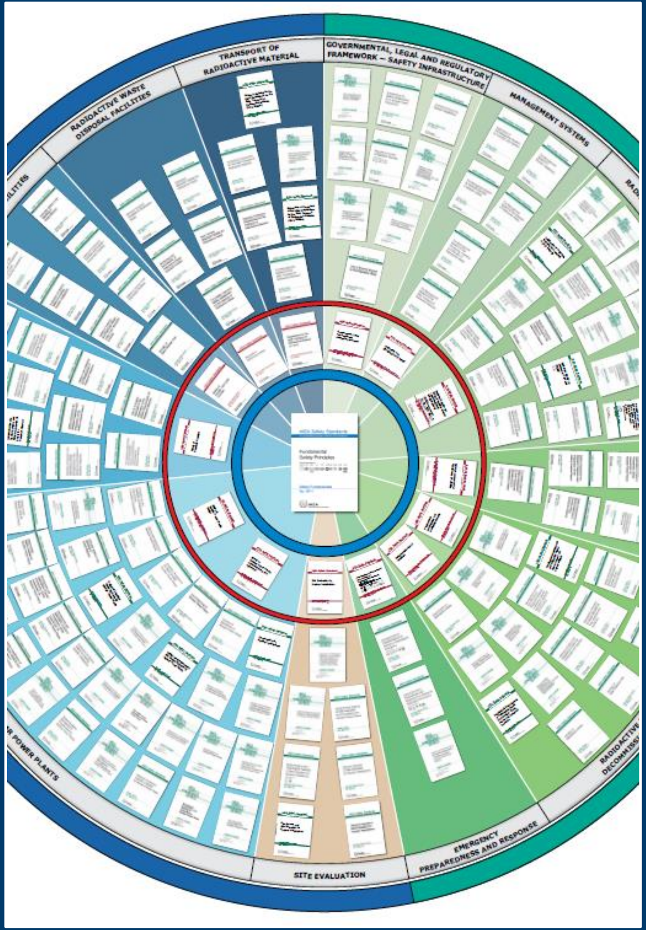
- At the beginning, several reactor technologies were conceived and tested, each distinguishing for peculiar merits.
- The expansion of the nuclear programmes, however, established the clear success of some of such technologies over the others; these are the light water (both as pressurized – PWR, and boiling – BWR) and heavy water (PHWR e CANDU) reactor technologies.

Generation II

What does it mean?

Higher safety and reliability

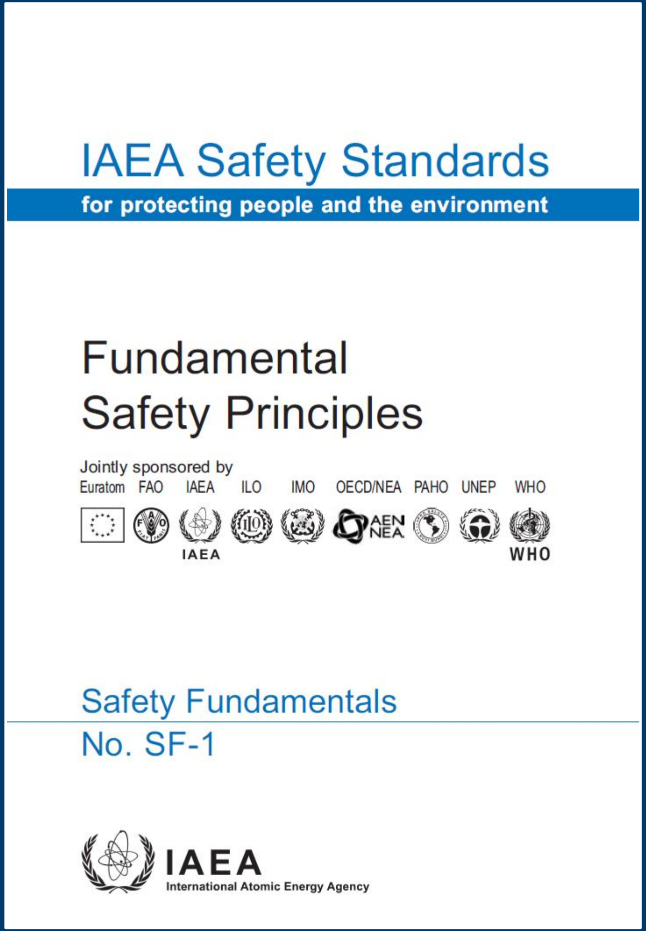
- Like in a virtuous circle, the affirmation of few technologies allowed to accumulate a relevant construction and operation experience.
- Leveraging this experience, it was possible to initiate a process of continuous improvement of the safety performance, also thanks to more and more advanced systems, to well-established design and verification criteria, and to the affirmation and consolidation of a real «safety culture».



It is worth recalling that…

…one of the duties of the ONU's International Atomic Energy Agency (IAEA) is to elaborate and foster the adoption of safety standards, ruling all activities in the nuclear field, including the production of energy, research and medical applications.

It is worth recalling that…



IAEA Safety Standards
for protecting people and the environment

Fundamental
Safety Principles

Jointly sponsored by
Euratom FAO IAEA ILO IMO OECD/NEA PAHO UNEP WHO

Safety Fundamentals
No. SF-1

IAEA
International Atomic Energy Agency

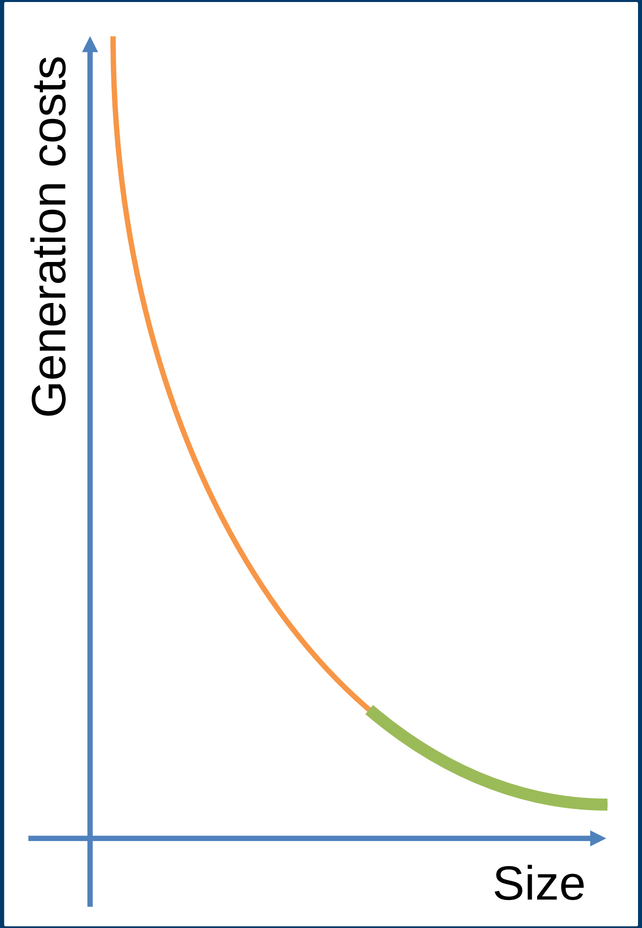
…among the processes that are regulated by the IAEA’s safety standards, there is also the process of licensing of any plant making use of or managing a radioactivity source, thus also of a nuclear power plant.

Generation II

What does it mean?

Higher generated power

- Thanks to the accumulated experience, and of the higher safety performance, it was possible to realize plants with continuously increasing size, thereby allowing to shift from the initial few MW (even just 5, in the Obninskaja NPP) to more than 1000 MW (1300 in the French «N4» reactors by Framatome or 1400 in the German «Konvoi» reactors by Siemens, both of PWR type).



It is worth recalling that…

…the increase in size leverages the so called *economy of scale*, which is the dilution of fixed costs (such as for construction) on a larger quantity of produced energy.

This brought the energy produced by Generation II reactors among the cheapest ever.

Generation II

Which are?

- All plants made in the nuclear boom
  (from mid ‘60s until mid ‘90s)
- The vast majority of the plants currently operating
  (while there is no Generation I reactor in operation anymore)

«Enrico Fermi» Power Plant (Trino, Italy)

260 MWe net capacity

Most powerful reactor in the world when started operation, on January 1st 1965

III

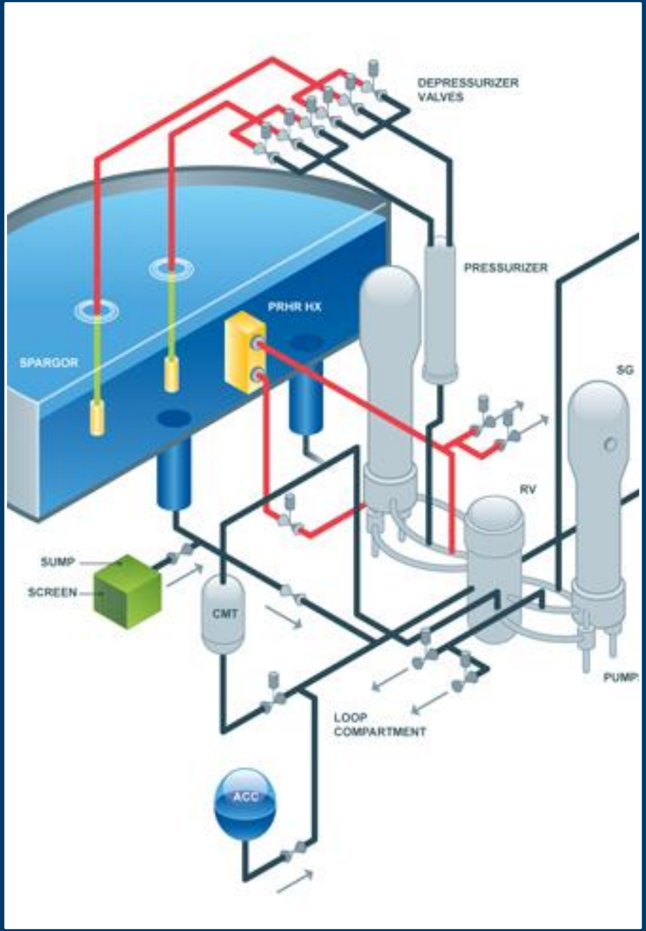
Generation III

Advanced water-cooled reactors

Generation III

What does it mean?

- Are all those plants derived, leveraging the accumulated experience, by further optimizing the reactors of the most promising technology
- The optimization areas are:
  - efficiency in the use of fuel
  - thermal efficiency
  - safety systems (notably, passive systems)
  - design standardization



It is worth recalling that…

…passive safety systems are based on physical principles (e.g., gravity, natural circulation) so that no action is needed to actuate and/or operate them.

Generation III

Which are?

- All plants currently being built
- Based on the most consolidated technologies:

- PWR (e.g., EPR, AP1000)
- BWR (e.g., ABWR)
- PHWR (e.g., CANDU6)

Vogtle 3 (Waynesboro, GA, USA)

1117 MWe net capacity

Started commercial operation on July 31st, 2023

III+

Generation III+

Evolutionary concepts

Generation III+

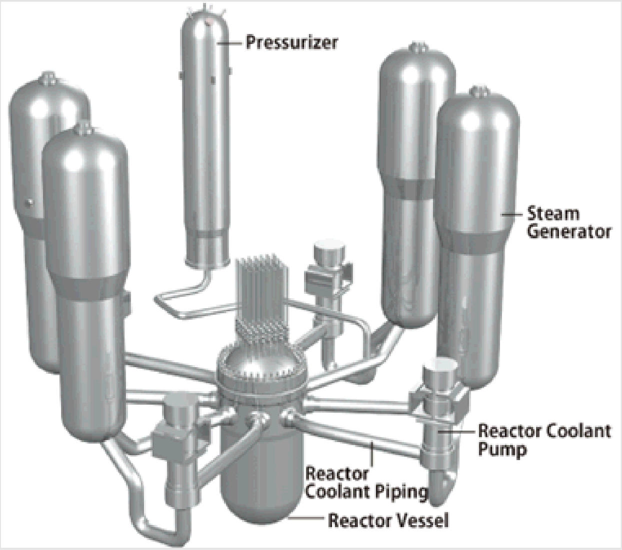
What does it mean?

- Are all those plants for which reactor optimization is pushed even further
- Generally, reactors in which passive provisions are massively used
  - A remarkable case is that of Small Modular Reactors (SMRs) of integral design

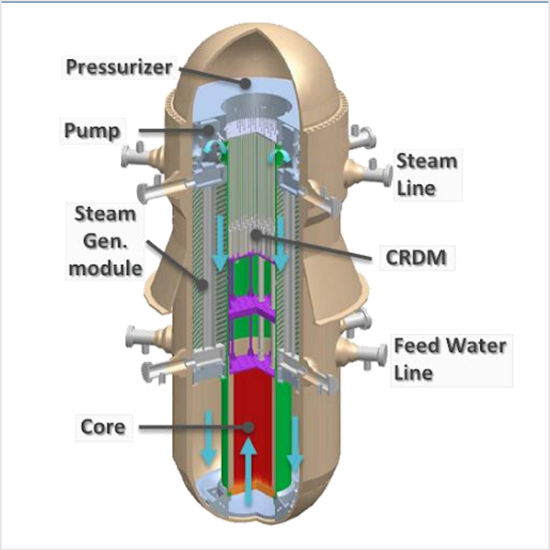
Generation III+

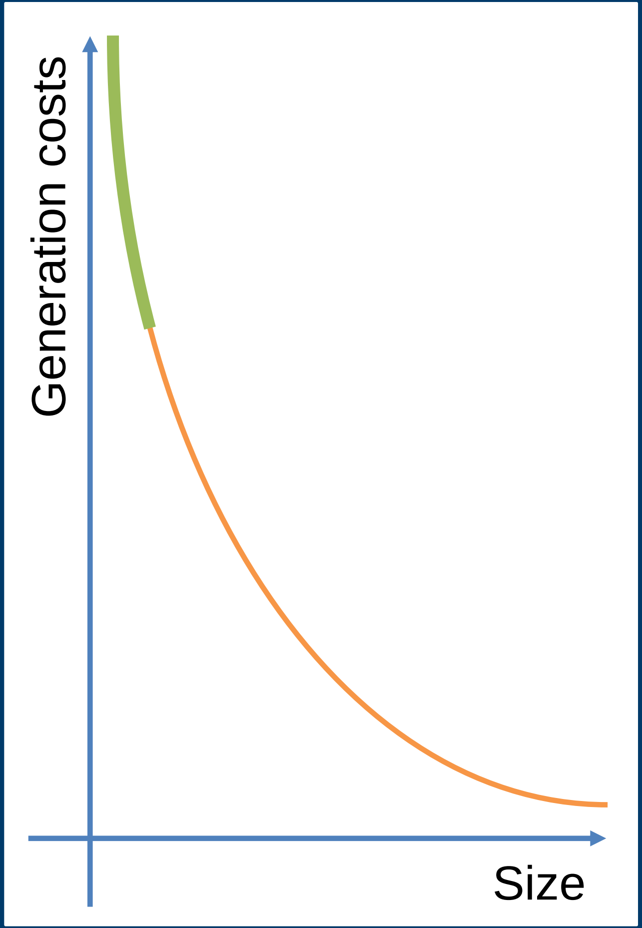
What does it mean?

PWR – standard design



PWR – integral design

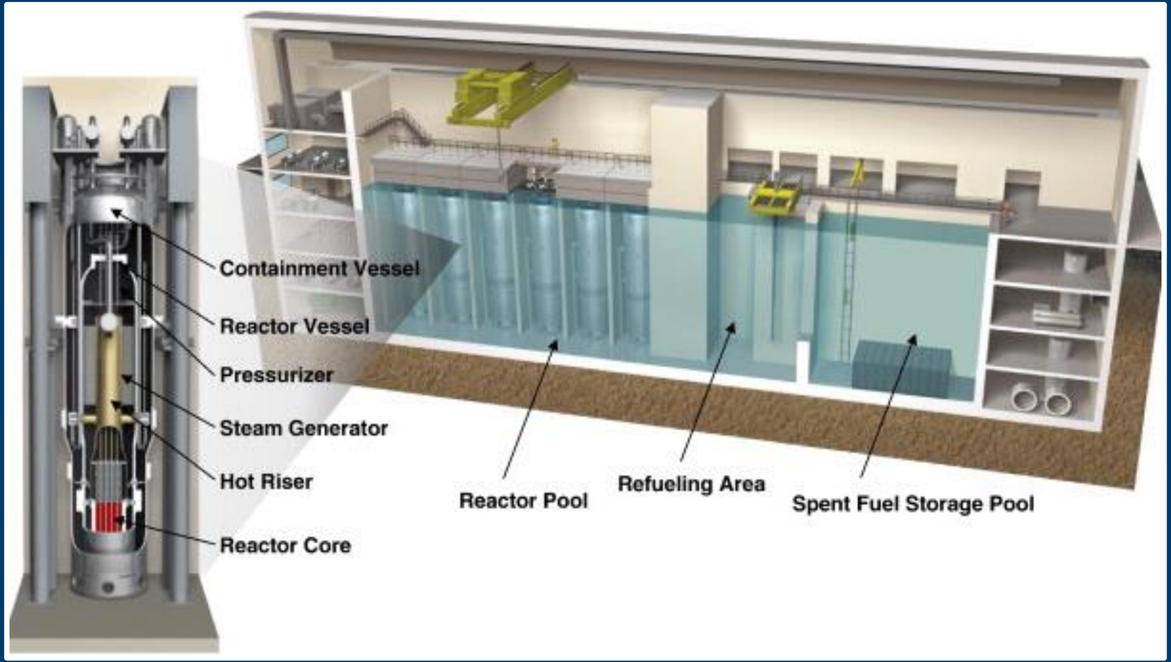




It is worth recalling that…

…the small size inhibits the economy of scale, so that other means are needed to achieve economics:

- modularization
- factory production
- series fabrication



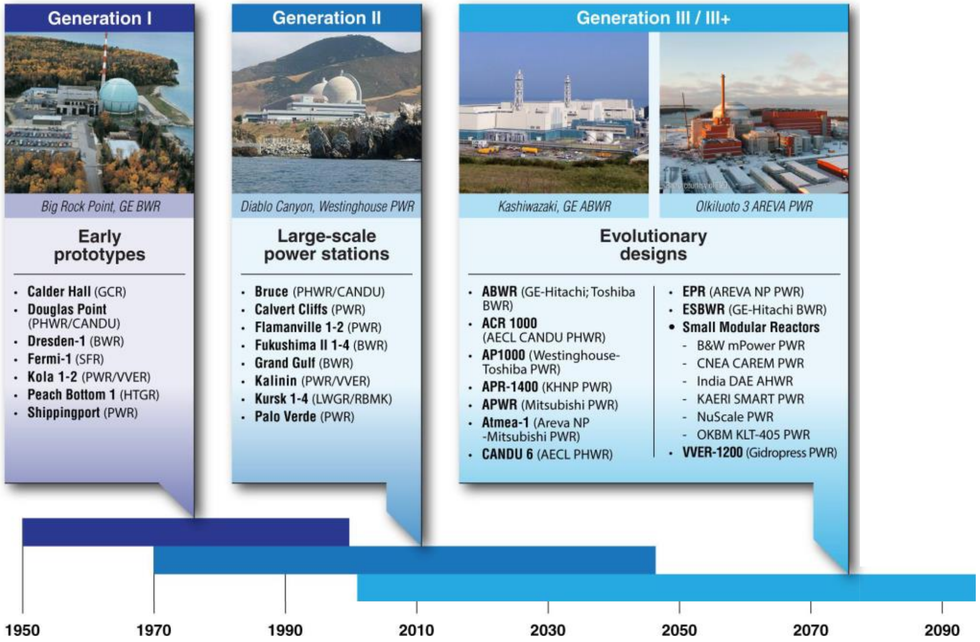
NuScale Power Module™

45 MWe per module

Units of up to 12 modules

A long way done…

Evolution of nuclear reactors



Generation I

Big Rock Point, GE BWR

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Generation II

Diablo Canyon, Westinghouse PWR

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Generation III / III+

Kashiwazaki, GE ABWR

Olkiluoto 3 AREVA PWR

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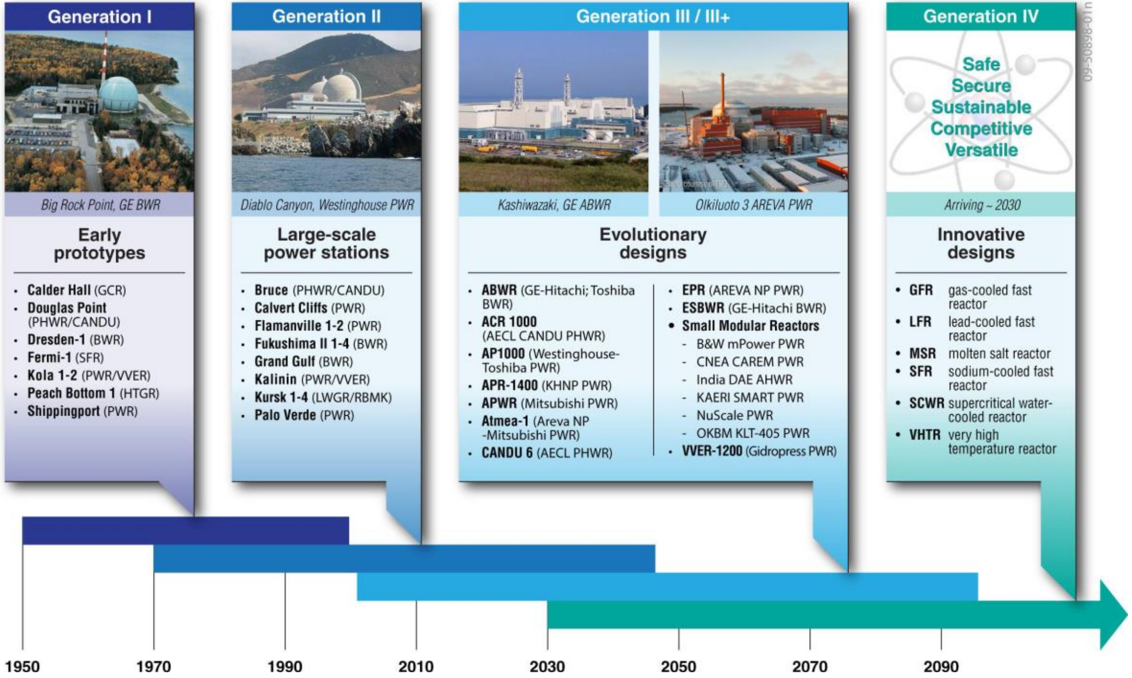
…a new perspective forward!

Evolution of nuclear reactors



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Generation IV

Safe
Secure
Sustainable
Competitive
Versatile

Arriving ~ 2030

Innovative designs

- **GFR** gas-cooled fast reactor
- **LFR** lead-cooled fast reactor
- **MSR** molten salt reactor
- **SFR** sodium-cooled fast reactor
- **SCWR** supercritical water-cooled reactor
- **VHTR** very high temperature reactor

IV

Generation IV

Revolutionary concepts

Nuclear energy

Attributes - today

No GHG emission

High energy concentration

Low cost

High reliability

High safety

Nuclear energy

Attributes - tomorrow

No GHG emission

High energy concentration and minimal waste

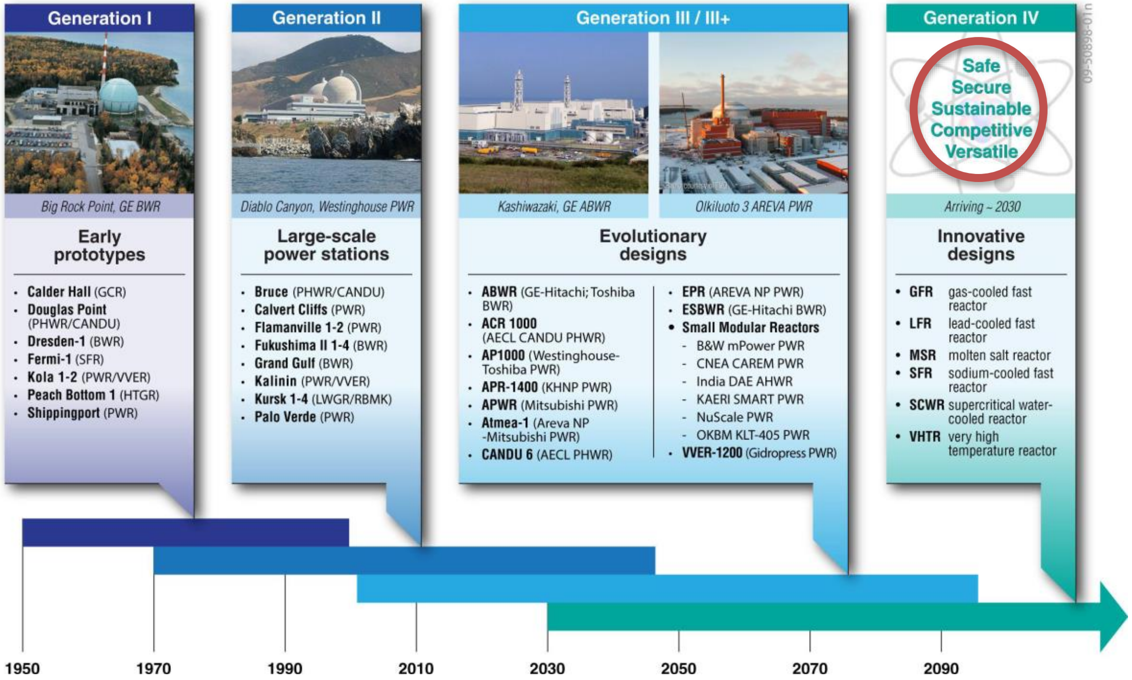
Low cost and low investment

High reliability

Inherent safety

…a new perspective forward!

Evolution of nuclear reactors



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Arriving ~ 2030

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VHTR	very high temperature reactor

Vision

Next generation nuclear systems: Generation IV

Sustainability

- Meet clean air objective and effective fuel utilization
- Minimise and manage the nuclear waste and notably reduce the long-term stewardship burden

Economics

- Clear life-cycle cost advantage over other energy sources
- Level of financial risk comparable to other energy projects

Proliferation resistance & physical protection

- Increase assurance of being very unattractive and least desirable route for diversion/theft of weapons-usable materials
- Provide increased physical protection against acts of terrorism

Safety & reliability

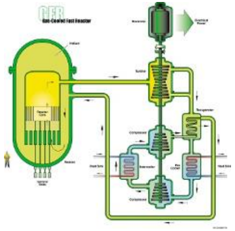
- Excel in safety & reliability of operation
- Very low likelihood and degree of core damage
- Eliminate the need for offsite emergency response

Vision

Next generation nuclear systems: Generation IV

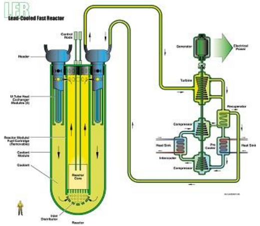
GFR

Gas-cooled
Fast Reactor



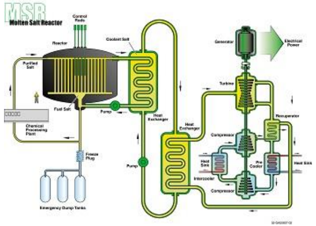
LFR

Lead-cooled
Fast Reactor



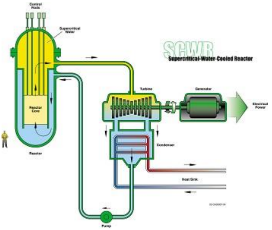
MSR

Molten
Salt
Reactor



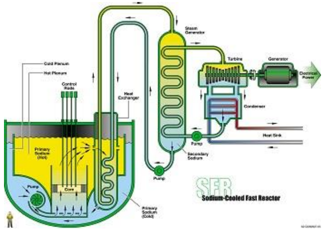
SCWR

Supercritical
Water
Reactor



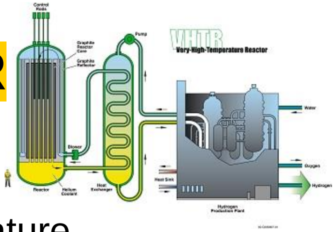
SFR

Sodium-
cooled
Fast
Reactor



VHTR

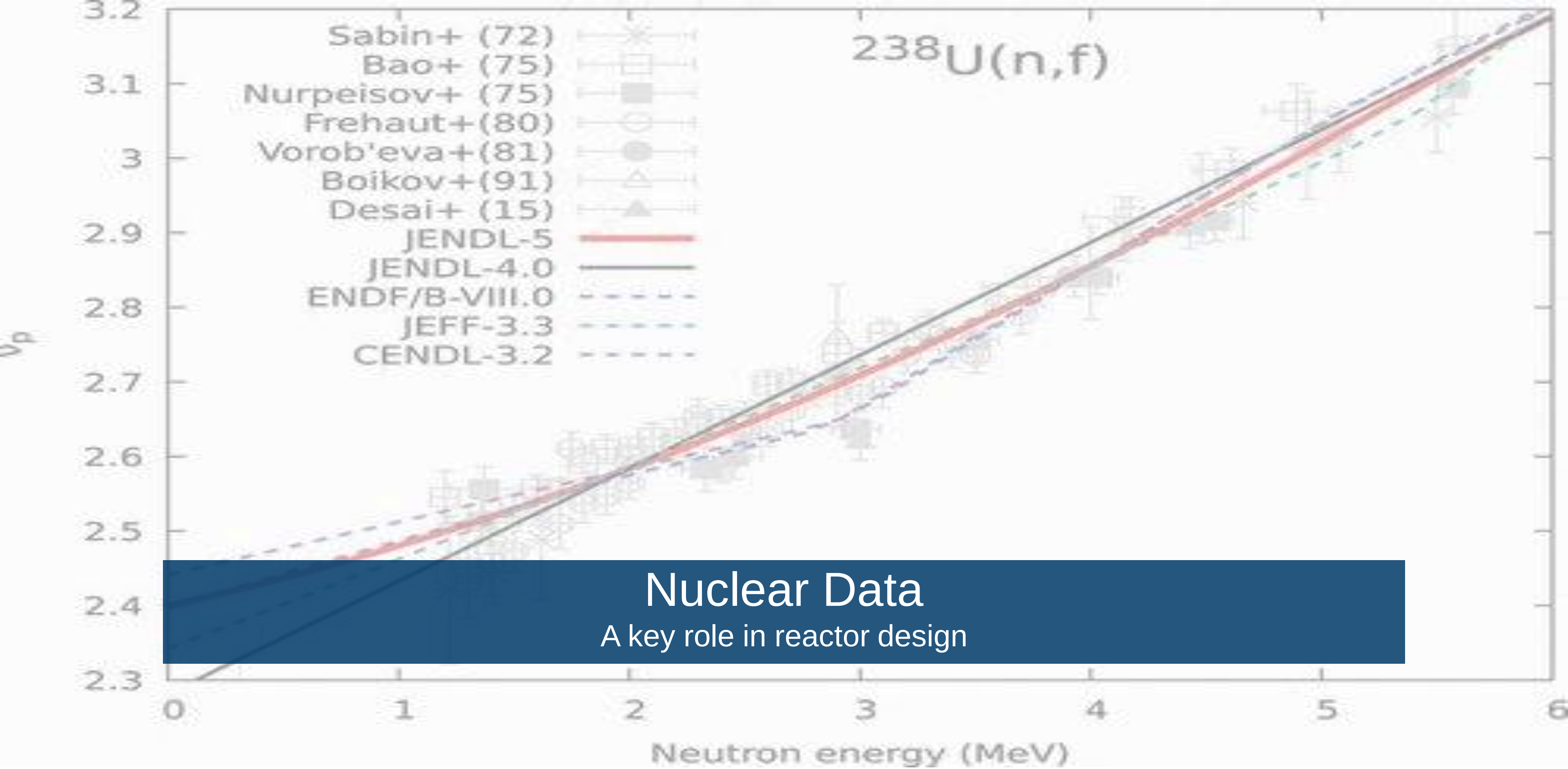
Very-
High
Temperature
Reactor



BREST-OD-300 (Seversk, Russian Federation)

300 MWe demonstrator

Steel reactor baseplate installed on January 17th, 2024

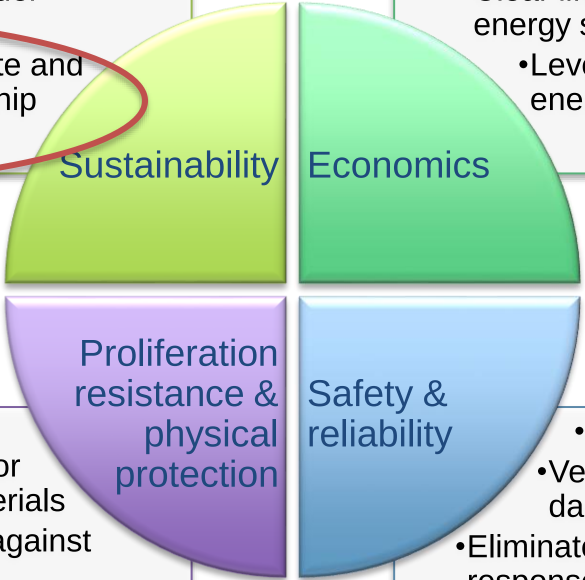


Nuclear Data

A key role in reactor design

Vision

Next generation nuclear systems: Generation IV



Sustainability

- Meet clean air objective and effective fuel utilization
- Minimize and manage the nuclear waste and notably reduce the long-term stewardship burden

Economics

- Clear life-cycle cost advantage over other energy sources
  - Level of financial risk comparable to other energy projects

Proliferation resistance & physical protection

- Increase assurance of being very unattractive and least desirable route for diversion/theft of weapons-usable materials
- Provide increased physical protection against acts of terrorism

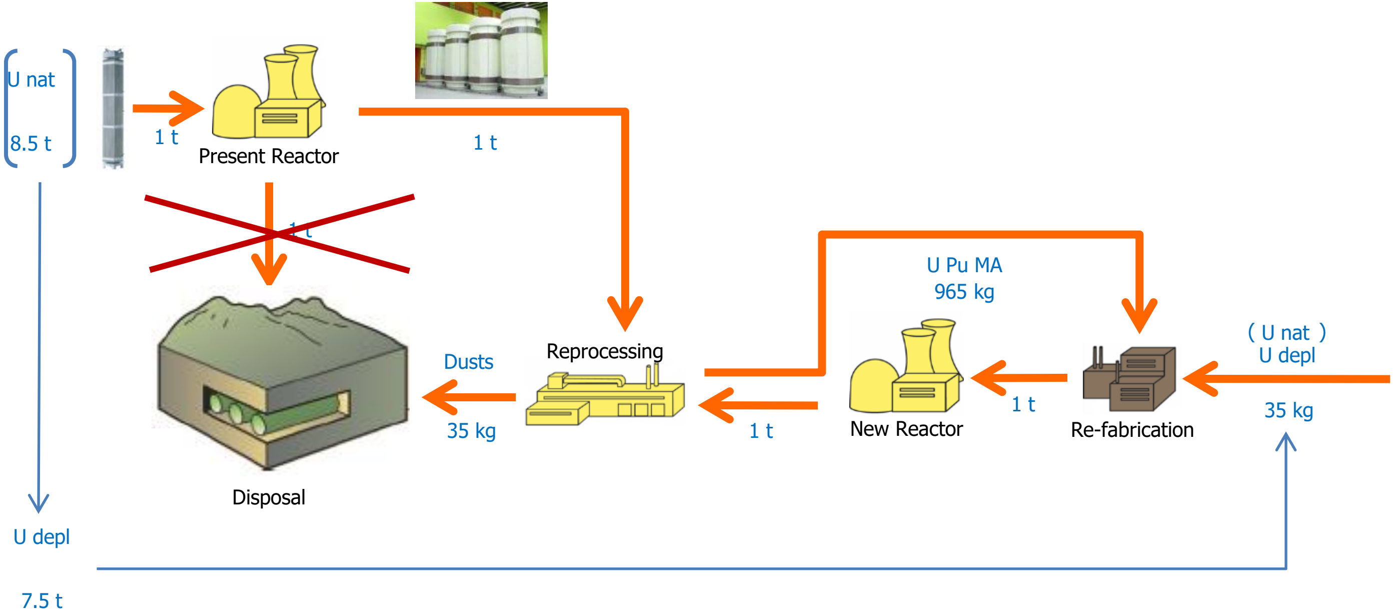
Safety & reliability

- Excel in safety & reliability of operation
  - Very low likelihood and degree of core damage
- Eliminate the need for offsite emergency response

Nuclear fuel cycle

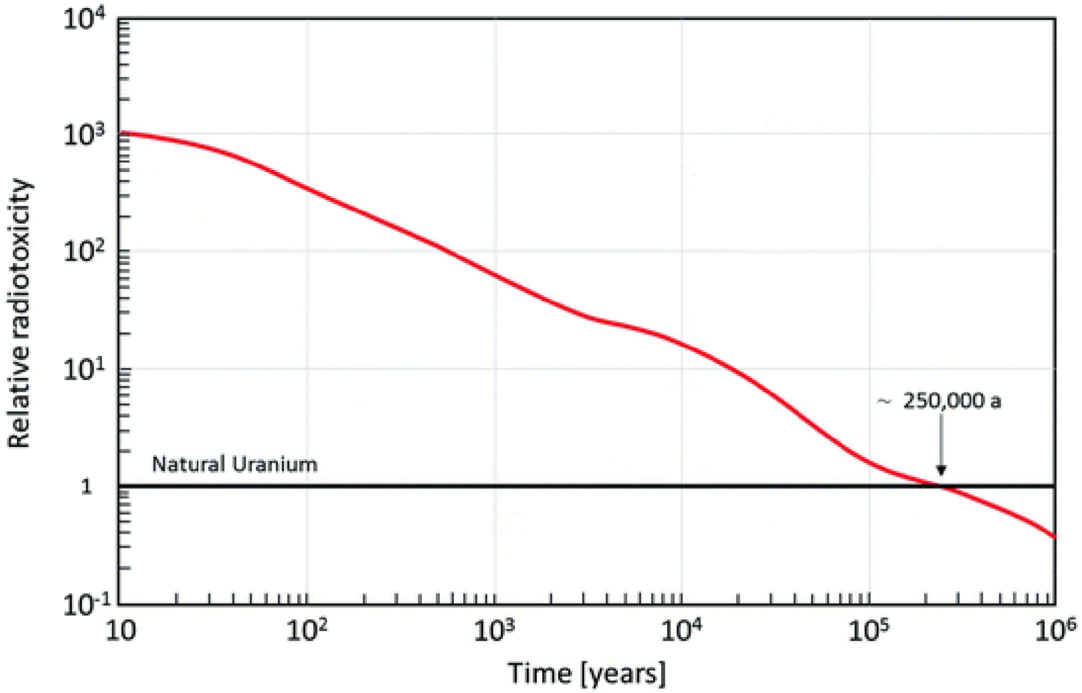
From open to closed

[See presentation by O. Cabellos for more details]



Enhanced sustainability

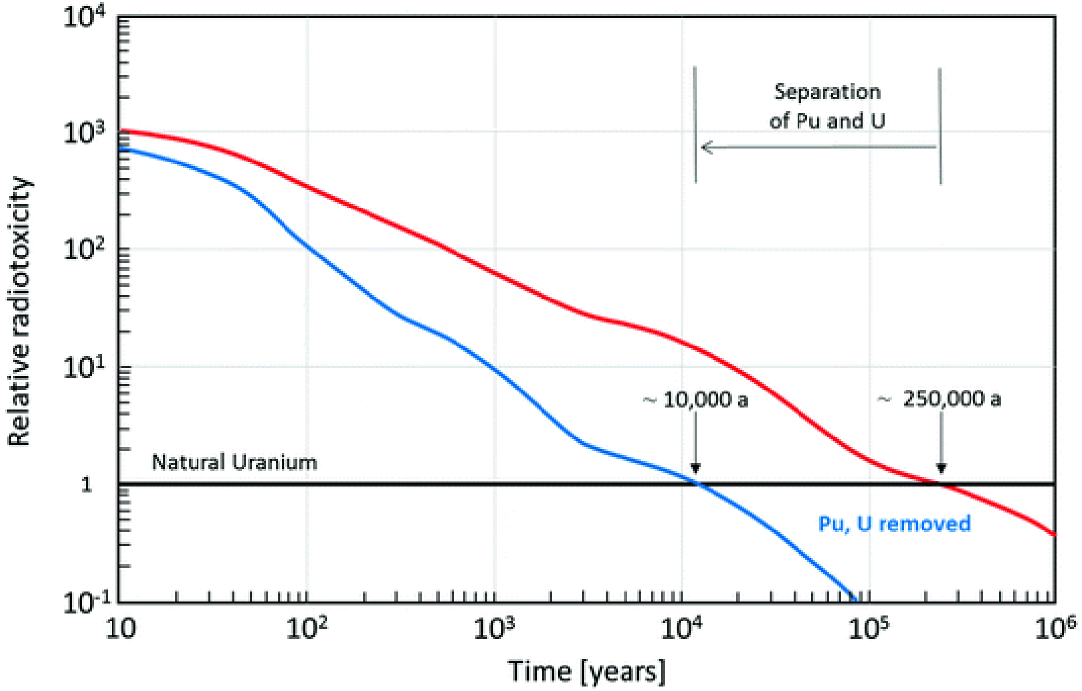
Even though the volume is small, thus the management is simple, the spent fuel from a plant of current generation has a high radiotoxicity, which reduces down to that of Uranium ore in times of the order of a hundred thousand years.



Enhanced sustainability

Current reactors moreover do not burn all the loaded fuel. In the spent fuel, hence, there are still valuable materials.

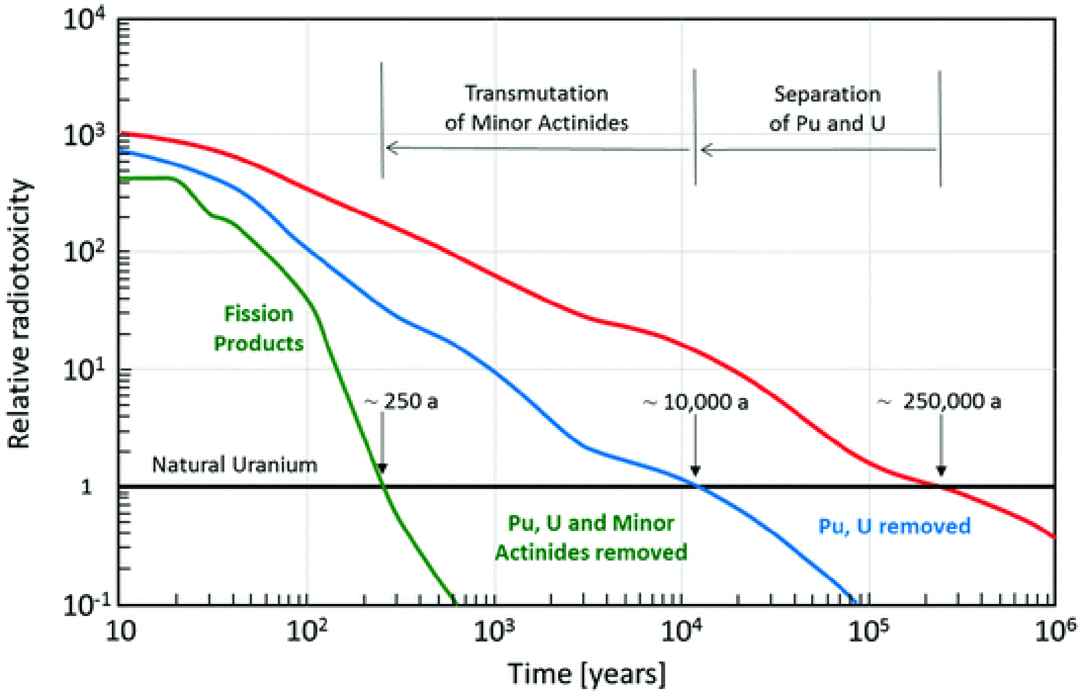
Some countries pursue the technique of reprocessing, to recover part of what is still useful for its reuse in the same reactors.



Enhanced sustainability

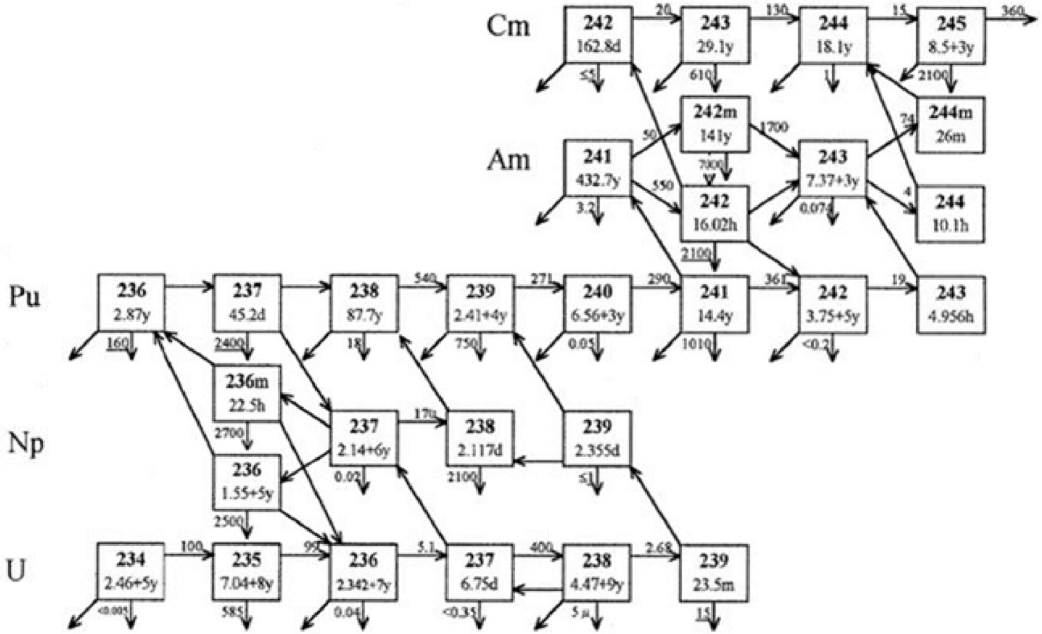
Fast spectrum reactors have the chance to fission (thus use) all actinide isotopes (and not just those of U and Pu).

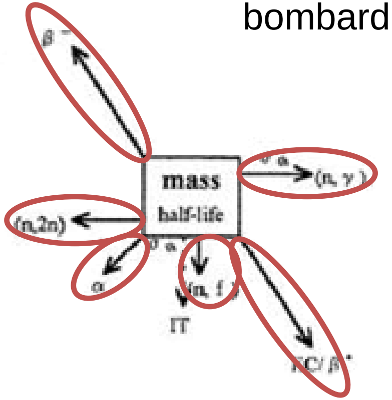
By this, also other species can be recovered in reprocessing, leaving as actual waste only the fission products. This allows reducing the time of surveillance for the waste down to few centuries.



Fuel cycle closure

Fuel evolution





Transmutation channels

Could be:

- spontaneous (i.e., by radioactive decay),
- induced (i.e., by neutron bombardment).

Fuel cycle closure

The physics of fuel evolution: Bateman’s equations

The evolution of the isotopic composition of the fuel is ruled by the Bateman’s equations:

$$\frac{dN_i}{dt} = \sum_{j \neq i} N_j(t)\left(\sigma_{j \to i}\phi + \lambda_{j \to i}\right) - N_i(t)\left(\sigma_i\phi + \lambda_i\right)$$

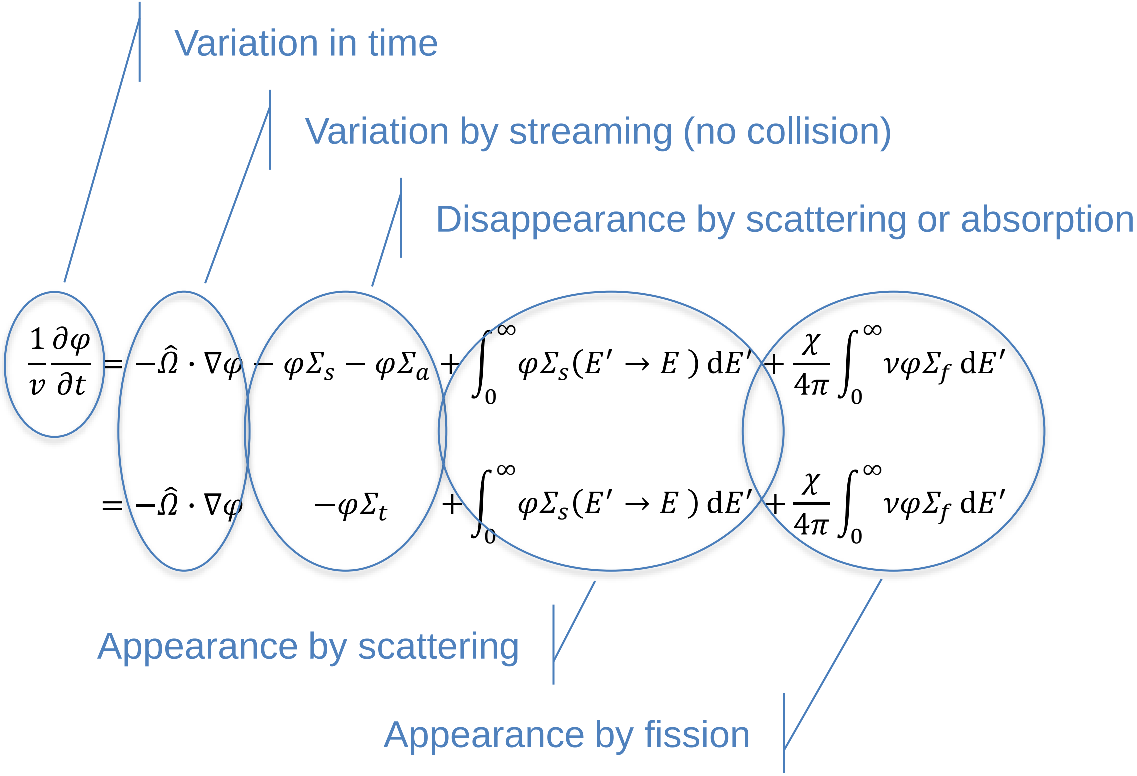
where

- $N_i(t)$ is the number of atoms of the i-th isotope at time t;
- σ_i is the total removal cross section of the i-th isotope, including the sum of those targeting all possible isotopes $j \neq i$, $\sigma_{i \to j}$;
- λ_i is the total decay constant of the i-th isotope, including the sum of those targeting all possible isotopes $j \neq i$, $\lambda_{i \to j}$;
- ϕ is the neutron flux integrated over the whole fuel volume.

Neutrons balance

In the reactor, the distribution of the neutrons φ in the $\Gamma(\vec{r},\vec{v}) \equiv \Gamma\left(\vec{r},\hat{\Omega},E\right)$ phase space is ruled by the Boltzmann equation, which represents a balance in an volume $\mathrm{d}\Gamma$ of the phase space.

All terms depend on the macroscopic cross sections, which include micro and atom densities (solution of Bateman's equations).



Variation in time

Variation by streaming (no collision)

Disappearance by scattering or absorption

$$\frac{1}{v}\frac{\partial\varphi}{\partial t} = -\hat{\Omega}\cdot\nabla\varphi - \varphi\Sigma_s - \varphi\Sigma_a + \int_0^\infty \varphi\Sigma_s(E' \to E\,)\,\mathrm{d}E' + \frac{\chi}{4\pi}\int_0^\infty \nu\varphi\Sigma_f\,\mathrm{d}E'$$

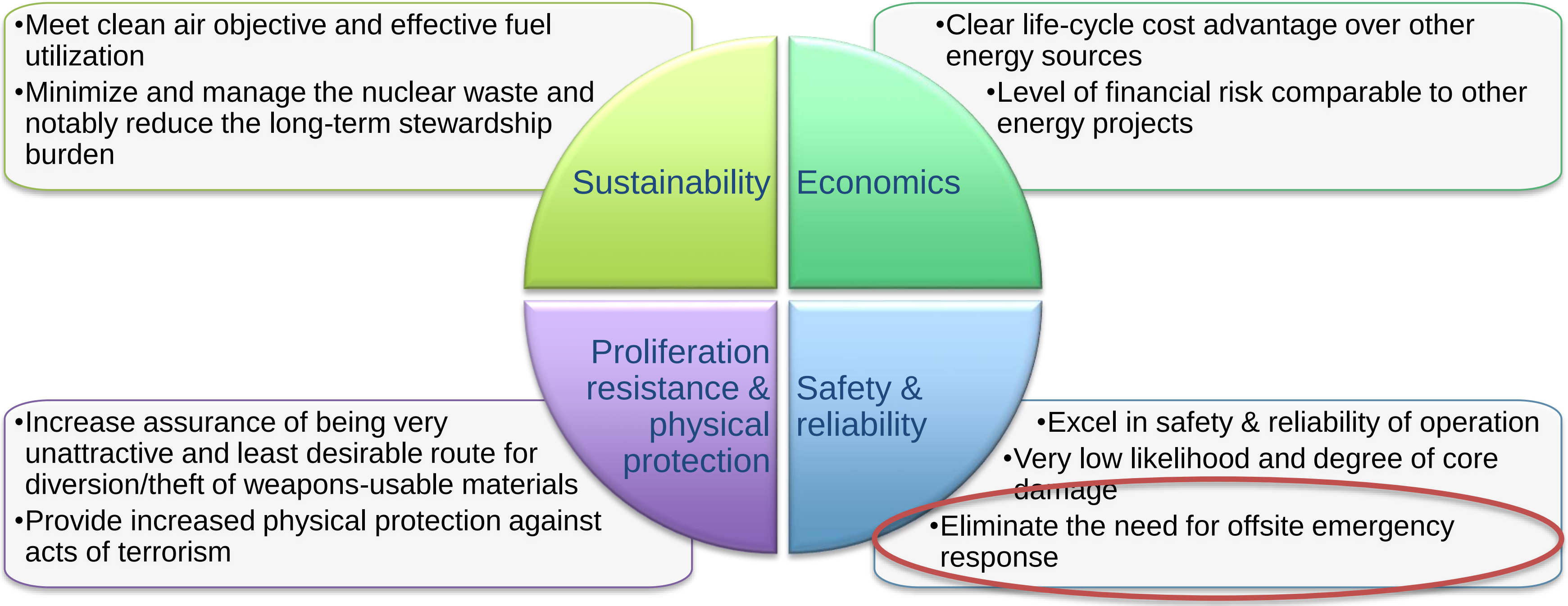
$$= -\hat{\Omega}\cdot\nabla\varphi \quad -\varphi\Sigma_t \quad + \int_0^\infty \varphi\Sigma_s(E' \to E\,)\,\mathrm{d}E' + \frac{\chi}{4\pi}\int_0^\infty \nu\varphi\Sigma_f\,\mathrm{d}E'$$

Appearance by scattering

Appearance by fission

Vision

Next generation nuclear systems: Generation IV



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Nuclear safety

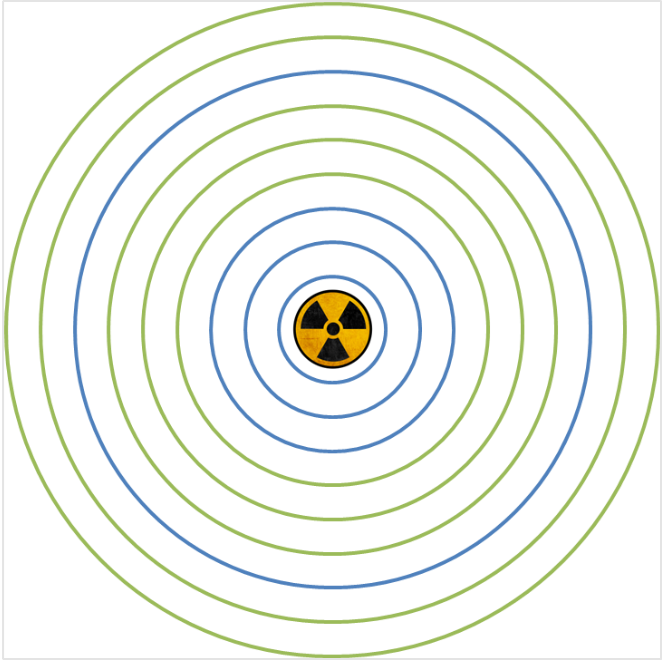
Safety principles

Defence in depth is one of the paramount and foundational principles for safety.

As seen, it stands on deploying

- **physical barriers**
- **engineered provisions**

as lines of defence.



Nuclear safety

Evolution of the approach

With time, the approach to nuclear safety has evolved:

Active safety

- Provisions requiring intervention to be deployed
- The most common in plants up to Gen-II

Passive safety

- Provisions able to deploy autonomously
- The most common in plants of Gen-III and even more III+

Inherent safety

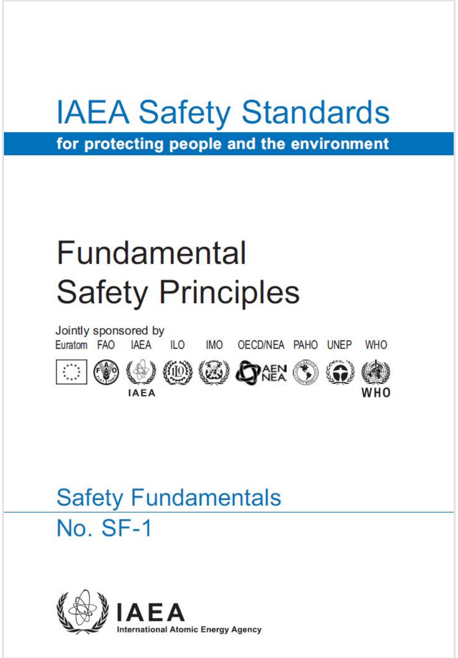
- Spontaneous provisions, intimately embedded
- The mandatory choice for plants of Gen-IV

Nuclear safety

Fundamental safety functions

Defined by the IAEA, summarize the essence itself of nuclear safety:

- **control of reactivity**
- **removal of heat**
- **confinement of radioactivity**



IAEA Safety Standards

for protecting people and the environment

Fundamental
Safety Principles

Jointly sponsored by
Euratom FAO IAEA ILO IMO OECD/NEA PAHO UNEP WHO

Safety Fundamentals
No. SF-1

IAEA
International Atomic Energy Agency

Criticality

Criticality is the ability of a system to sustain a fission chain reaction.

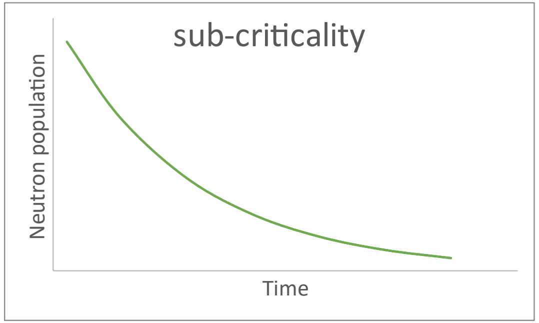
Dividing the neutron population into «generations», criticality can be measured by the multiplication factor, as the ratio between the neutrons of two subsequent generations.

$$k = \frac{N^{(i+1)}}{N^{(i)}}$$

Criticality

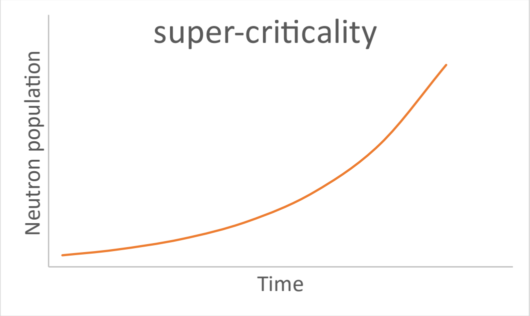
Depending on the value of k, three cases exist:

- **sub-criticality** $k < 1$
- **criticality** $k = 1$
- **super-criticality** $k > 1$



At each generation, the number of neutrons is **reduced**.
The fission chain reaction is thus destined to **extinguish**.

At each generation, the number of neutrons is **preserved**.
The fission chain reaction is thus destined to **survive**.



At each generation, the number of neutrons is **increased**.
The fission chain reaction is thus destined to **expand**.

Criticality

Extending the balance equation to the entire system and the entire range of energies, we can observe that criticality is a combination of three contributions:

- production
- removal (by absorption)
- removal (by leakage)

$$k_{\text{eff}} = \frac{\boxed{\nu\Sigma_f}}{\boxed{\Sigma_a} + \boxed{\mathcal{L}}}$$

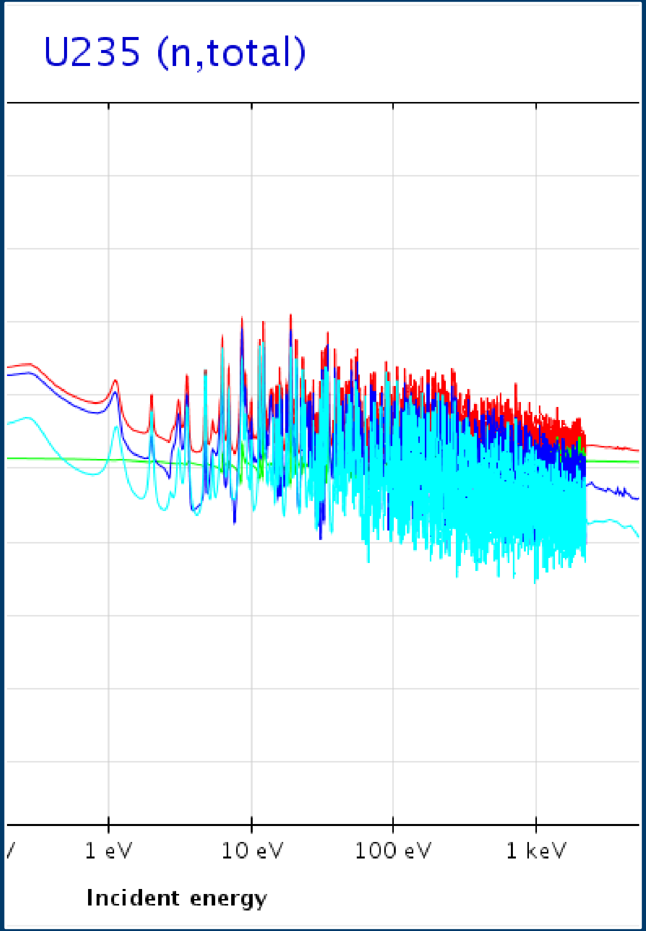
Nuclear safety

Inherent safety to control the reactivity

By properly arranging the materials (on which the cross sections in all the terms of the formula depend) and the volume and shape of the domain (which contribute to the leakage term), it is possible to obtain a system which inherently reduces its reactivity upon any accidental:

- increase of power
- increase of temperature
- reduction of coolant flowrate

$$k_{\text{eff}} = \frac{\nu\Sigma_f}{\Sigma_a + \mathcal{L}}$$



It could be legitimate to ask…

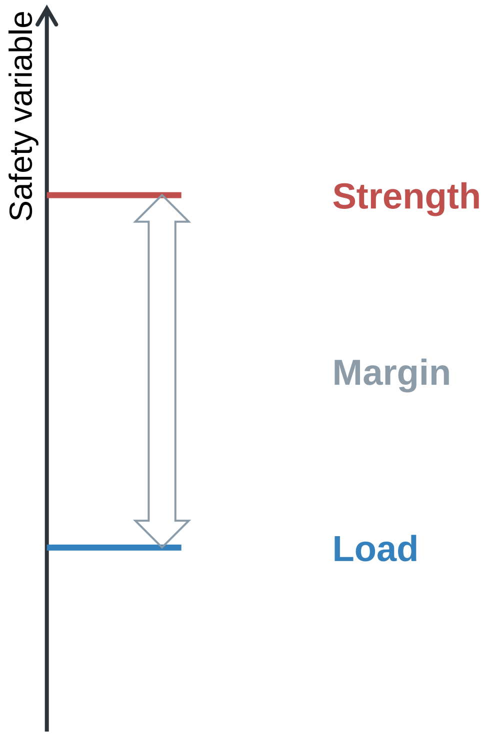
…where's the need for nuclear data, since the cross sections are all known pretty well?

(as it is proven by the operation itself of nuclear reactors worldwide…)

Limits and margins

For any component – and notably those safety-related – design aims at setting appropriate margins, as “the difference (conservatism) between the actual state (load) and the damage state (strength)”.

[OECD/NEA’s Task Group on Safety Margins Action Plan]

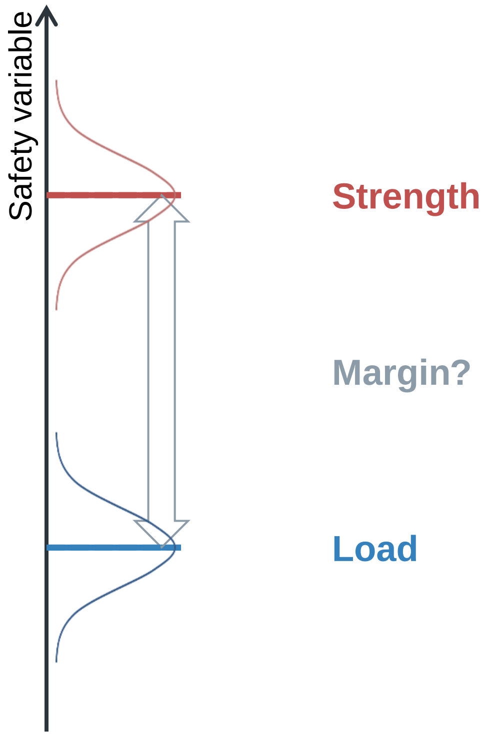


Limits and margins

However, things are never so easy, because of uncertainties

- in establishing the actual resisting strength, and
- in anticipating the load actually applied.

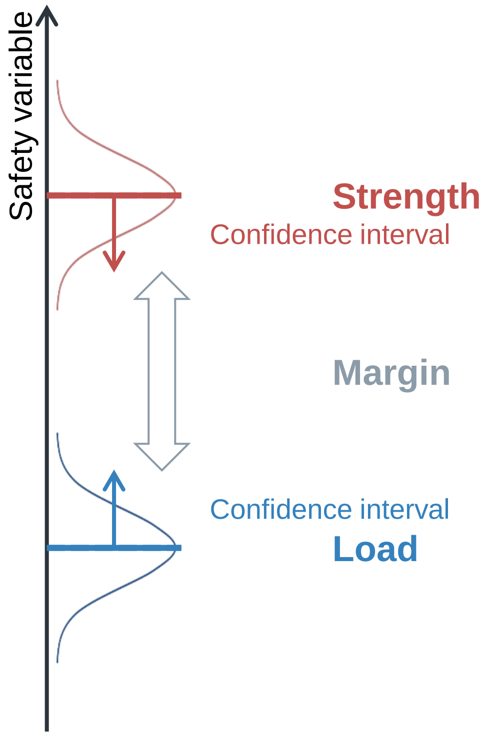
This reflects in the difficulty to evaluate the residual margin, to ensure it still remains non-null.



Limits and margins

Risk assessment is a typical engineering approach to establish a degree of confidence, and to retrieve the associated interval in the uncertainty range so that the actual value falls within such range with the assumed confidence.

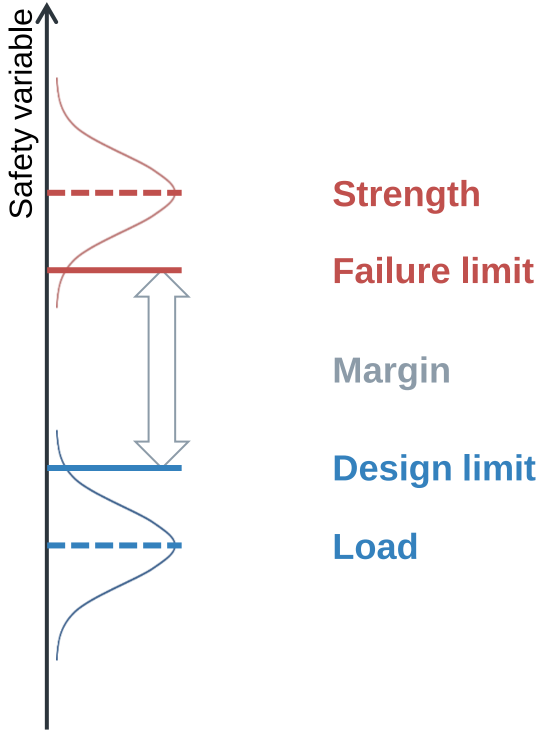
By this, clear bounds can be defined again, to ensure a non-null margin.



Limits and margins

The lower bound of the confidence interval related to strength is known as «Failure limit».

The companion, upper bound of the confidence interval related to load is known as «Design limit».

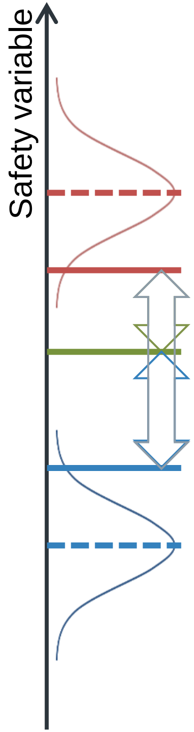


Limits and margins

In nuclear, however, a further limit is set by the Regulator: the «Safety limit».

This limit is set according to a Safety margin defined in the norms, and is typically country-specific.

What remains of the original margin is called Design margin, and is matter of optimization.



Strength

Failure limit

Safety Margin

Safety limit

Margin

Design Margin

Design limit

Load

Giacomo Grasso

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