Lecture 5
Nuclear Energy

PHY 555 – Energy & Environment

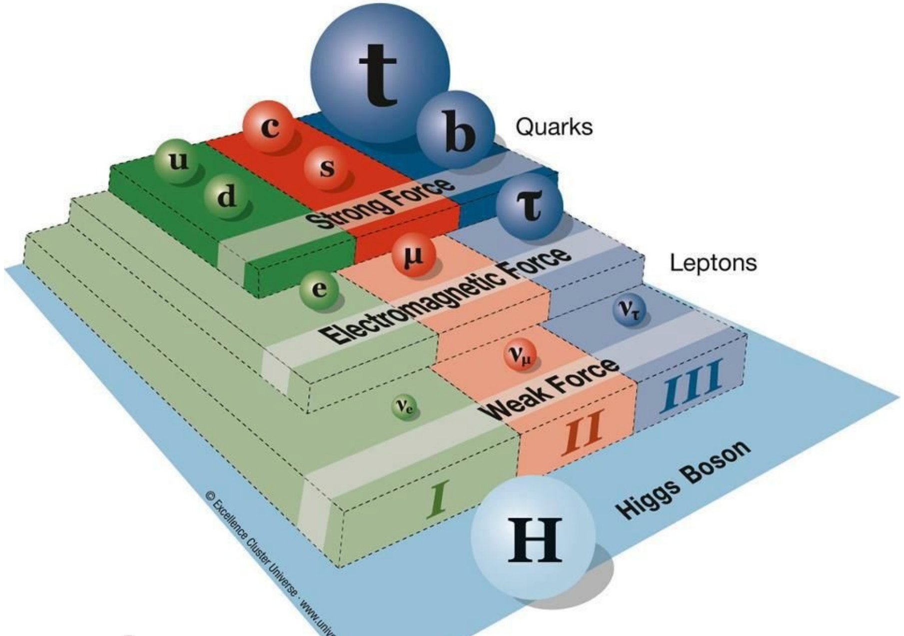
Erik Johnson, Mathieu de Naurois, Daniel Suchet

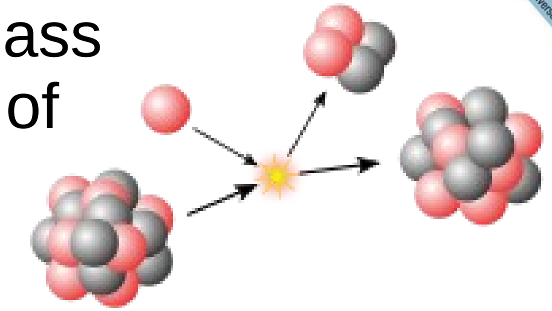
Lecture 5 – Nuclear Energy

- **I. Basics of nuclear physics**
- II. Fission Power Plants
- III. Fast Breeders – Generation IV
- IV. Fusion Energy, current status, challenges and outlook
- V. Conclusions

What is nuclear energy?

- Binding energy of the nucleons, binding quarks into hadrons
- Correspond to one of the 4 fundamental forces:
  strong nuclear force
- Mediated by the exchange of gluons (vector bosons)
- Energy can be recovered by changing nuclei content (nuclear reactions)
- Carry ~ 10^6 × more energy per unit mass than chemical reaction (arrangement of atoms in molecules)





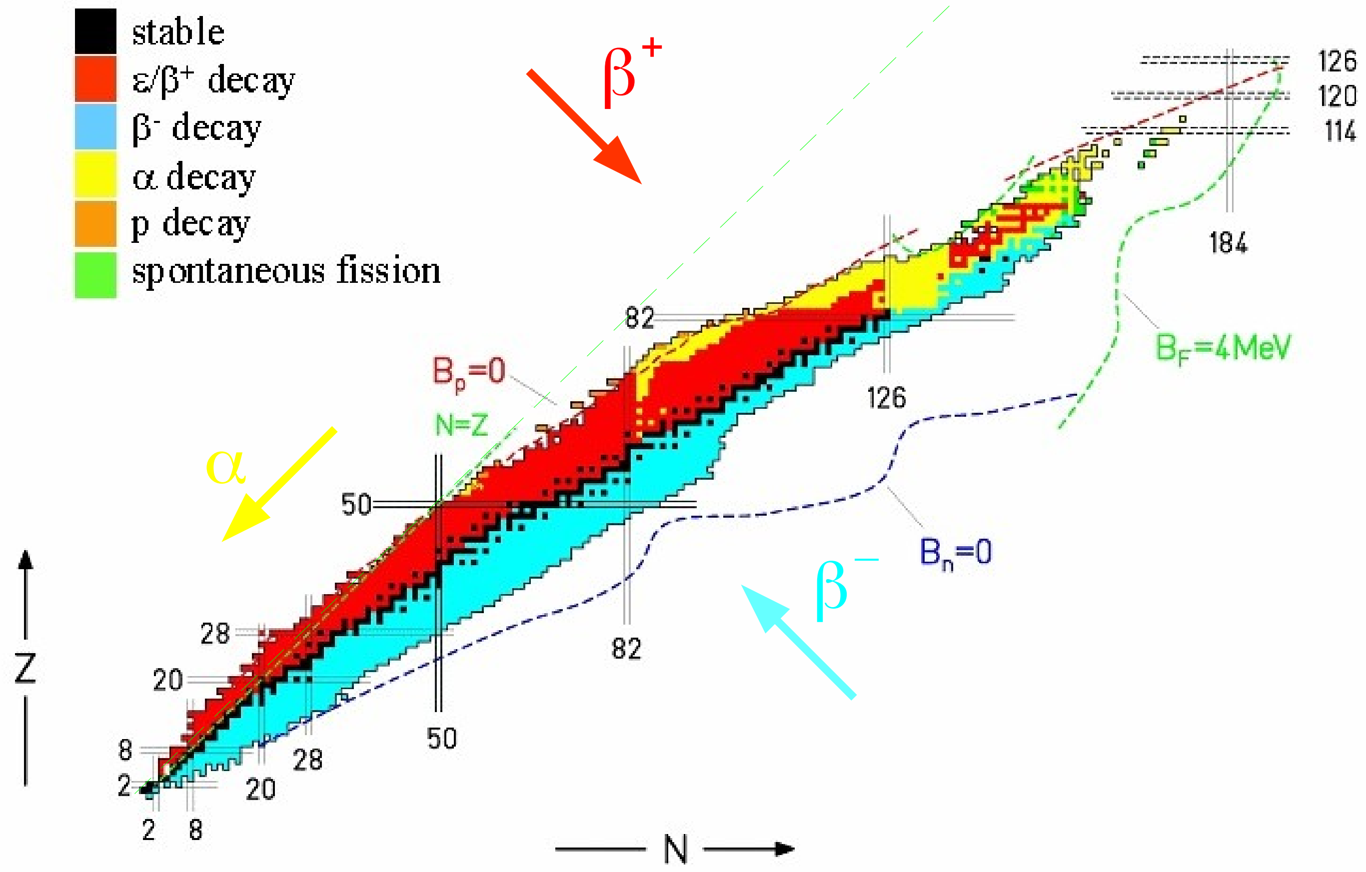
Stability Valley

- Representation of known nuclei in a (N, Z) graph indicates a stability line
- Nuclei on both sides of this line are radioactive (β^+/β^-)
  - Weak interaction ($W^\pm$)

$$n \rightarrow p + e^- + \bar{\nu}_e \quad (\beta^-)$$

$$p \rightarrow n + e^+ + \nu_e \quad (\beta^+)$$

- Heavier nuclei can disintegrate via α decay or even spontaneous fission
- Responsible for natural radioactivity



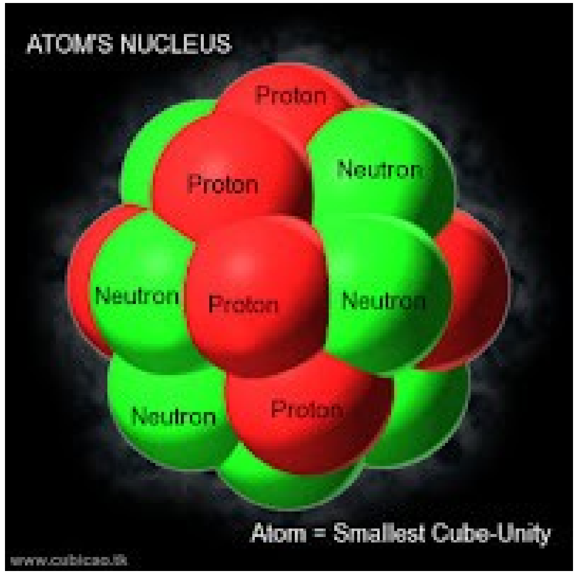
Liquid Drop Model

- Simple of model of nuclear matter: **incompressible** fluid with a **very high density** (Bethe-von Weiszäcker model – 1936) : a nuclei is similar to a liquid ‘*drop*’.
- Separating a nuclei in its constituents (single nucleons) requires the binding energy B(Z,N) :

$$B(Z,N)=a_V A-a_S A^{2/3}-a_C\frac{Z^2}{A^{1/3}}-a_A\frac{(A-2Z)^2}{A}+\begin{cases}\delta & (pp)\\ 0 & (pi)\\ -\delta & (ii)\end{cases}$$

$$a_V=15{,}67\,\mathrm{MeV},\quad a_S=17{,}23\,\mathrm{MeV},\quad a_C=0{,}696\,\mathrm{MeV}$$

$$a_A=23{,}28\,\mathrm{MeV},\quad \delta\approx\frac{12\,\mathrm{MeV}}{A^{1/2}}$$

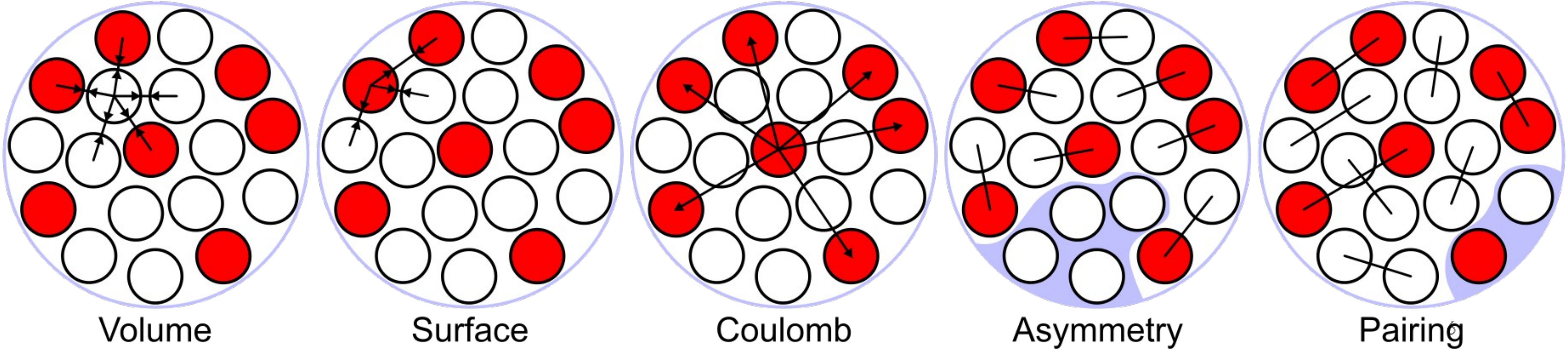


Liquid drop model Interpretation

$$B(Z,N) = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \begin{cases} \delta & (pp) \\ 0 & (pi) \\ -\delta & (ii) \end{cases}$$

$$a_V = 15{,}67\,\mathrm{MeV}, \quad a_S = 17{,}23\,\mathrm{MeV}, \quad a_C = 0{,}696\,\mathrm{MeV}$$

$$a_A = 23{,}28\,\mathrm{MeV}, \quad \delta \approx \frac{12\,\mathrm{MeV}}{A^{1/2}}$$

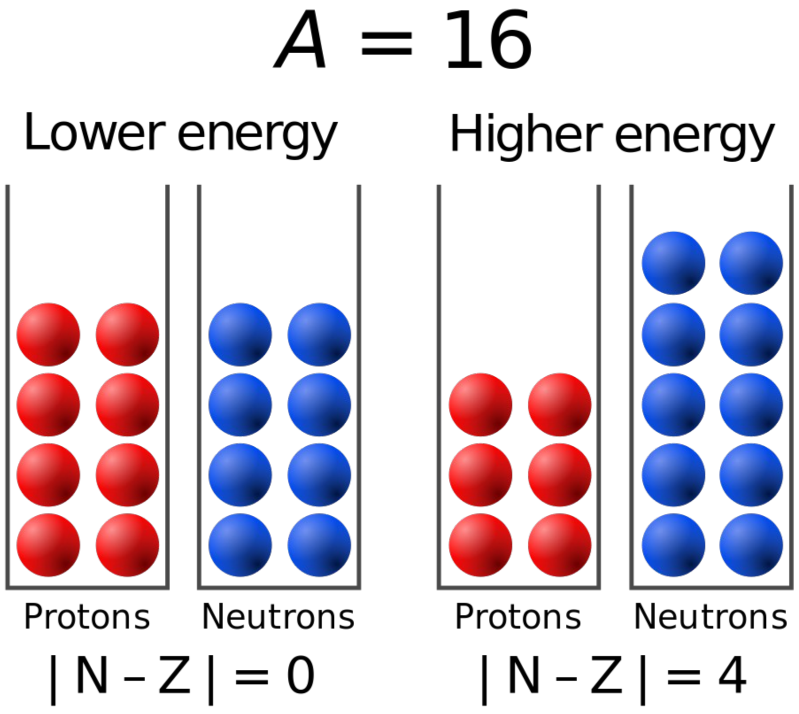


Asymmetry term

- Arises from Pauli exclusion principle

$$B_A(Z,N) = -a_A \frac{(A-2Z)^2}{A}$$

- Protons & neutrons are fermions
- Each quantum level can accommodate 2 particles (opposite spin)
- Lower levels are occupied for identical numbers of protons & neutrons

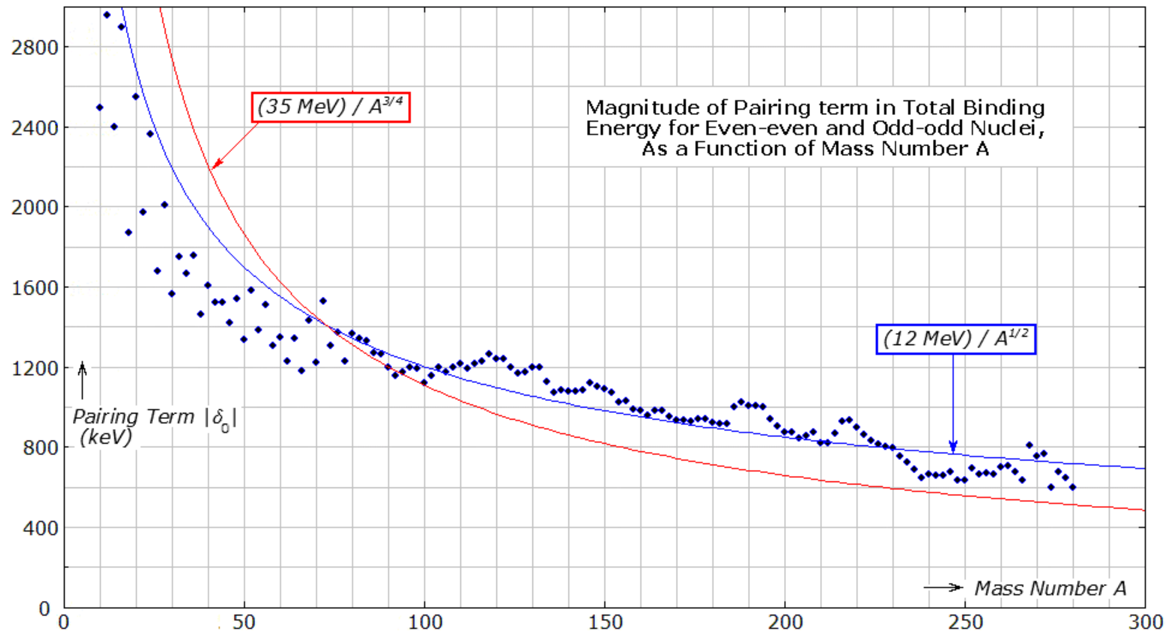


Pairing term

- Pairwise interaction, corresponding to the spin-coupling

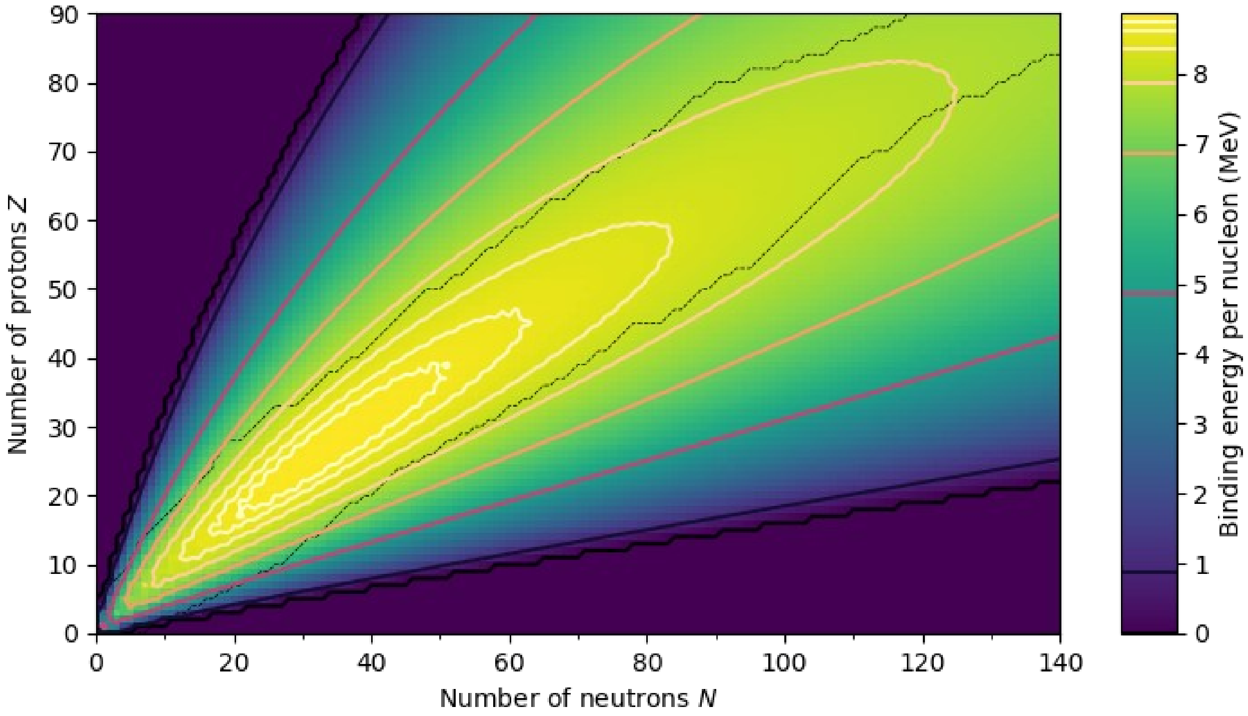
$$\delta(Z,N)=\begin{cases}\delta_0 & (Z,N\,\text{event})\\ 0 & (A\,\text{odd})\\ -\delta_0 & (Z,N\,\text{odd})\end{cases}$$

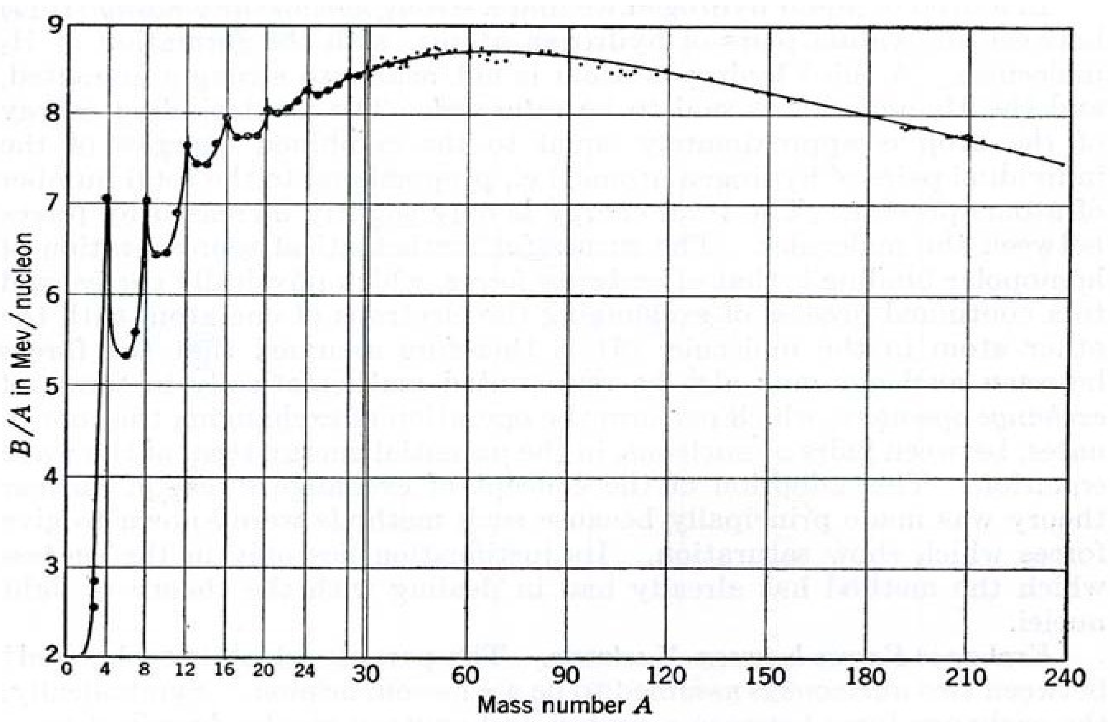
- Nuclei with complete shells (even number of protons/nucleons) are stabilized
- Value of δ_0 of the order of 1000 keV, slowly decreasing with mass number



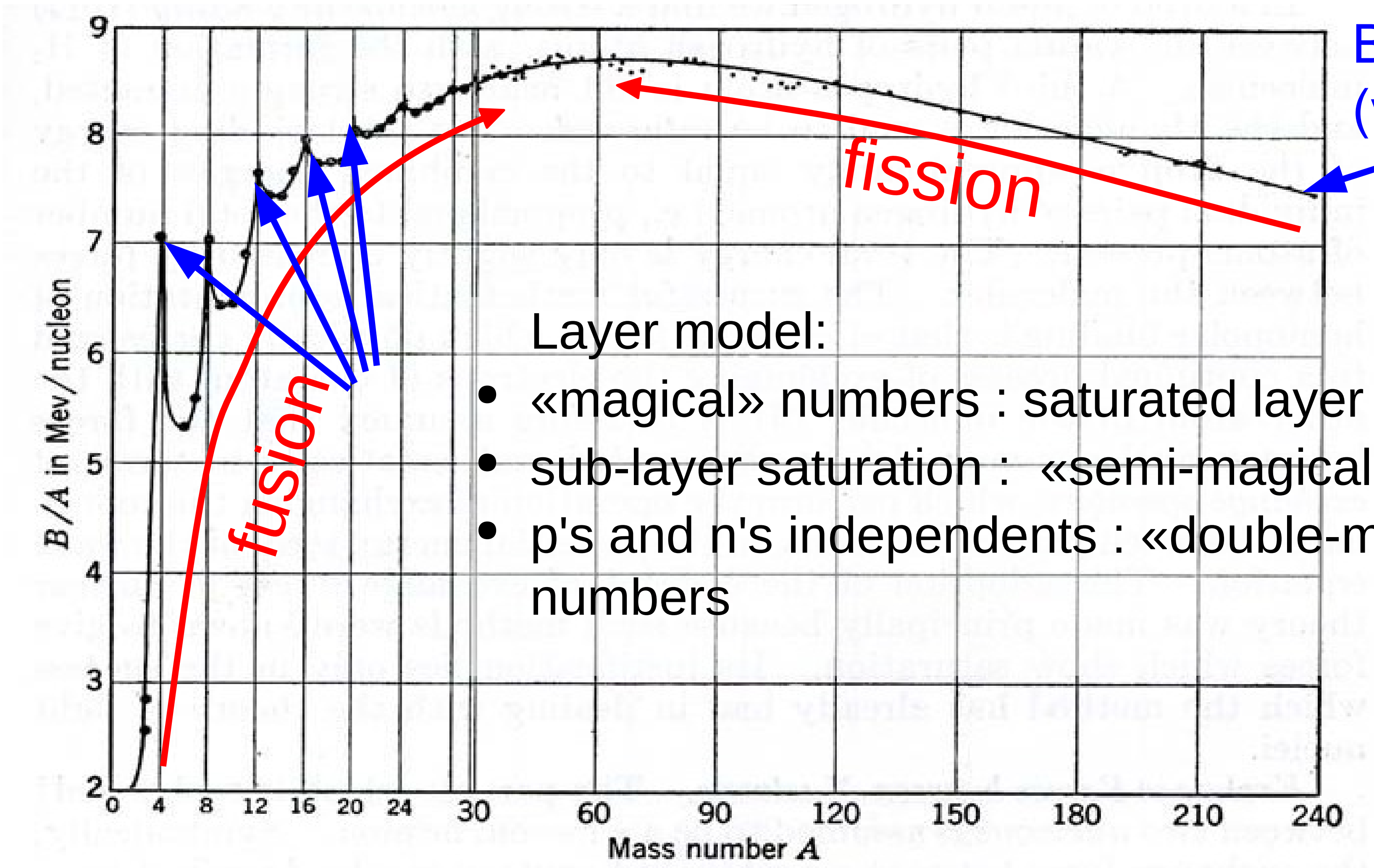
Liquid Drop Model Predictions

- Prediction of liquid drop mode accurate to ~ 100 keV
- Properly reproduced binding energy of most known nuclei
- Most stable nuclei is Iron (Fe)





Two ways of nuclear energy



B/A ~ constant [8 MeV/nucleon]
(volume E term dominant)

Layer model:

- «magical» numbers : saturated layer (orbital layer)
- sub-layer saturation : «semi-magical» numbers
- p's and n's independents : «double-magical» numbers

Fig. 3.1 Average binding energy B/A in Mev per nucleon for the naturally occurring nuclides (and Be^8), as a function of mass number A. Note the change of magnification in the A scale at $A = 30$. The Pauli four-shells in the lightest nuclei are

Lecture 5 – Nuclear Energy

I. Basics of nuclear physics

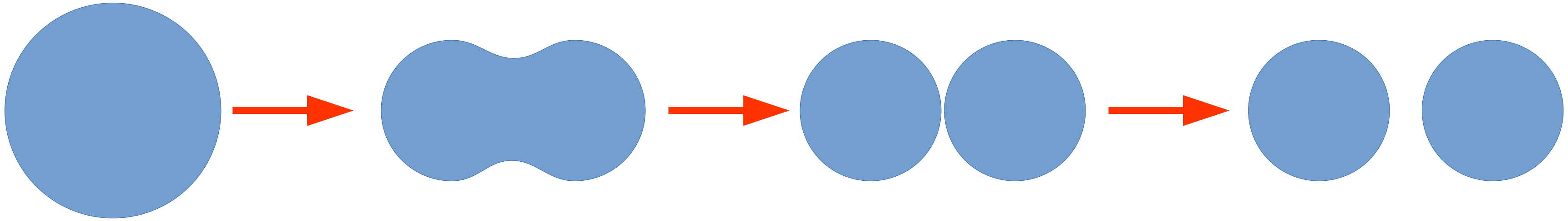
II. Fission Power Plants

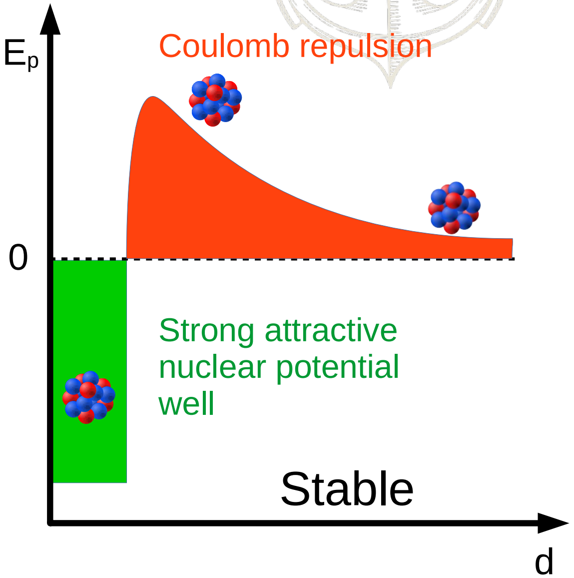
III. Fusion Energy, current status, challenges and outlook

IV. Conclusions

Spontaneous fission

- Nuclei that can spontaneously break into 2 smaller nuclei

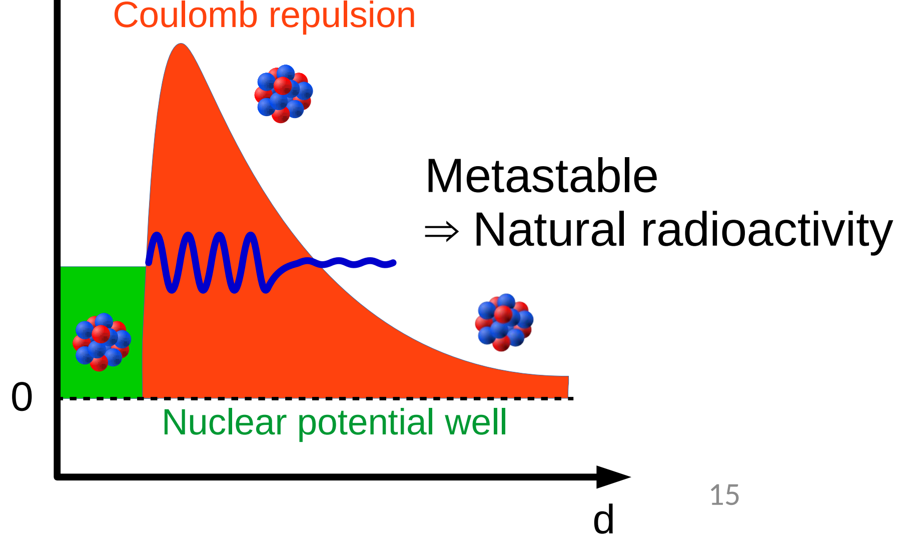




- The emitted fragment has to overcome a strong coulomb barrier

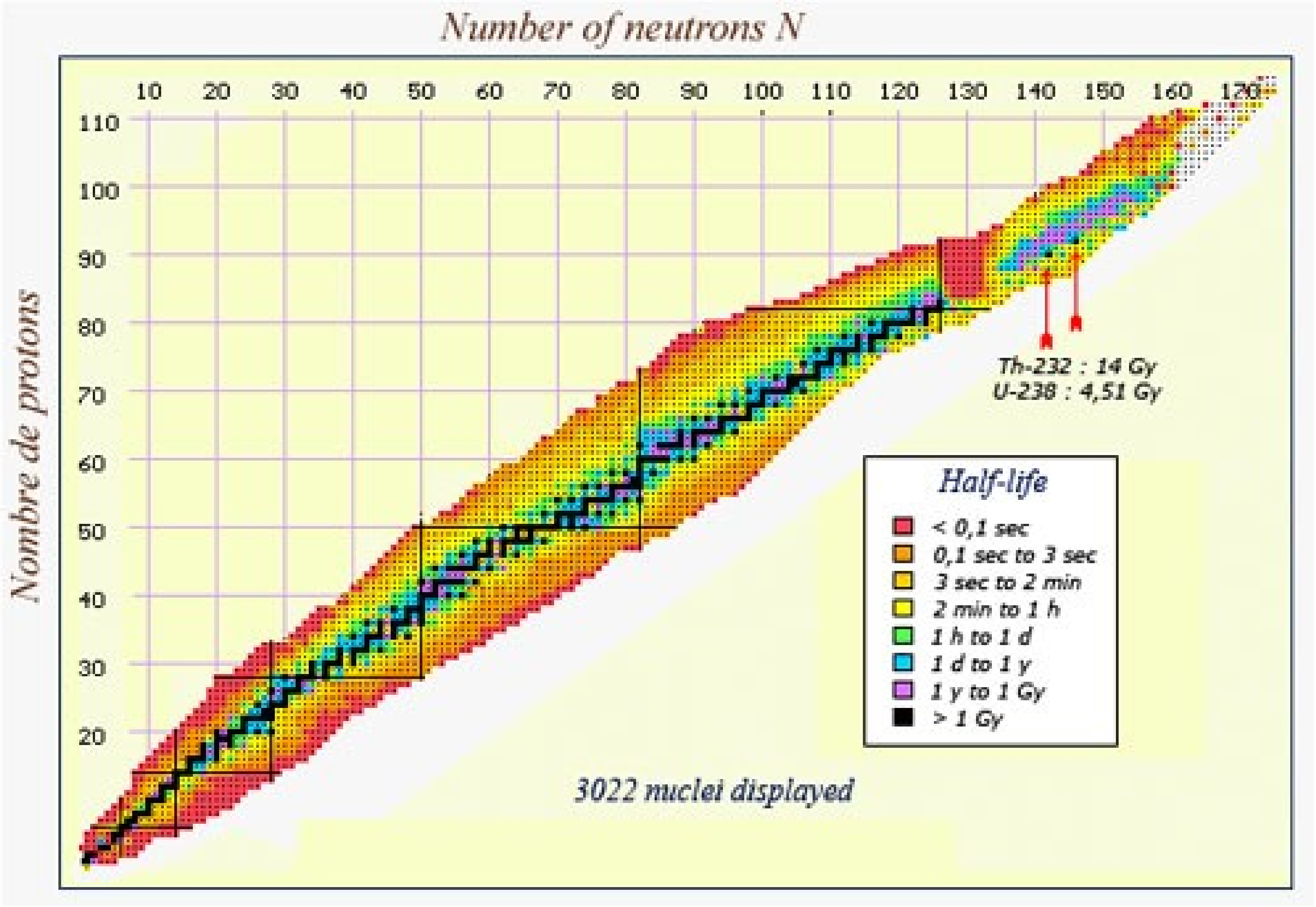
$$E_C \approx \frac{1}{4\pi\epsilon_0}\frac{(Ze/2)^2}{2R_0(A/2)^{1/3}}$$

- Quantum tunnelling allows spontaneous fission at very diverse rate



Natural radioactive elements

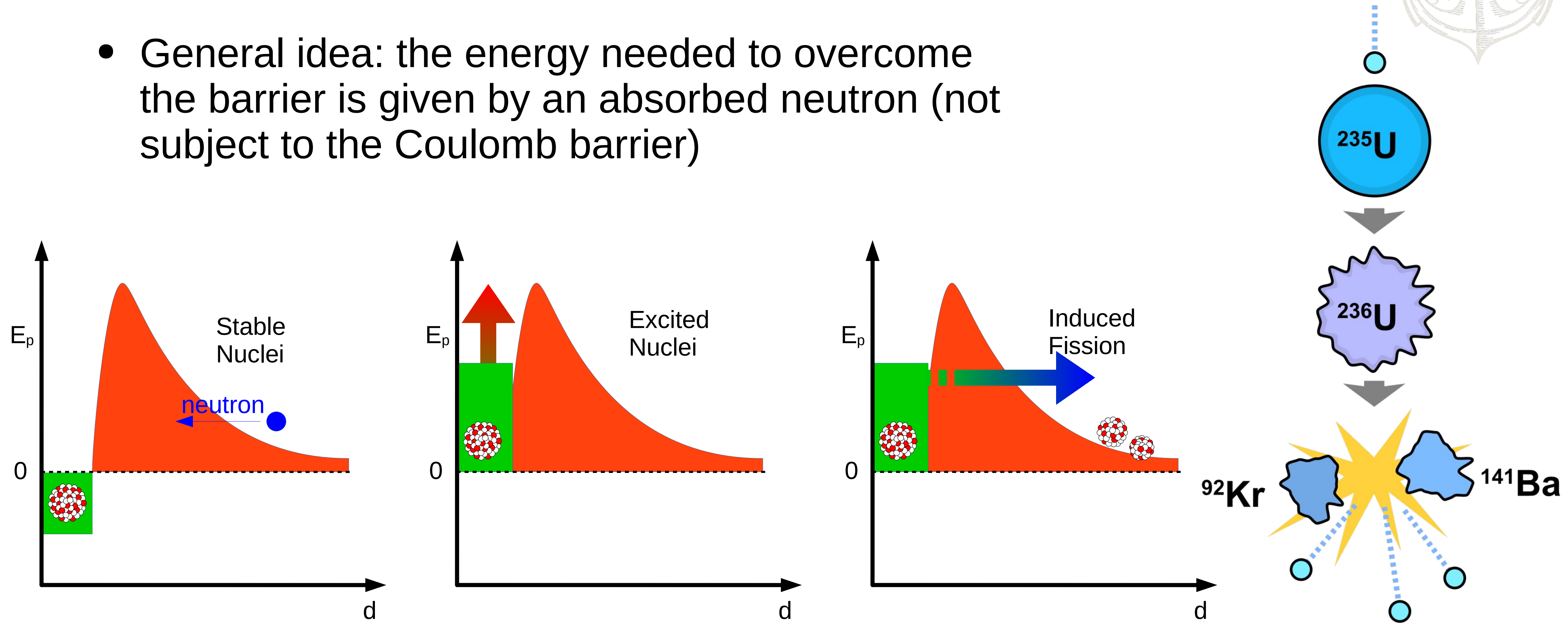
- Larger distances to the stability valley correspond to shorter lifetimes
- Ranges from < 0.1s (and even less for artificial isotopes) to Gyr



https://www.radioactivity.eu.com, ©NUCLEUS

Induced fission

- General idea: the energy needed to overcome the barrier is given by an absorbed neutron (not subject to the Coulomb barrier)

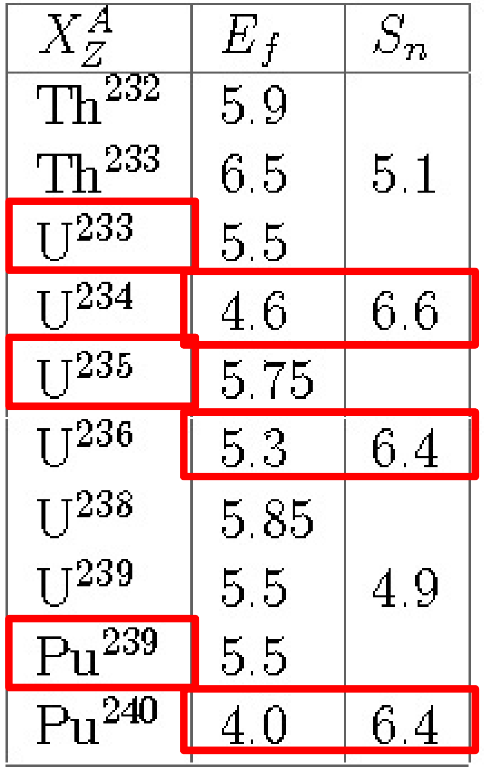


Induced Fission – Fissile nucleus

- Let's consider the neutron capture by a nucleus : ${}^{A-1}_{Z}X + n \rightarrow {}^{A}_{Z}X$
- Separation energy of the last nucleus reads:

$$S_n = B(Z,N) - B(Z,N-1)$$

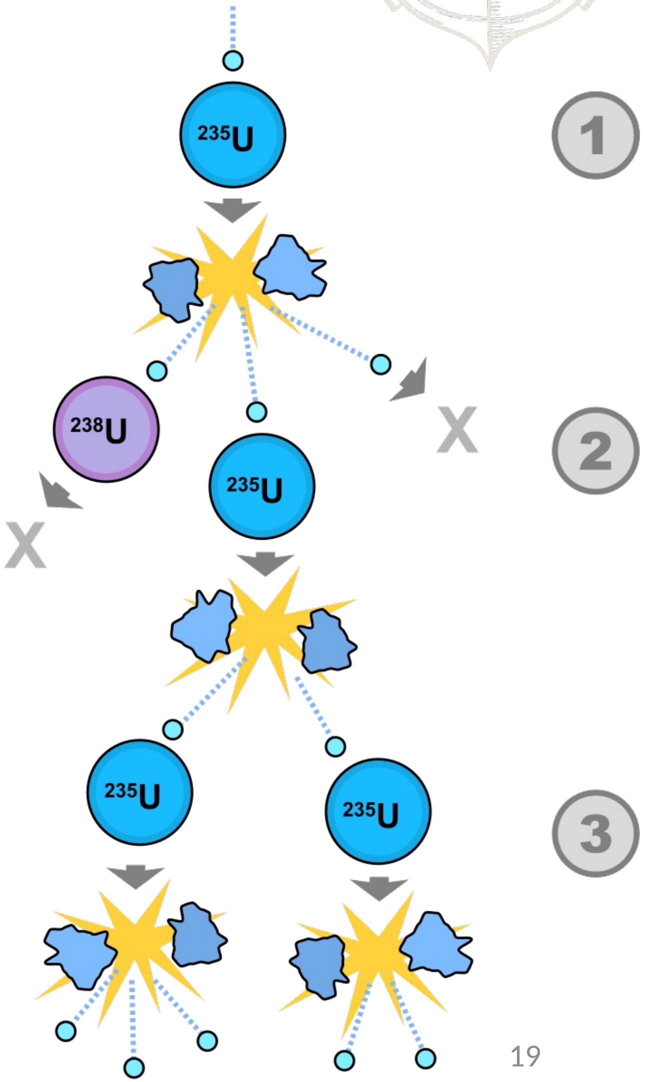
  (This is also the energy released in the neutron capture)
- Spin pairing term is critical:
  - (Z,N-1) even-odd (^{235}U) $S_n = f(A) - f(A-1) + \delta$
  - (Z,N-1) even-even (^{238}U) $S_n = f(A) - f(A-1) - \delta$
- If $S_n > E_f$, fission of the nucleus ${}^{A-1}_{Z}X$ by capture of a slow neutron is possible.
- **Odd** isotopes (^{233}U, ^{235}U, and ^{239}Pu) are fissile with slow neutrons because they reach a higher level of excitation
- Other nuclei can be fissile with fast neutrons (kinetic energy)



X_Z^A	E_f	S_n
Th^{232}	5.9	
Th^{233}	6.5	5.1
U^{233}	5.5	
U^{234}	4.6	6.6
U^{235}	5.75	
U^{236}	5.3	6.4
U^{238}	5.85	
U^{239}	5.5	4.9
Pu^{239}	5.5	
Pu^{240}	4.0	6.4

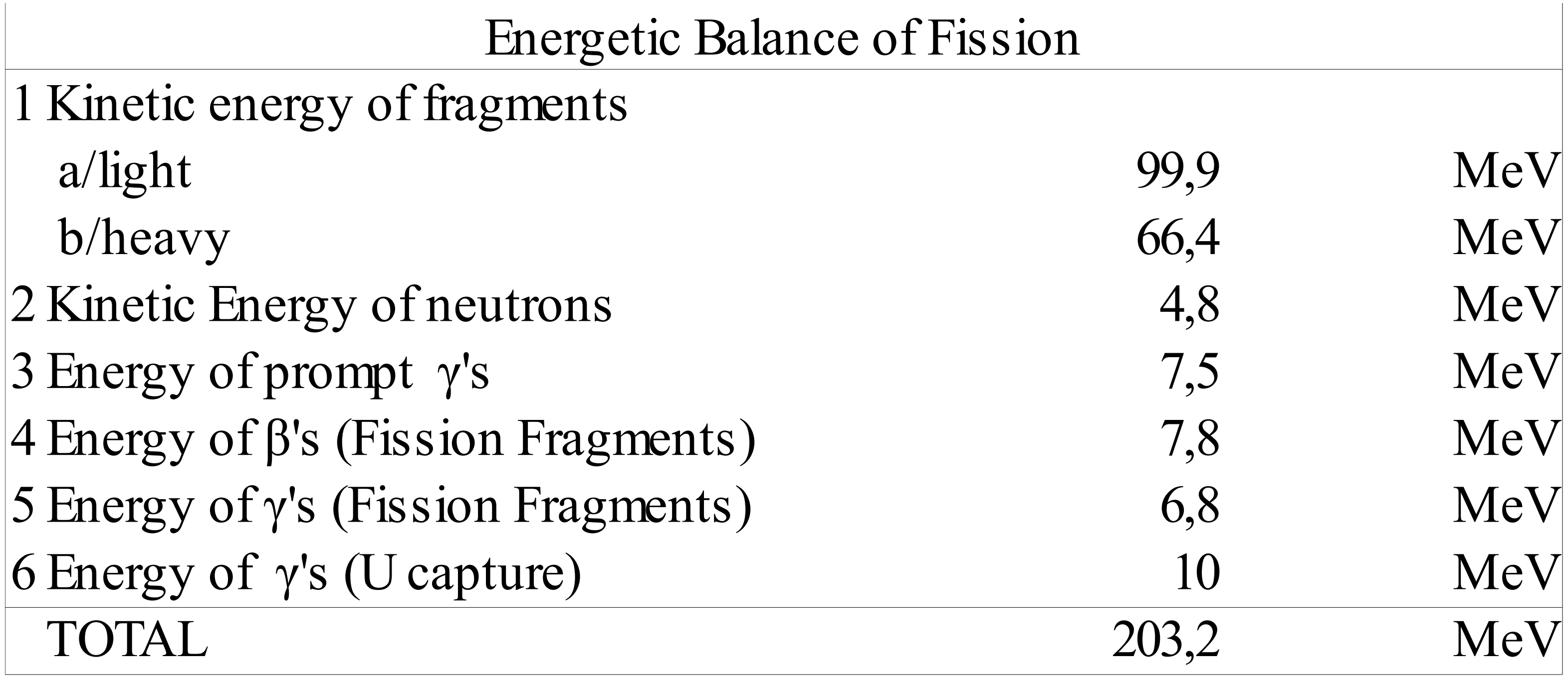
Principle of fission reactor: chain reaction

- Nuclear fission produces a handful of neutrinos (2.5 – 3) which can induce further induced fissions and so one
- Without control, exponential increase (A-Bomb)
- Rate of increase depends on fuel composition (fraction of fissile nuclei), speed of neutrons (moderation) and use of control rods
- 2 “types” of emitted neutrons:
  - “prompt” neutrons emitted directly in fission process
  - “delayed” neutrons produced in subsequent radioactive decay of fission products (0.2 – 55 s)



Energetic Balance of Fission

- A fission reactions releases around 200 MeV ($\Delta E \sim Q c^2$, A=235)
  - Mostly in kinetic energy of fragments
  - Detailed balance:



Energetic Balance of Fission		
1 Kinetic energy of fragments		
a/light	99,9	MeV
b/heavy	66,4	MeV
2 Kinetic Energy of neutrons	4,8	MeV
3 Energy of prompt γ's	7,5	MeV
4 Energy of β's (Fission Fragments)	7,8	MeV
5 Energy of γ's (Fission Fragments)	6,8	MeV
6 Energy of γ's (U capture)	10	MeV
TOTAL	203,2	MeV

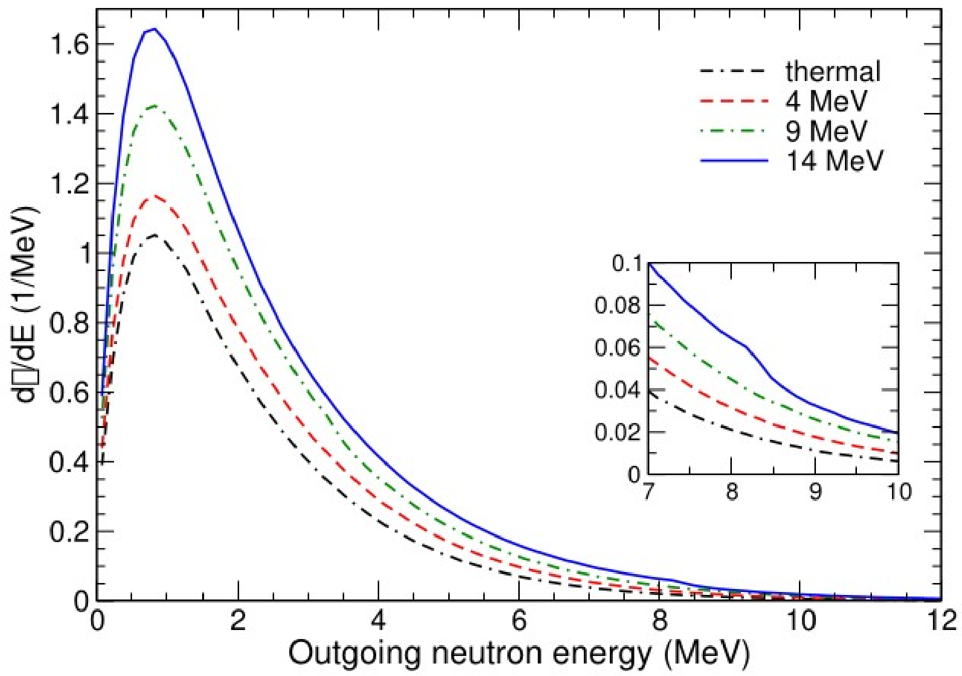
Neutron productions

- $\bar{\nu}$ denotes usually the average number of fission neutrons.
  - Depends on the neutron energy

$$\bar{\nu}(E)=\nu_0+\alpha E_{[MeV]}$$

	ν_0	α
^{233}**U**	2.482 ± 0.004	0.075 ± 0.010
^{235}**U**	2.432 ± 0.008	0.066 ± 0.016
^{239}**Pu**	2.874 ± 0.011	0.138 ± 0.005

- Fission neutrons have a energy spectrum centred on ~2 MeV
- Almost instantaneous (10^{-12} s)
- Additional neutrons, from fission products decay, are released later: "delayed" neutrons. They have to be taken into account in the final balance



Neutron multiplication factor and criticality

- Multiplication factor k can be computed by the so-called Six factor formula
- Evolution of number of neutrons depends on “mean generation time” (Λ)

$$k = \frac{\text{neutrons produced by fission}}{\text{neutron disappearance}} \qquad N(t) \propto N_0 \exp\left(\frac{((k-1)t)}{\Lambda}\right)$$

  - k < 1 (sub-criticality): The system cannot sustain a chain reaction, activity dies out over time.
  - k = 1 (criticality): Every fission causes an average of one more fission, leading to a constant fission rate (and power). Nuclear power plants operate with k = 1 unless the power level is being increased or decreased.
  - k > 1 (super-criticality): Exponential increase ⇒ Nuclear weapons
- Fuel composition is designed to be sub-critical for prompt-neutrons, and criticality is adjusted on delayed neutrons

Fate of a neutron

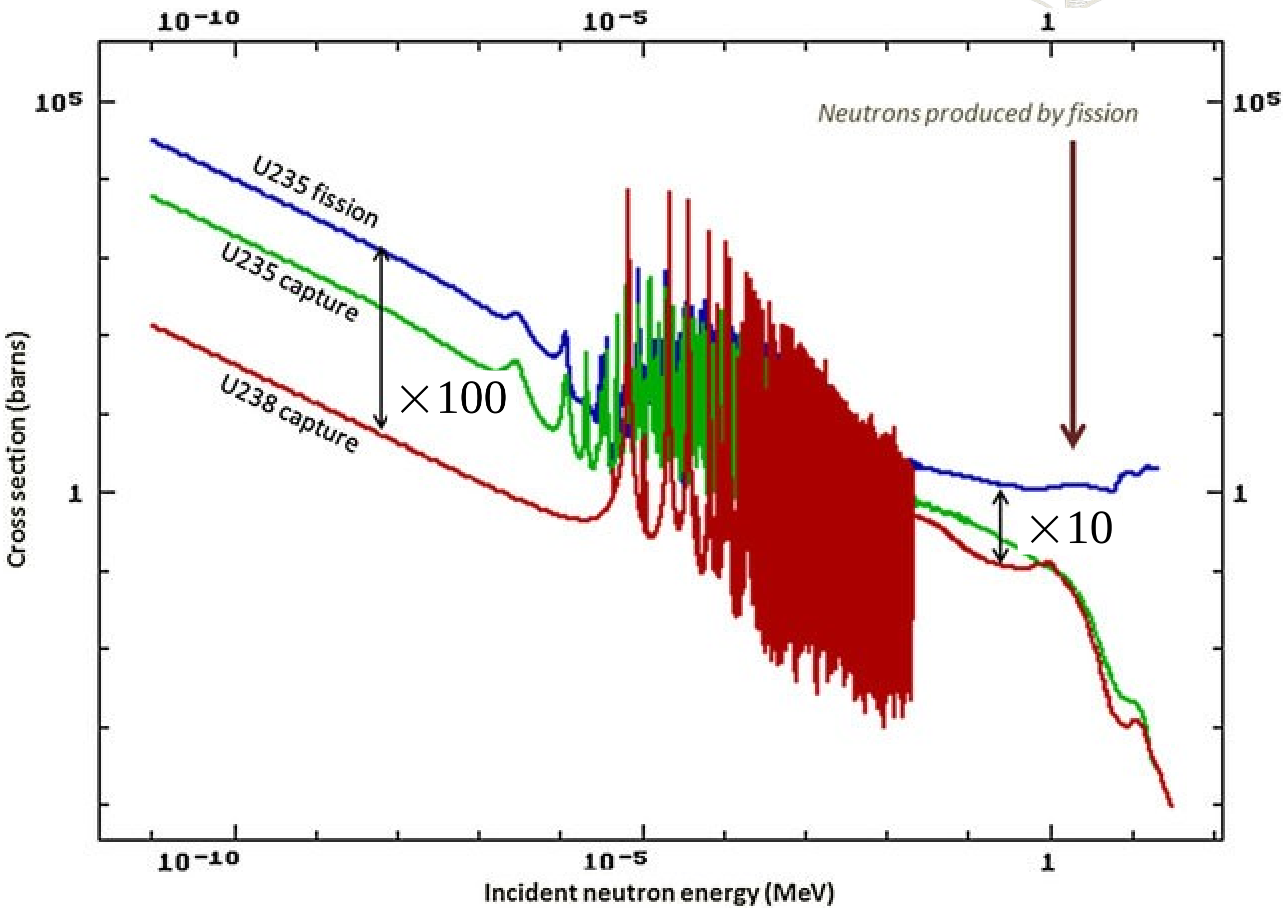
- Fraction of fissile Uranium:

$$\epsilon = \frac{^{235}U}{U_{\text{tot}}}$$

- In natural uranium, ε = 0.7%
- At ~1 MeV, the fission cross section is ~ 10 times larger that the capture one.
- A neutron will induce a fission with probability

$$P = \frac{\epsilon\,\sigma_{\text{fission}}}{\epsilon\,\sigma_{\text{fission}} + \sigma_{\text{capture}}} \approx 6.5\,\%$$

- This is **not enough** to sustain chain reactions

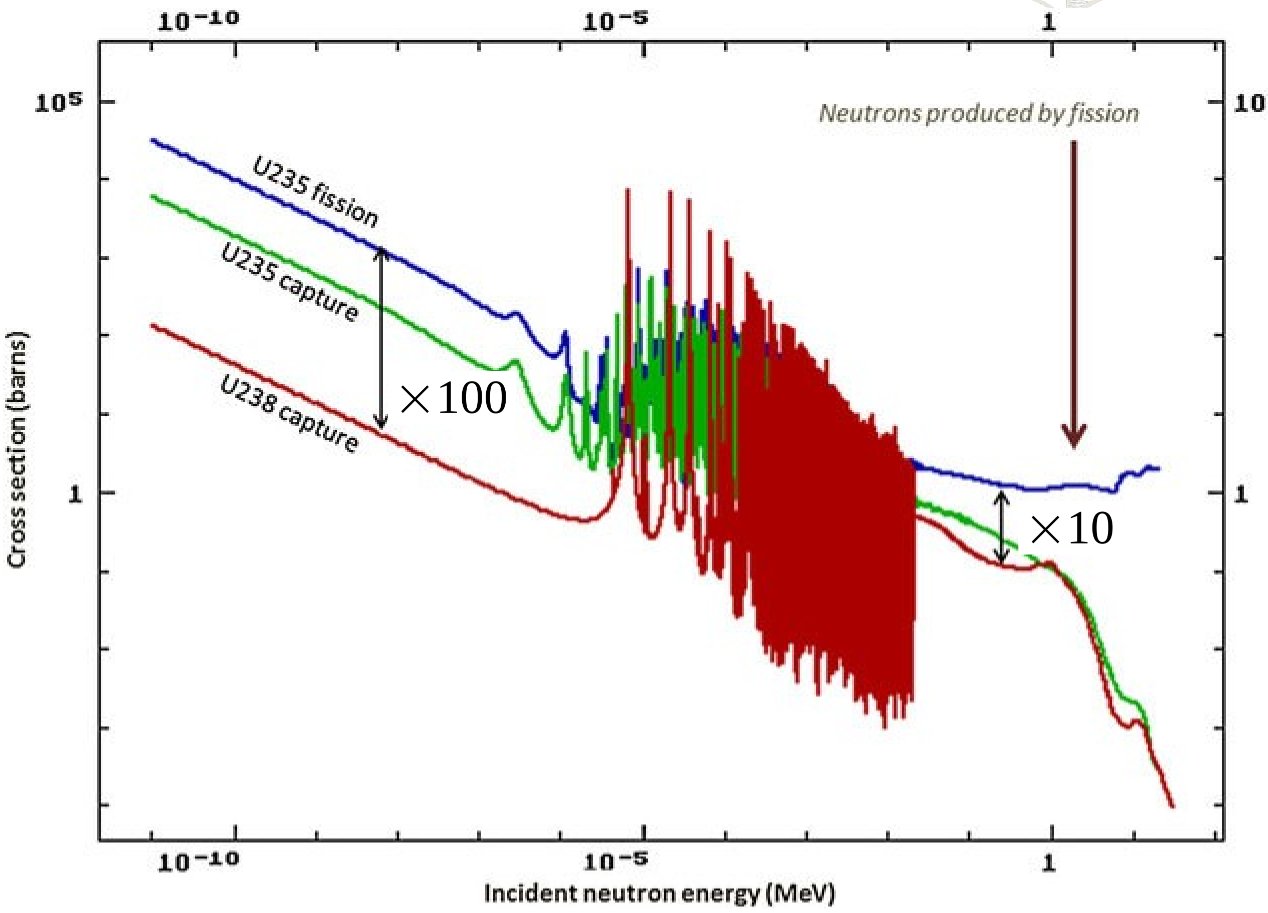


Sustainable chain reaction

- In natural Uranium chain reactions cannot be sustained
- Solutions:
  - Increase concentration of ^{235}U ⇒ Enriched Uranium
  - Increase $\sigma_{\text{fission}} / \sigma_{\text{capture}}$ ⇒ Lower the neutron energy (“moderation”)
- At ~ eV energies, with ε = 4.5%

$$P = \frac{\epsilon\,\sigma_{\text{fission}}}{\epsilon\,\sigma_{\text{fission}} + \sigma_{\text{capture}}} \approx 82\,\%$$

- Chain reactions can be sustained



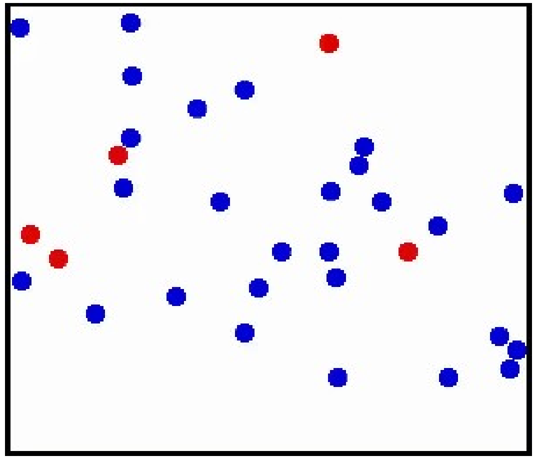
Moderator

- Medium that **reduces** the speed of fast neutrons, without **absorbing** them
- Physics: light element are more efficient in reducing speed (kinematics)

$$\xi = \ln \frac{E_0}{E} = 1 + \frac{(A-1)^2}{2A} \ln\left(\frac{A-1}{A+1}\right)$$

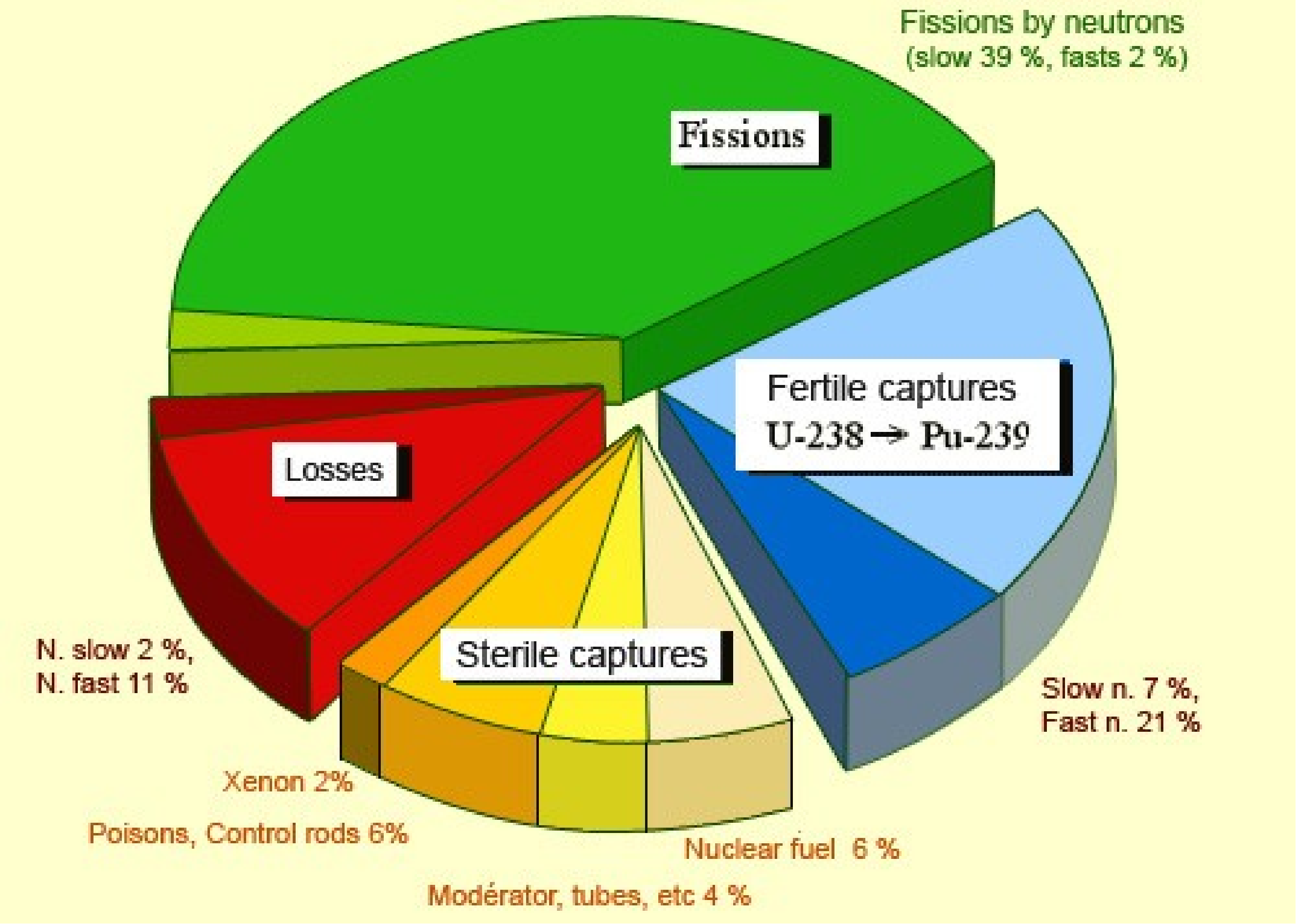
See PC

- Should be free of neutron-absorbing impurities such as Boron.
- Commonly used material:
  - Water: good moderation capability but neutron absorption by hydrogen (75% of reactors) ⇒ Enriched U
  - Heavy water: less absorption (5% of reactors) but expensive
  - Graphite: can work with natural Uranium (20% of reactors)



Neutron balance

- Neutron balance in a pressurized water reactor
- Creation by fissions (induced & spontaneous)
- Losses by:
  - Fertile capture
  - Sterile capture (reactor building elements)
  - Escape (leakage)



Reactivity Control

- Several tools used to control the criticality of a reactor
  - **Control rods** made of neutron poisons (boron, cadmium, silver, hafnium or indium)
    - when all rods in place, k ~ 0, the reactor stops
    - rods adjustment on measured neutron flux
    - based on delayed neutrons, reaction time O(s)
    - need real-time control by operators/devices
  - **Temperature of the coolant** as moderator
    - Increased temperature ⇒ less dense moderator ⇒ reduced moderation ⇒ higher energy neutrons ⇒ lower fission rate
  - **Temperature of the coolant** as neutron poison
    - Increased temperature ⇒ less dense moderator ⇒ less neutron absorption ⇒ higher fission rate
  - Emergency procedure ("**Scram**"): massive release of neutron poison (Boron)

Lecture 5 – Nuclear Energy

I. Basics of nuclear physics

II. Fission Power Plants

III. Fast Breeders – Generation IV

IV. Fusion Energy, current status, challenges and outlook

V. Conclusions

Classification of fission reactors – I

- Type of nuclear reaction:
  - Thermal neutrons: rely on **moderator** to increase the fission rate and enhance probability of fission with respect to neutron capture
    - Use of low-enriched or even natural Uranium
  - Fast neutron reactors, or “fast breeder”: use **fast** neutron to sustain the reaction
    - Need more enriched fuel
    - Can burn a larger fraction of nuclear fuel
    - Produce less long-activity waste
- Type of moderator
  - Graphite moderated reactors
  - Water moderated reactors (light or heavy)
  - Molten salt reactors
  - Liquid metal cooled reactors

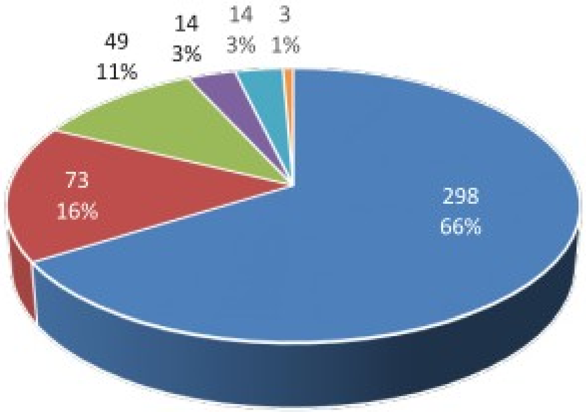
Classification of fission reactors – II

- Type of coolant:
    - Water cooled reactors (93% of current reactors)
    - Molten salt reactors
    - Liquid metal cooled reactors
    - Gas cooled reactors
    - Organic nuclear reactors
- Phase of fuel:
    - Solid fuelled (most common)
    - Fluid fuelled (Aqueous homogeneous reactor, Molten salt reactor)
    - Gas fuelled (proposed)
- Shape, end used, ...

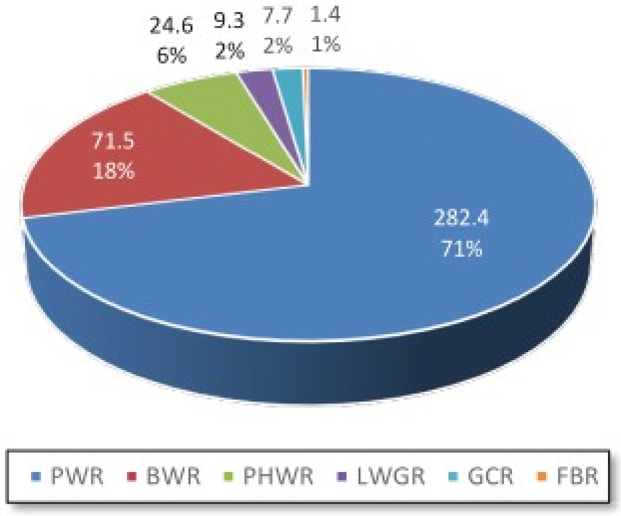
Most common designs (thermal neutrons)

- Pressurized water reactors (**PWR**)
- Boiling water reactors (**BWR**)
- Pressurized Heavy Water Reactor (**PHWR**)
- Light Water Graphite Reactor (**RBMK** - **LWGR**)
- Gas-cooled reactor (**GCR**) and advanced gas-cooled reactor (**AGR**)
- Pebble-bed reactors (**PBR**)
- Aqueous homogeneous reactor (**AHR**)

Number of reactors

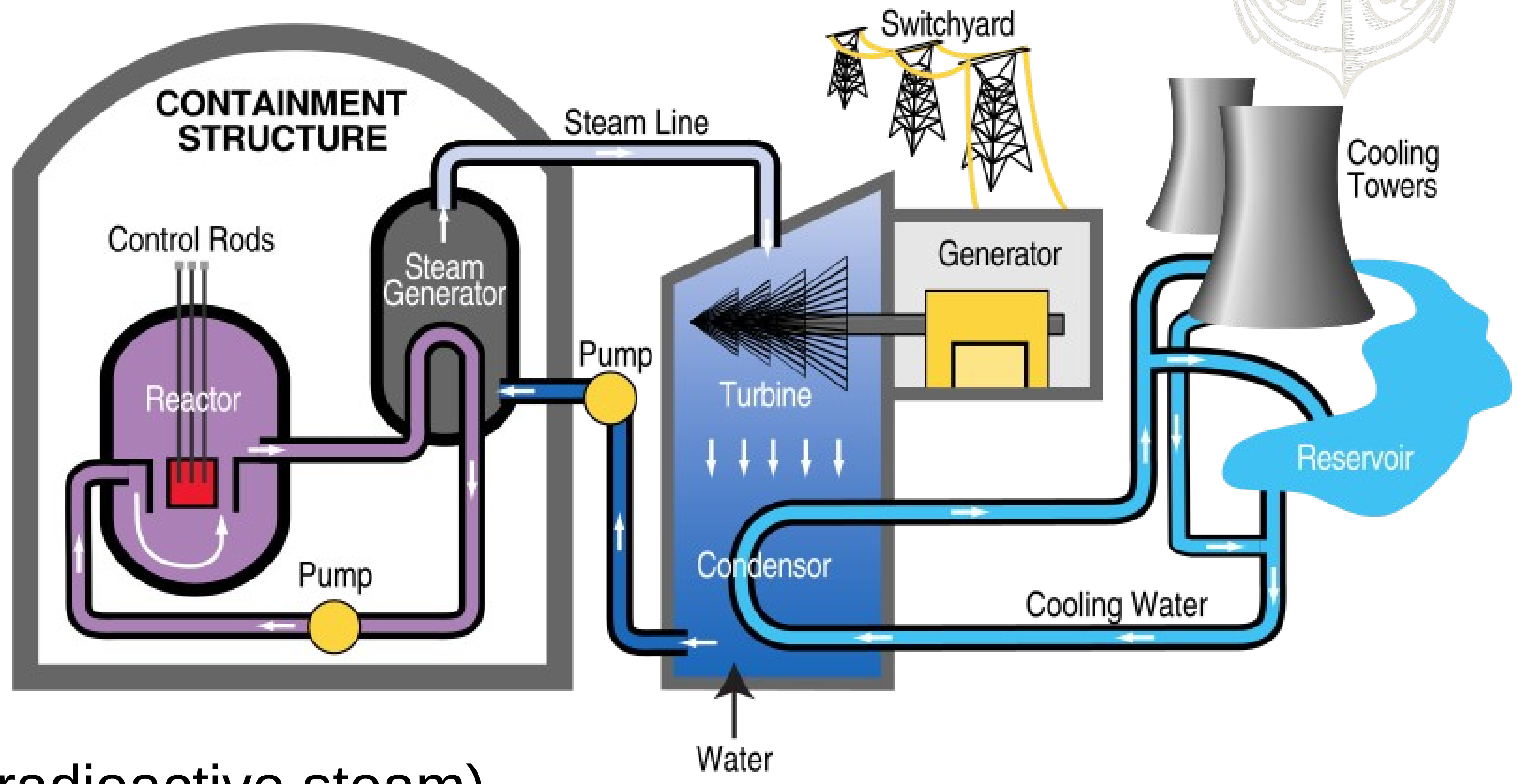


Electrical Power (GW)



Overall design of water-based reactors

- Nuclear reactor used to produce steam
    - Either directly in the reactor (**BWR**)
    - Or using a secondary circuit (**PWR**)
- Steam used in turbines to generate power
- Cooling system to condensate the water (no release of possibly radioactive steam)

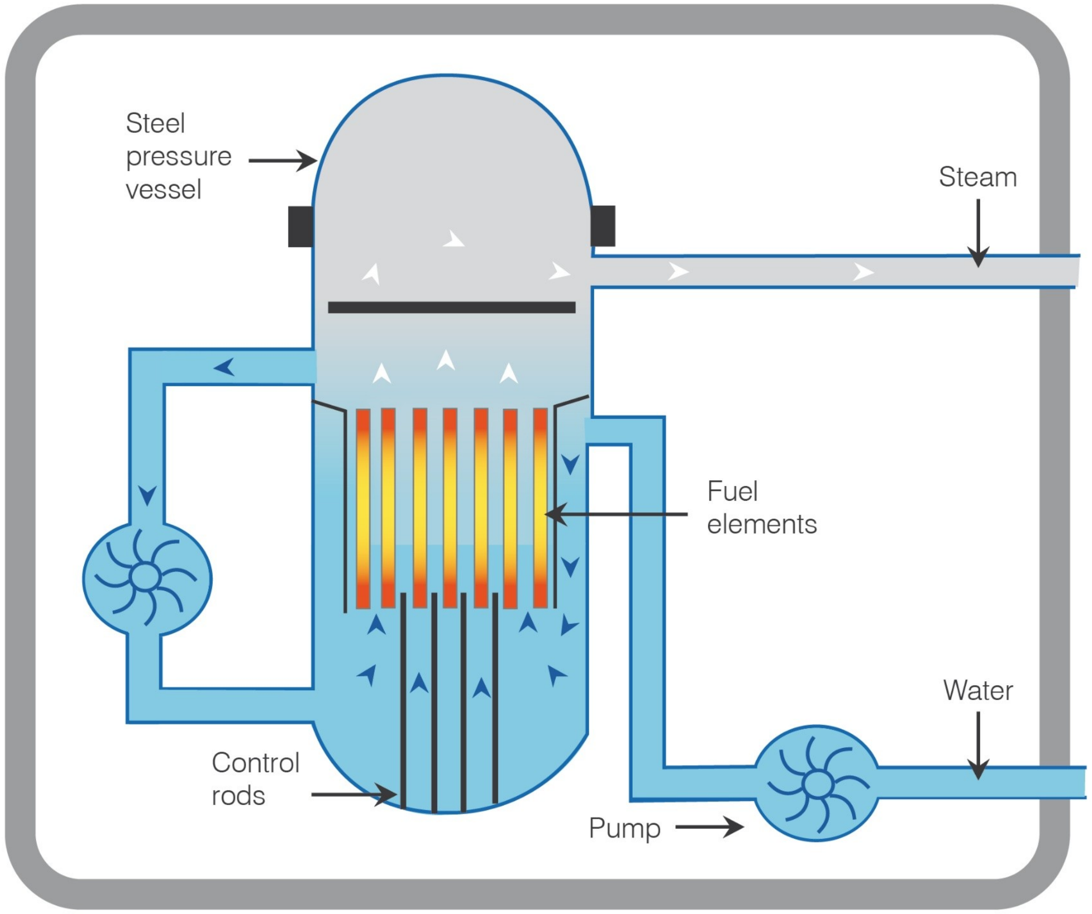


Boiling water reactors – BWR

- Simplest design, modest size
- Use water as **moderator** & **coolant**
- Steam directly produced in reactor by evaporation
- Water returned to reactor core after condensation
- Operating point: 285°C, 75 bars
- Control:
  - Control rods (inserted from below – in liquid phase)
  - Water flow in the reactor

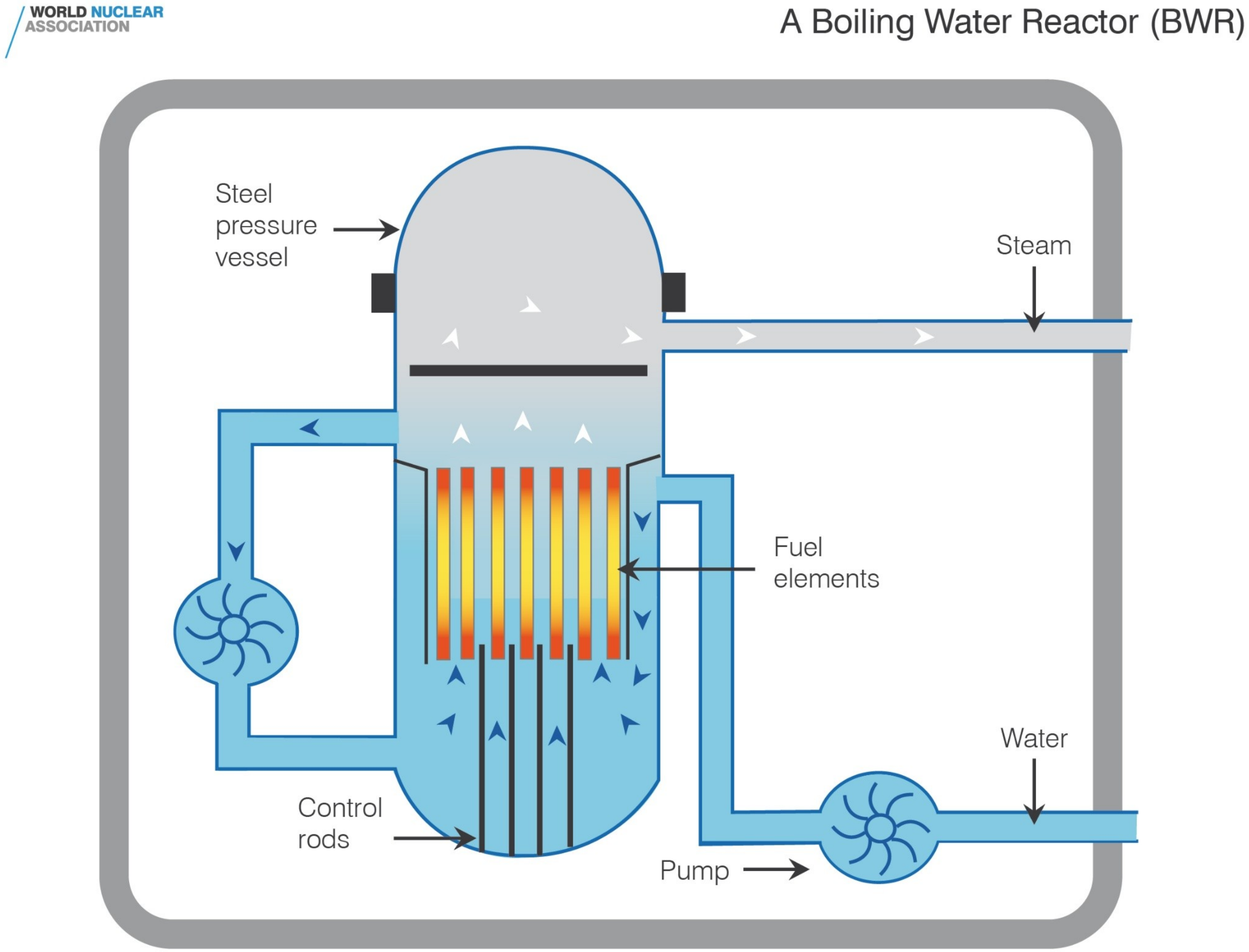
WORLD NUCLEAR ASSOCIATION

A Boiling Water Reactor (BWR)



Boiling water reactors – BWR

- Relatively low yield (due to temperature)
- Contamination of the turbine by short-lived activation products (mostly ${}^{16}\text{O} \Rightarrow {}^{16}\text{N}$)



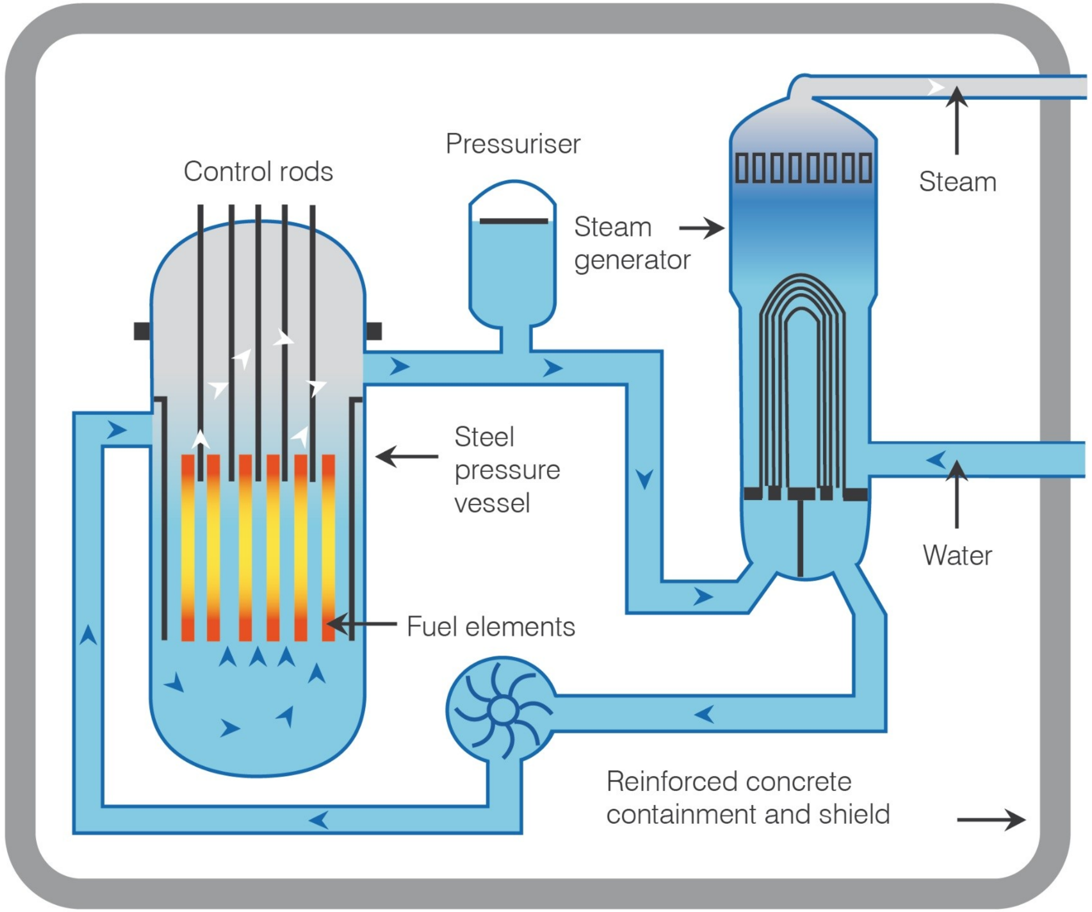
Pressurized Water Reactors – PWR

- Use water as **moderator** & **coolant**
- High pressure (155 bars) to avoid water boiling (steel pressure vessel)
- Maximum theoretical temperature 374°C (critical point), usually around 345°C
- Passive safety through water dilatation in response to increased temperature (less moderation, decreased fission rate) ”negative temperature coefficient of reactivity”

⇒ **very stable, self regulating**

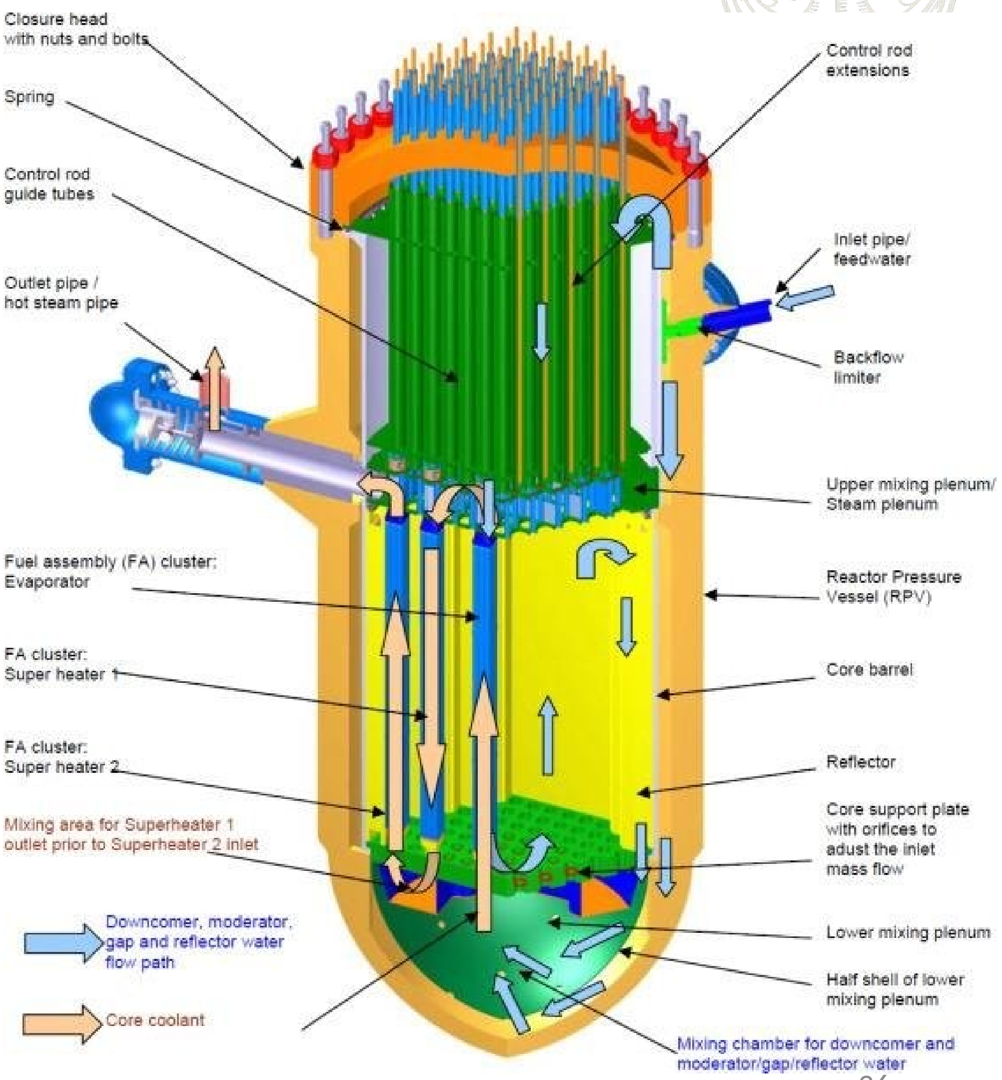
WORLD NUCLEAR ASSOCIATION

A Pressurized Water Reactor (PWR)



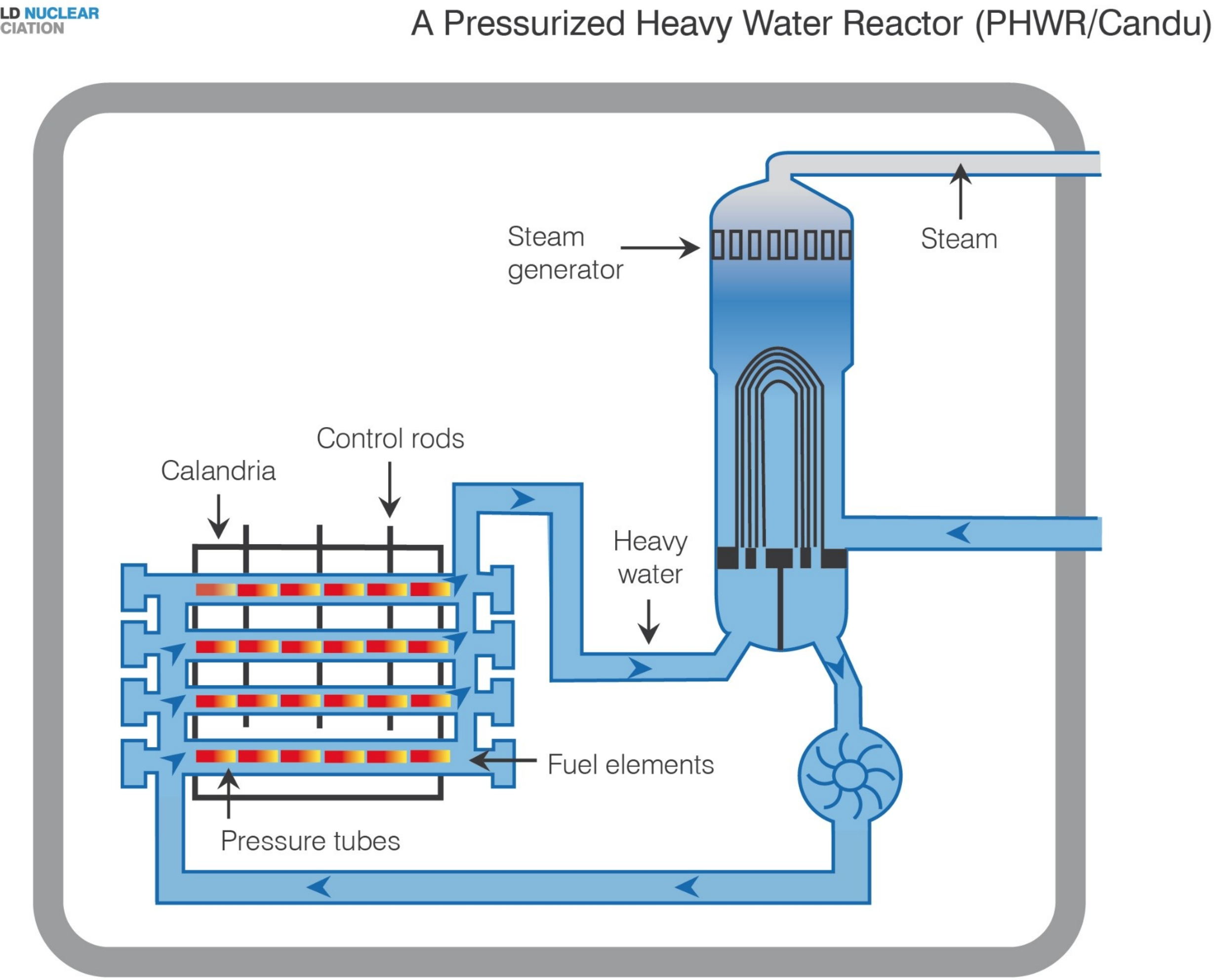
Pressurized Water Reactors – PWR

- Steam generation in a **secondary** circuit, not in contact with radioactive material
- Large containment, enclosing reactor, steam generator & pressurizer
- Boron & Cadmium control rods used maintain system temperature, can passively **scram** the reactor in case of power loss (rod fall by gravity)
- Refuelling on ~ 18-24 month cycle (1/3 of core)
- Require enriched Uranium
- **Increased** yield w.r.t. BWR



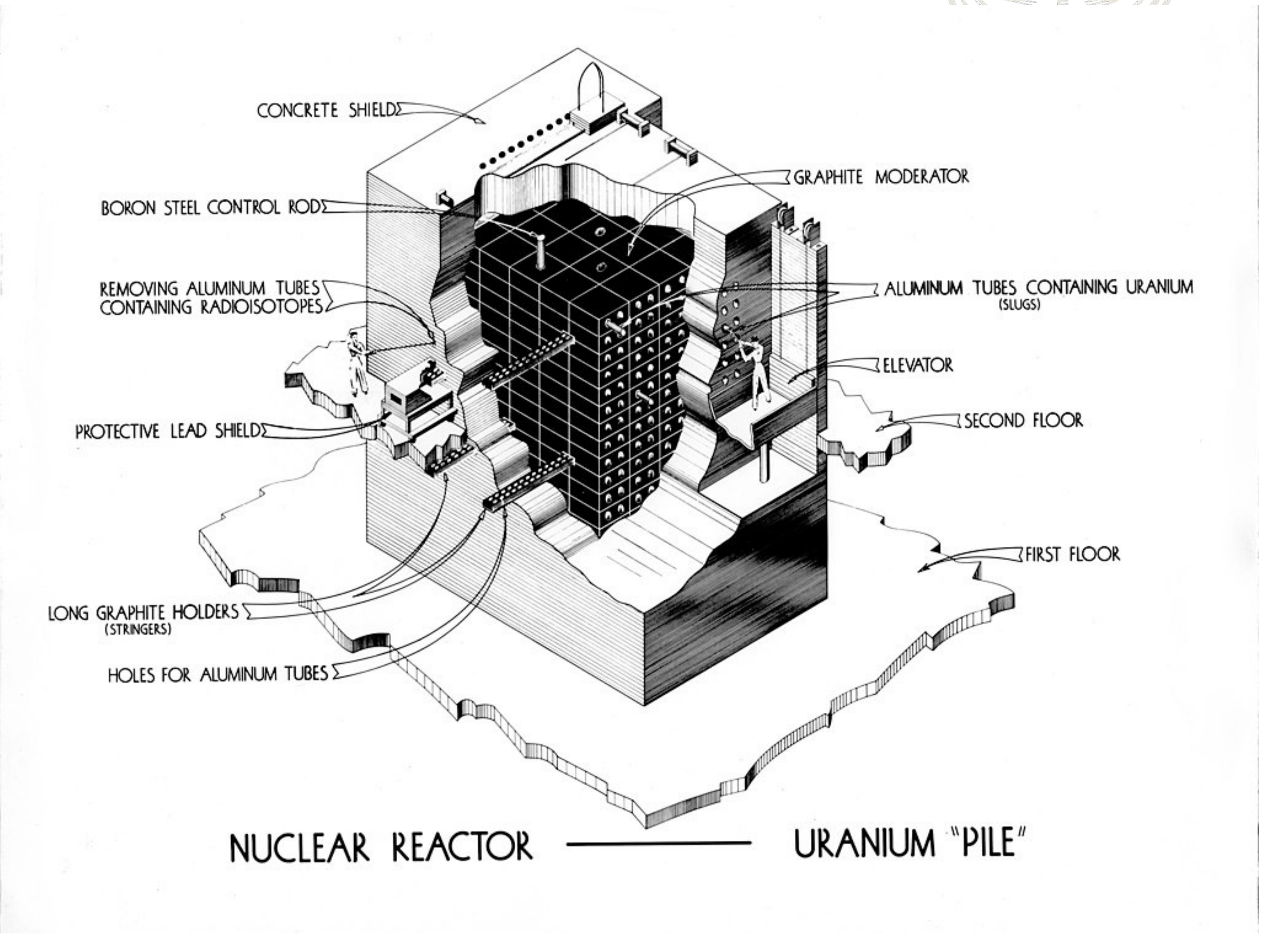
Pressurized **Heavy Water** Reactors

- Uses **D_2O** as **coolant** and **moderator**
- Much less neutron absorption
  ⇒ can use natural U (or very low enriched U) as fuel
- Cost of heavy water O(100$)/kg compensated by lower cost of fuel
- But more frequent refuelling (reduced energy content of natural U)
- Larger production of ^{239}Pu from absorption on ^{238}U ⇒ fissile material suitable for nuclear bombs
- Operating at ~ 300°C
- Rather compact design (less heat)



Graphite-moderated reactor

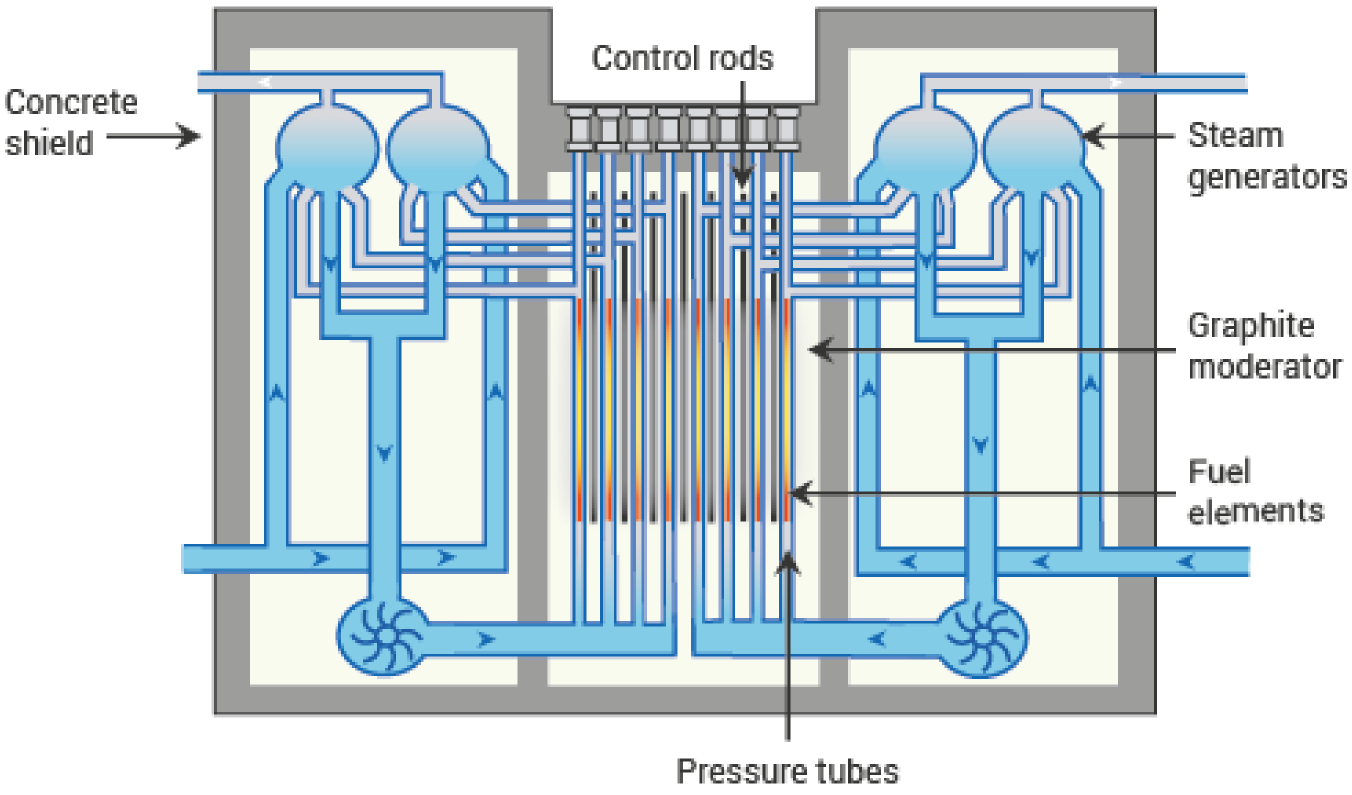
- Use of solid graphite as moderator ⇒ can use natural U (or very low enriched U) as fuel
- Compact design of core (solid)
- First artificial nuclear reactor (Chicago Pile-1, 1942)
- Can use either **gas** (carbon dioxide or helium) or **water** as coolant



Light Water Graphite-moderated Reactor

- Use of solid graphite as moderator ⇒ can use natural U (or very low enriched U) as fuel
- Water coolant
- Mostly used in Russia – RBMK (Russian: реактор большой мощности канальный, РБМК; reaktor bolshoy moshchnosti kanalnyy, "high-power channel-type reactor")

A Light Water Graphite-moderated Reactor (LWGR/RBMK)

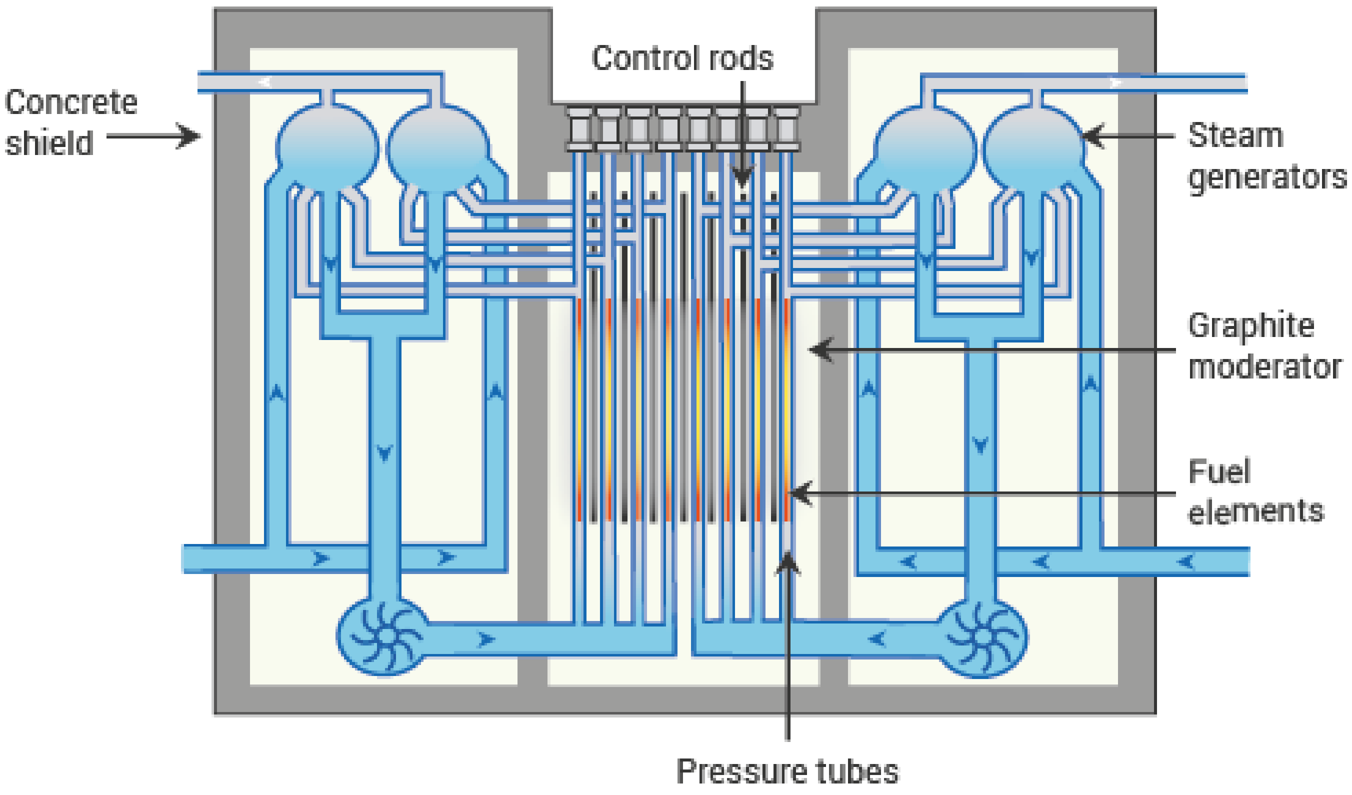


Light Water Graphite-moderated Reactor

- Main problem: “Positive void coefficient”:
  - Excess steam generation reduces the cooling of the reactor and neutron absorption by water
  - But unchanged moderation capabilities

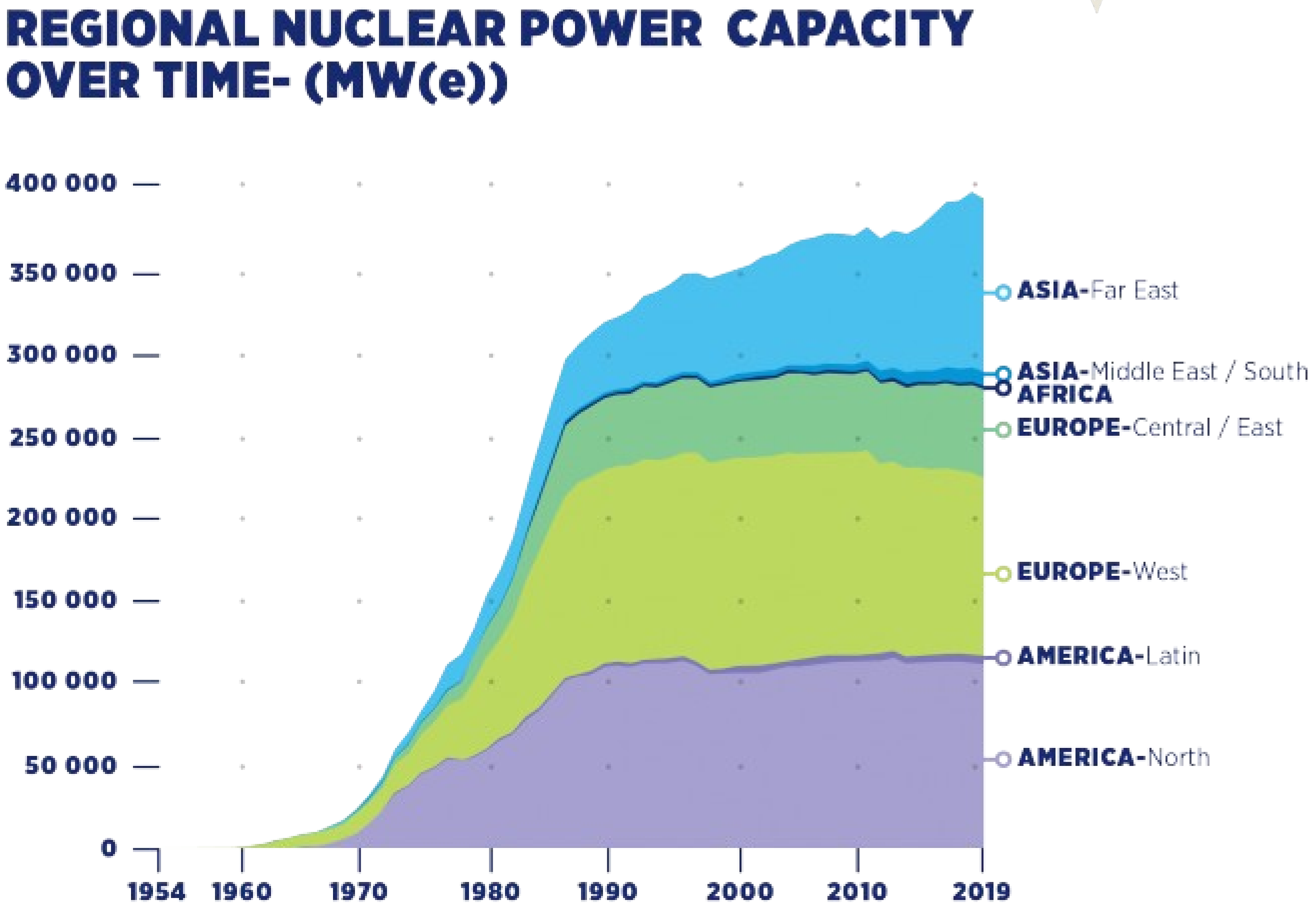
    ⇒ increased reaction rate
- **Instability** at low power level
- Chernobyl disaster (1986)

A Light Water Graphite-moderated Reactor (LWGR/RBMK)



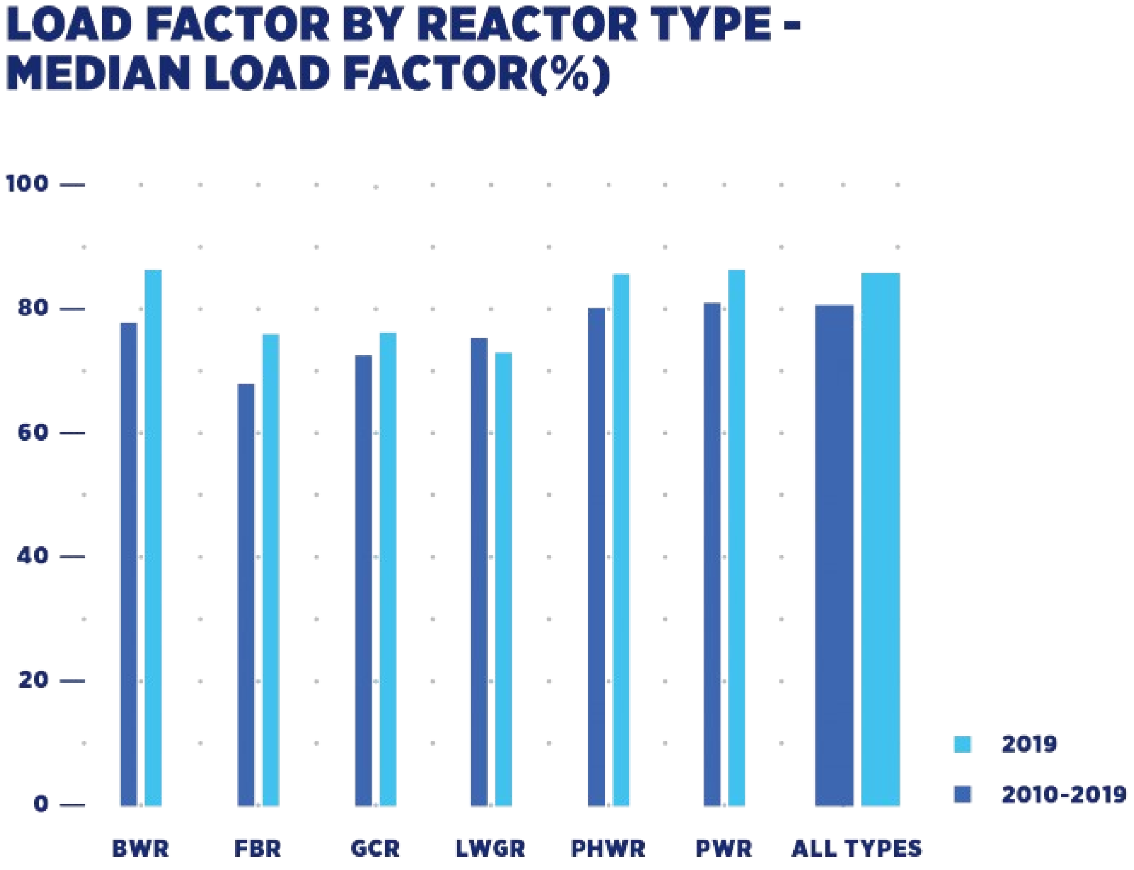
Nuclear Energy Figures

- Nuclear energy mostly developed in the 1970’s to 1990’s in developed countries
- Accidents (Three Miles Island & Tchernobyl) stopped this evolution
- Asia (China) currently taking over


REGIONAL NUCLEAR POWER CAPACITY OVER TIME- (MW(e))

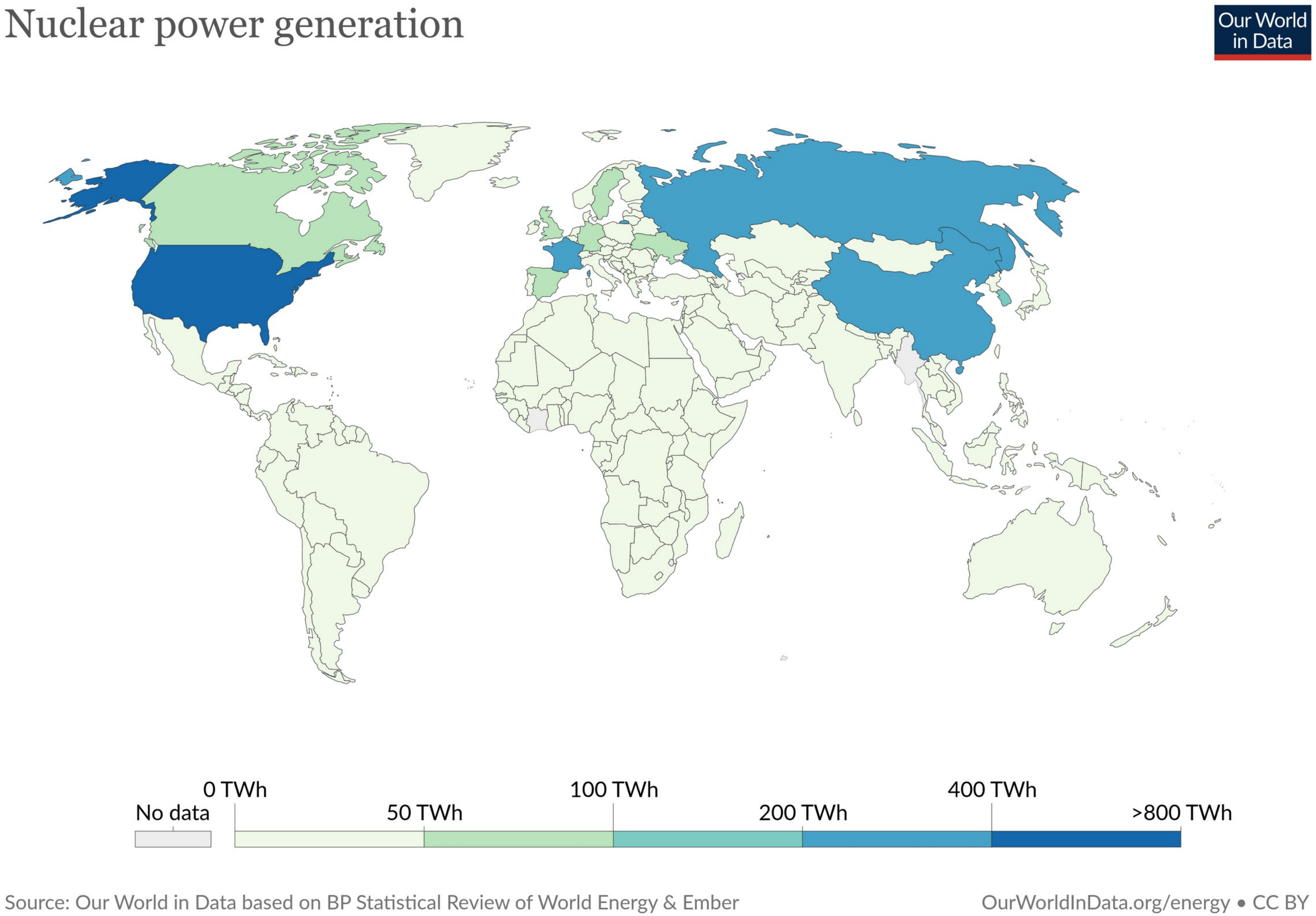
Load factor

- Nuclear reactors have high load factor ~ 80%



Nuclear energy generation

- Few countries have currently access to nuclear electricity

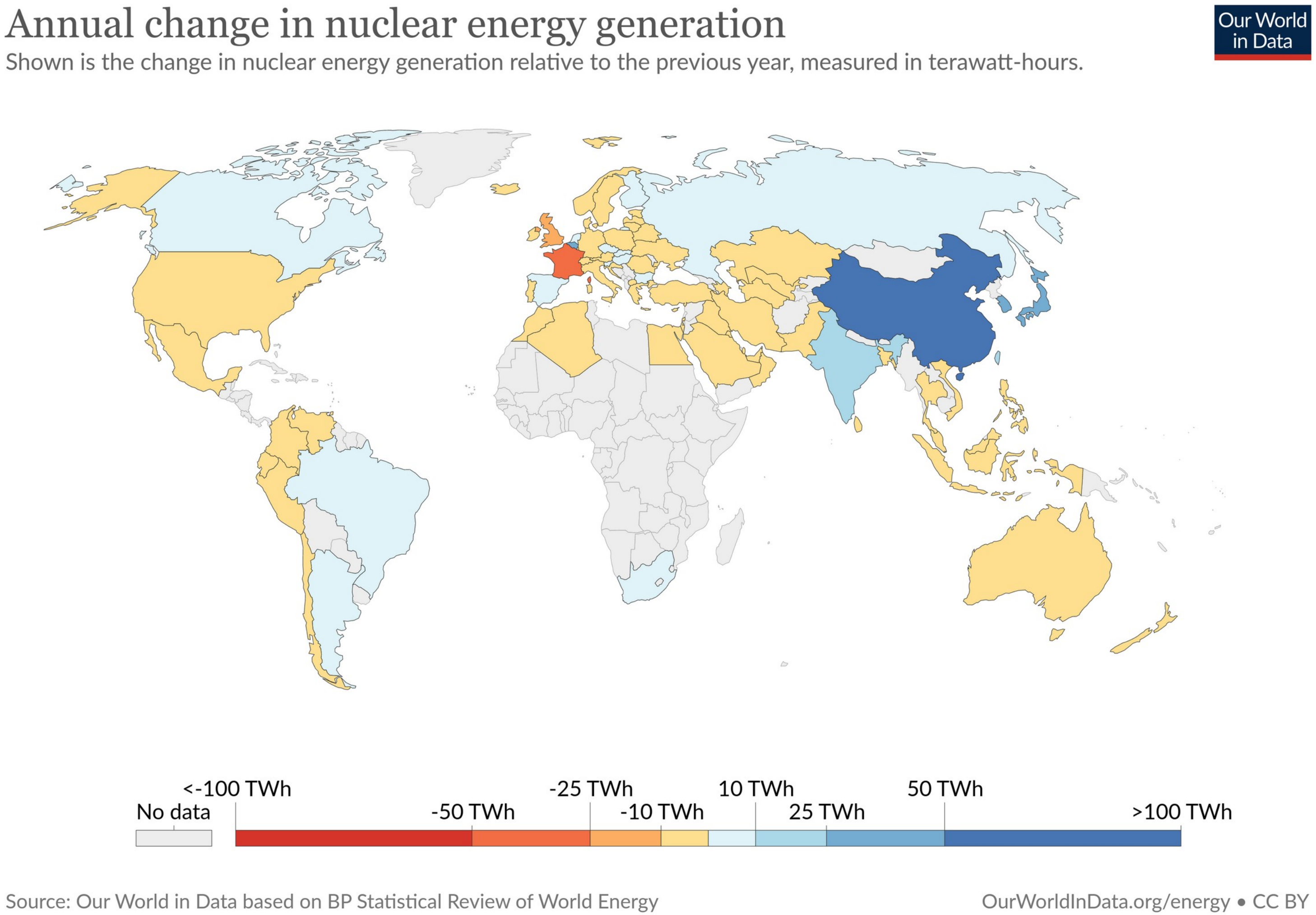

Nuclear power generation

Source: Our World in Data based on BP Statistical Review of World Energy & Ember

OurWorldInData.org/energy • CC BY

Evolution

- China investing on nuclear reactors



Annual change in nuclear energy generation

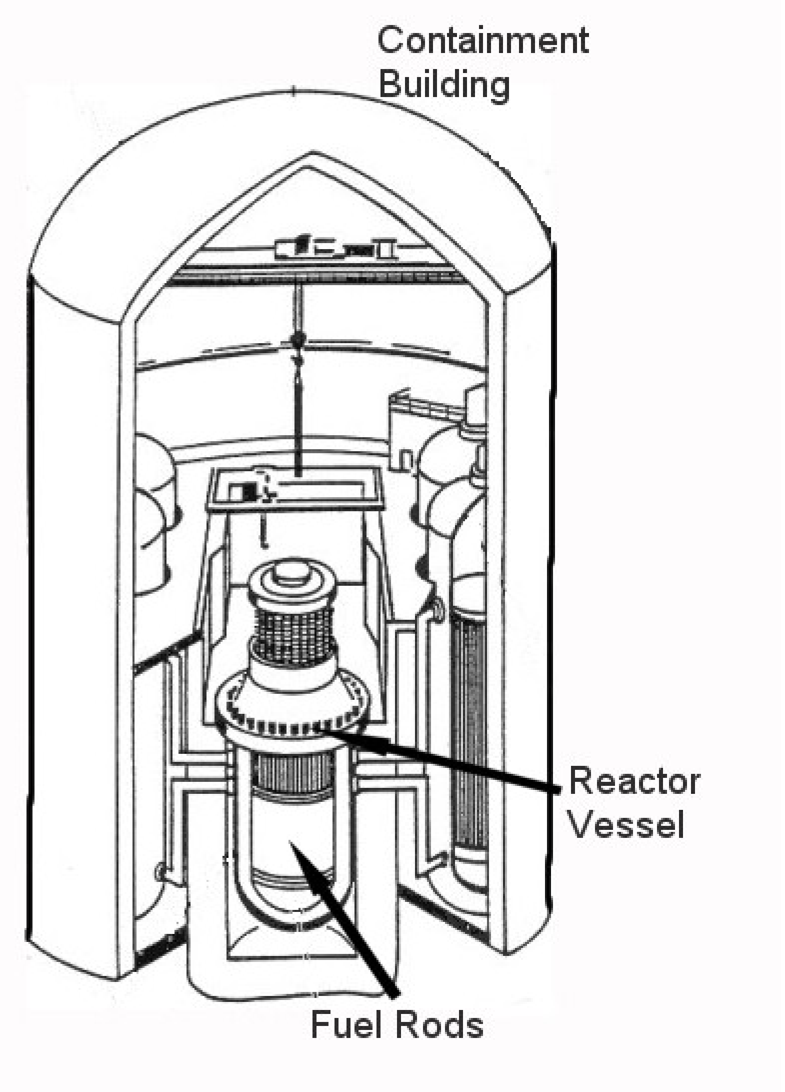
Shown is the change in nuclear energy generation relative to the previous year, measured in terawatt-hours.

Source: Our World in Data based on BP Statistical Review of World Energy

OurWorldInData.org/energy • CC BY

Safety elements

- **Passive** security
  - Containment building (contain escape of radioactive steam or gas)
  - Core catching (in case of fuel melt-down)
- **Active** security
  - Control rods
  - High pressure coolant injection system
  - Automatic de-pressurization system
  - Isolation cooling system
  - Emergency electrical systems (Diesel generators, flywheels, batteries)
  - Emergency service water system
  - ...

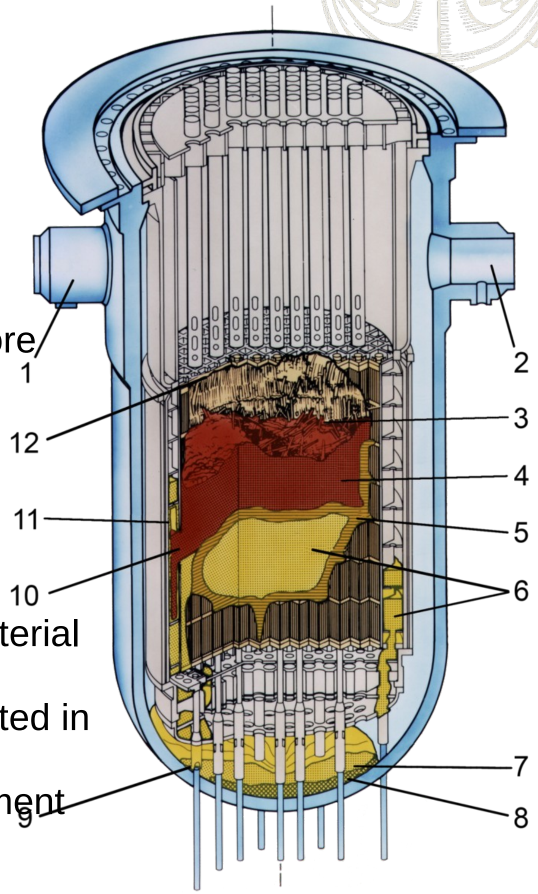


Accidents – Three Miles Island – 1979

- Most significant accident in U.S. commercial nuclear power plant history
- Partial meltdown of Unit 2 reactor (PWR) caused by a failure in secondary system
  - Blockage in a resin filters in secondary loop (designed to stop mineral)
  - Usual method of forcing the stuck resin out with compressed air did not succeed
  - Water founds its way into an instrument air line ⇒ stop of feed-water pumps ⇒ turbine trip (4:00 am) ⇒ stop of heat transfer
  - Temperature & pressure increase in reactor ⇒ emergency shut-down initiated
  - In 8 seconds, control rods were inserted but temperature continued to increase due to decay heat (radioactive decay of fission products)
  - Auxiliary feed pumps were off for maintenance
  - Pilot-operated relief valve at the top of the pressurizer triggered to release excess pressure. Remained stuck-open @ 4:11 am (design flaw) ⇒ coolant escape (de-pressurization) ⇒ partial core meltdown @ 6:00 am

Accidents – Three Miles Island – 1979

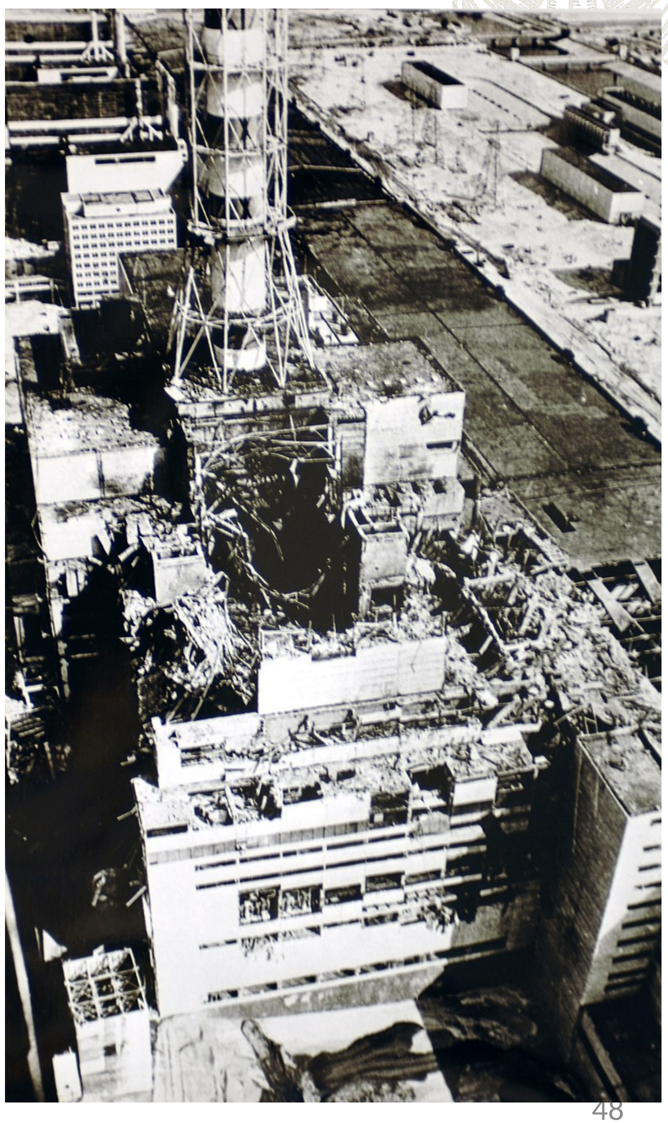
- Mixture of mechanical failures and human errors (did not recognize the situation as a loss-of-coolant accident)
- Ambiguous control room indicators
- Crystallized anti-nuclear safety concerns among activists and the general public
- Resulted in new regulations for the nuclear industry
- Partial meltdown resulted in the release of radioactive gases and radioactive iodine into the environment
- No significant increase of rate of cancer
- Cleanup 1979 ⇒ 1993



NRC graphic of TMI-2 core end-state configuration.
1 - 2B inlet
2 - 1A inlet
3 - cavity
4 - loose core debris
5 - crust
6 - previously molten material
7 - lower plenum debris
8 - possible region depleted in uranium
9 - ablated incore instrument guide
10 - hole in baffle plate
11 - coating of previously-molten material on bypass region interior surfaces
12 - upper grid damage

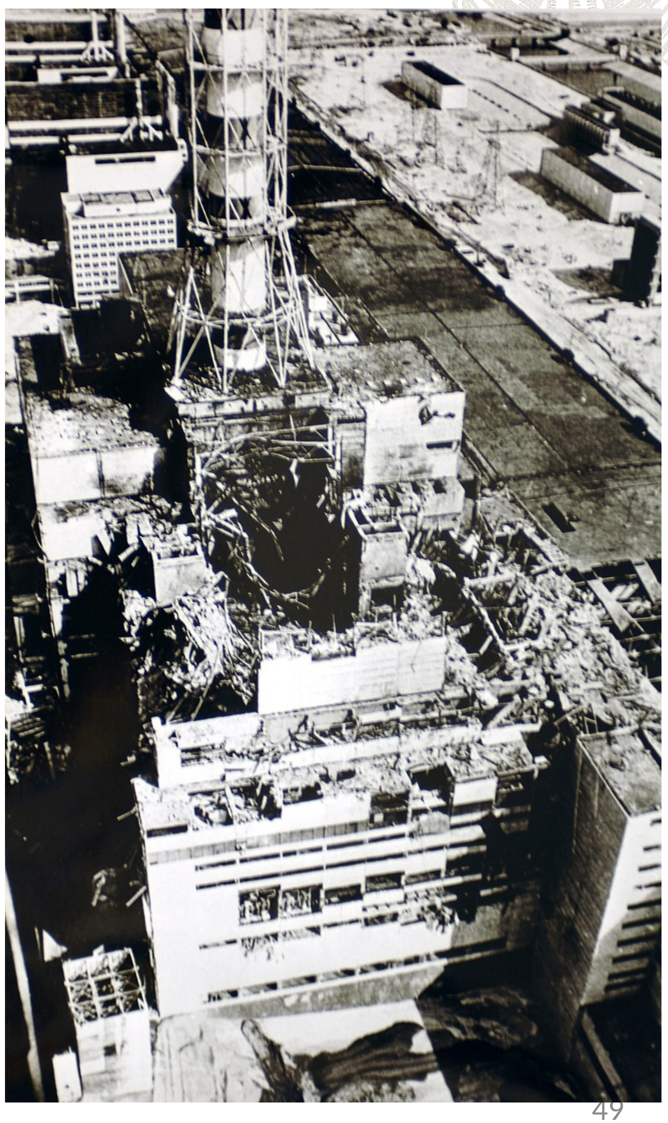
Accidents – Tchernobyl – 1986

- One of the two nuclear energy accidents rated at **seven**
- Occurred during a safety test on the steam turbine of RMBK nuclear reactor:
  - In case of station blackout, power needed to pump water into the core could be provided by inertia of the steam turbine (until diesel generator take over)
- Test preparation
  - Deactivation of emergency core cooling system
  - Gradual decrease of reactor power to ~ 700 MW
  - 4 pumps on grid, 4 pumps on turbine
- Test procedure
  - Steam supply to turbine closed off, reactor shut down
  - 4 pumps on turbine inertia (free-wheeling down)
  - Start of diesel engine



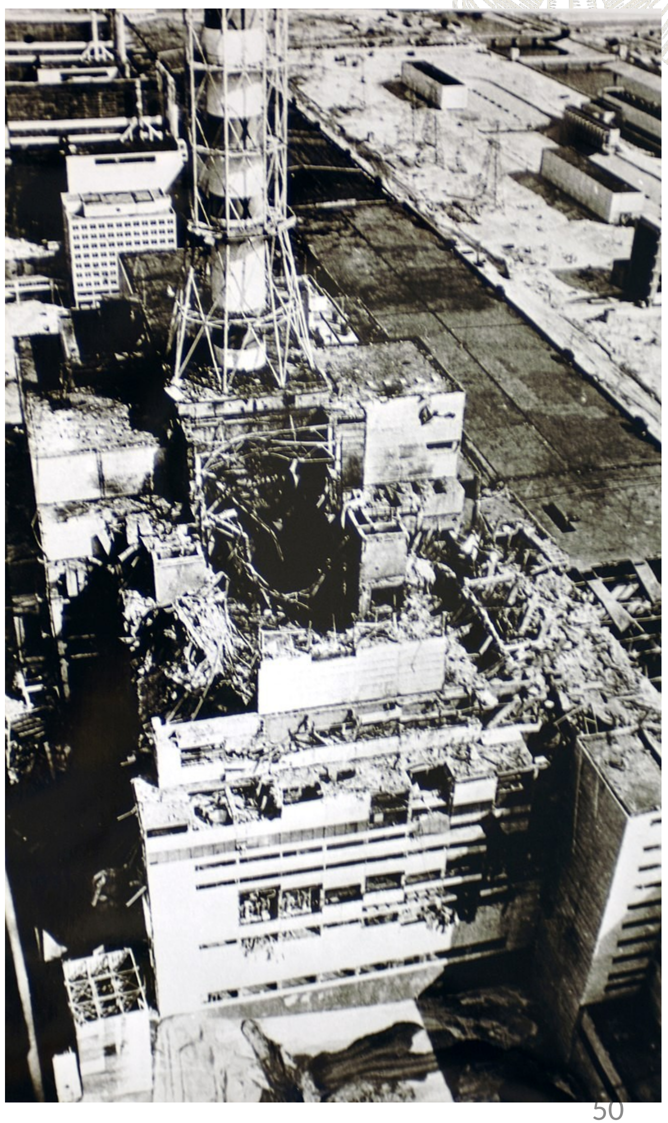
Accidents – Tchernobyl – 1986

- Accident chronology – Test preparation
  - Emergency core cooling system disabled
  - Gradual decrease of reactor power to ~ 700 MW
  - Power continued dropping to ~ 500 MW due to neutron absorption by ^{135}Xe (fission product), burned off quickly in normal operation conditions ($^{135}\text{Xe} + n \rightarrow {}^{136}\text{Xe}$)
  - Power unexpectedly dropped to ~ 30 MW (human error?)
  - Personnel removed numerous control rods to restore the power (poisoning by ^{135}Xe hindered the rise of reactor power) ⇒ Power restored to ~ 200 MW after 20 minutes, but unstable core temperatures



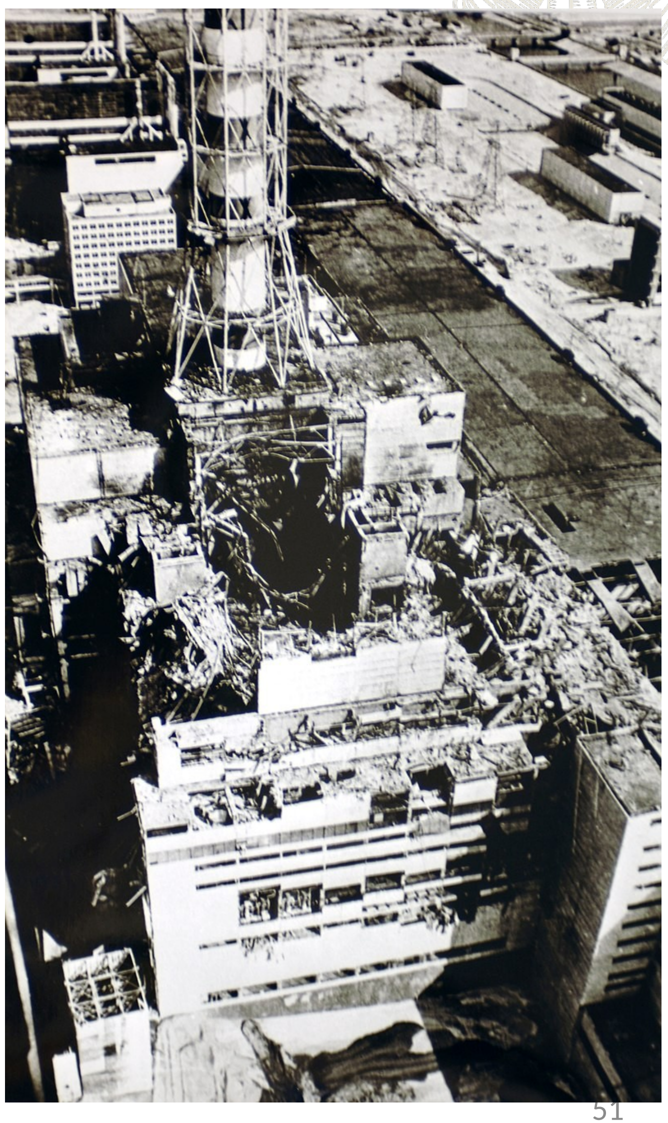
Accidents – Tchernobyl – 1986

- Accident chronology – Test preparation
  - Two additional circulating pumps activated ⇒ lower core temperature ⇒ more liquid water in core ⇒ more neutron absorption ⇒ decreased fission activity
  - Operators responded by removing more manual control rods to maintain power (~ half of the rods removed)
  - Excessive high coolant flow rate entering the reactor close to boiling point



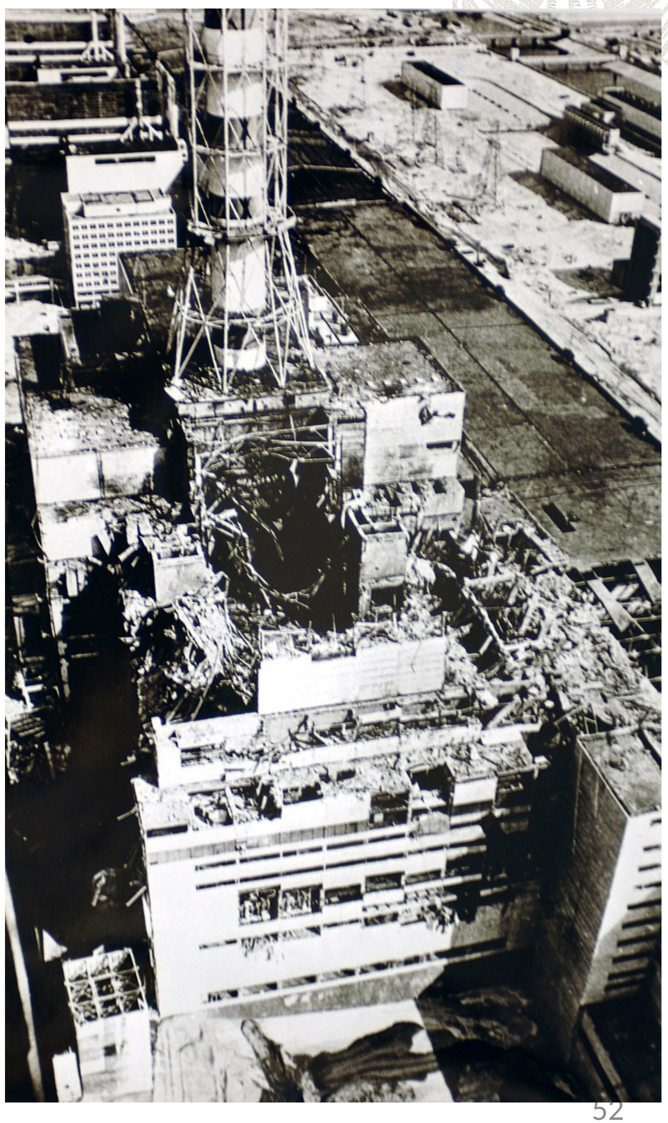
Accidents – Tchernobyl – 1986

- Accident chronology – Test
    - **01:23:04**: start of test. Steam to turbines was shut down. Diesels generators started. Decreasing momentum of turbine ⇒ decreased water flow rate ⇒ formation of steam voids ⇒ less neutron capture ⇒ increased activity
    - **01:23:40**: Emergency shut-down initiated (“Scram”) ⇒ Insertion of control rods (0.4 m/s). Control rods had graphite moderator at their end to boost reactor output when displacing water (“positive scram”) ⇒ Unexpected increase of reactor activity
    - A few seconds after, power spike occurred, causing fuel rods to fracture (overheating). In 3 second power rose to 530 MW



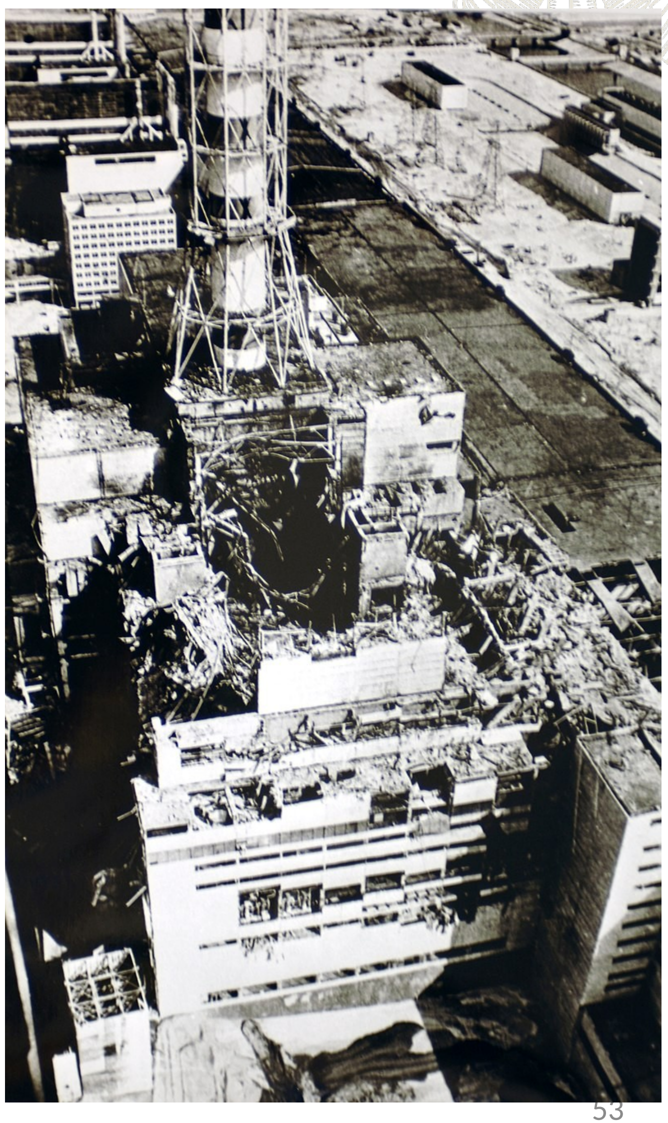
Accidents – Tchernobyl – 1986

- Accident chronology – Test
    - Power increase ⇒ rapid increase of steam pressure, less water ⇒ less neutron capture ⇒ further power increase
    - Reactor output increased to 30 000 MW!
    - Steam explosion, destruction of reactor and building, rupture of most of the coolant lines
    - Coolant flashed to steam and escaped the reactor
    - Further increase of reactor power (no coolant)
    - Second major explosion 2-3 seconds after dispersed the damaged core and ejected hot lumps of graphite ⇒ spread of radioactive fallout and contamination, graphite fire
    - Radiation level ~ 200 Gray/hr (lethal dose ~ 5 G.yr)
    - Evacuation of Pripyat decided 36 hours after initial blast



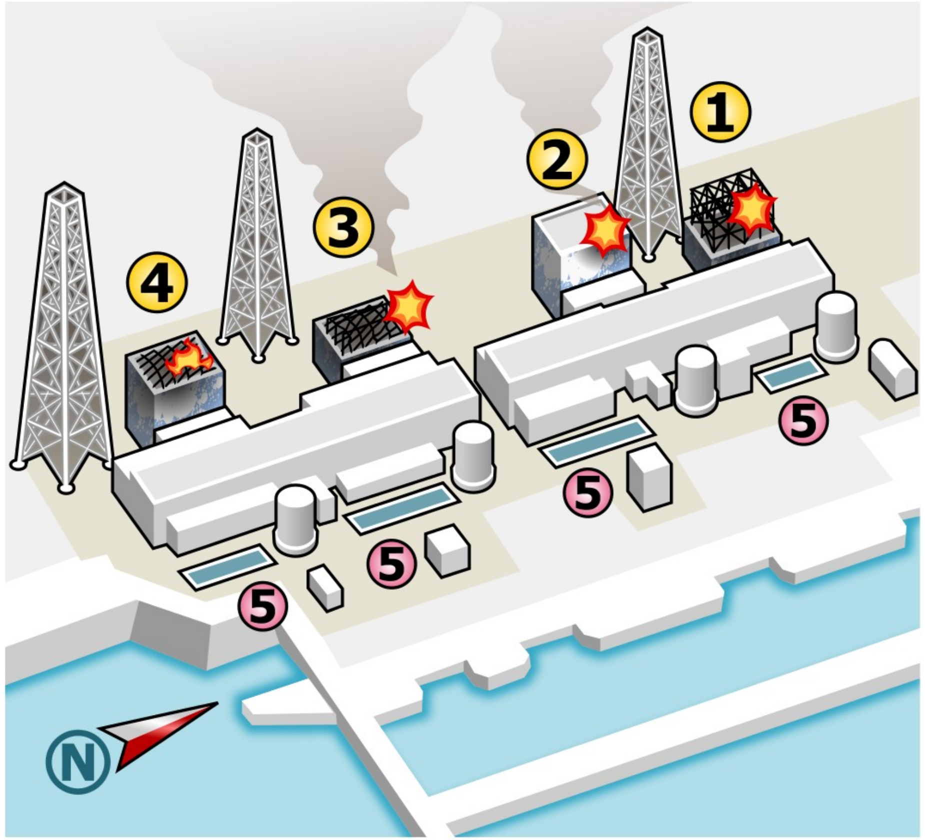
Accidents – Tchernobyl – 1986

- Accident – Human toll
  - ~350 000 resettled persons from severely contaminated areas (~30 km around power plant)
  - 600,000 people recognised as liquidators (credited with limiting both the immediate and long-term damage from the disaster)
    - ~60 000 dead in 2006, 160 000 disabled
    - death tool caused by accident quite uncertain (50 death directly attributed to radiation, ~ 4000 estimated by World Health Organisation in 2005)



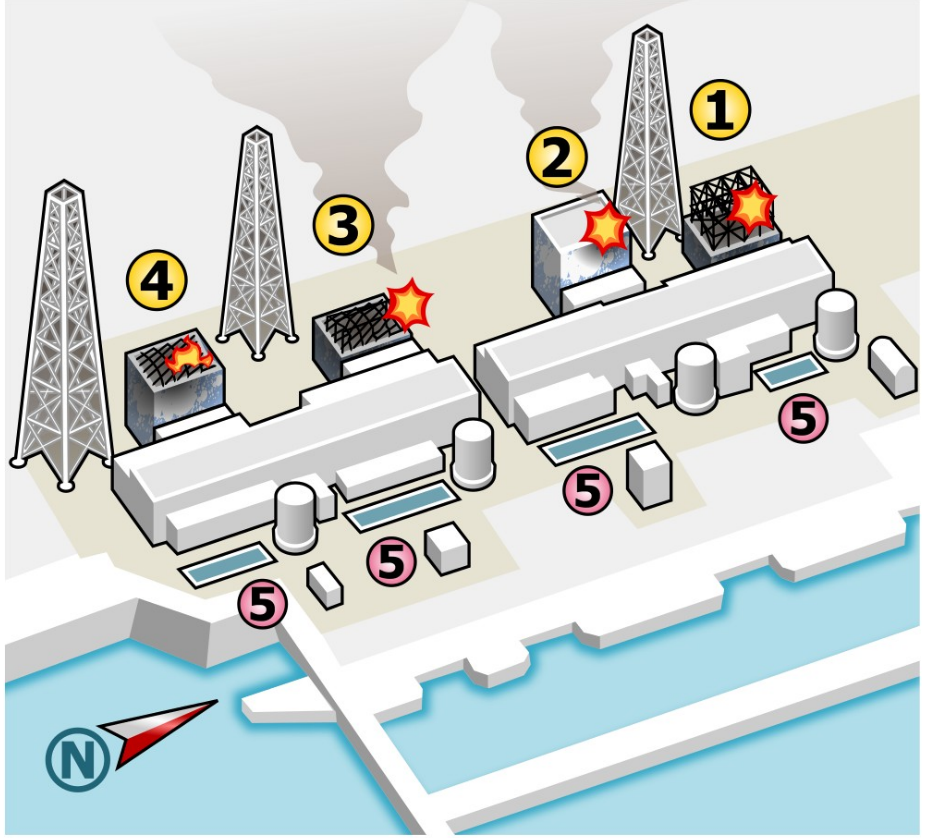
Accidents – Fukushima – 2011

- Triggered by the Tōhoku earthquake and tsunami on Friday, 11th March 2011
- Reactors initiated immediate shut-down
- Electricity supply failed
- Emergency diesel generators started to sustain the cooling of stopped reactors (decay heat)
- 14m high Tsunami swept over the plant’s seawall and flooded the lower parts of the reactors
- Failure of emergency generators ⇒ power loss ⇒ stop of coolant circulation ⇒ increasing core temperature ⇒ three nuclear meltdowns, followed by hydrogen explosions between March 12th and 15th.



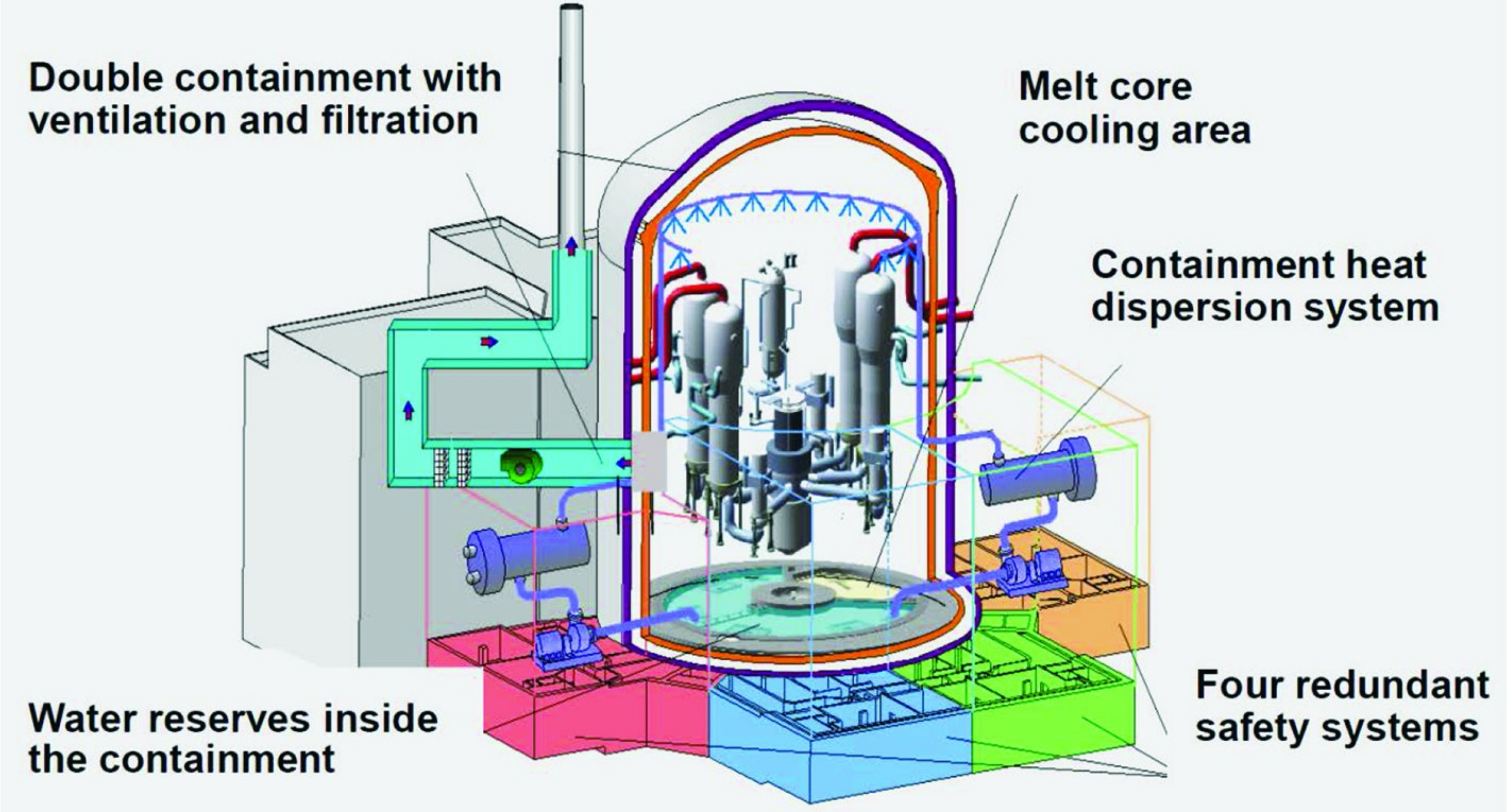
Accidents – Fukushima – 2011

- Consequences:
  - Evacuation of a 20 km zone around power plant (~154 000 residents)
  - Large amount of contaminated water released into the Pacific Ocean (^{137}Cs)
  - No death directly attributed to radiation exposure (18 500 death caused by earthquake & tsunami)
  - 137 thyroid cancer in 2015, not clear if above usual levels



EPR (generation 3+)

- Improvement over current pressurized water reactors
- Yield 32% ⇒ 36% (improved turbines)
- More fuel flexibility (100% MOX)
- Life time
  40 years ⇒ 60 years
- Improved security :
  melt core recovery (corium)

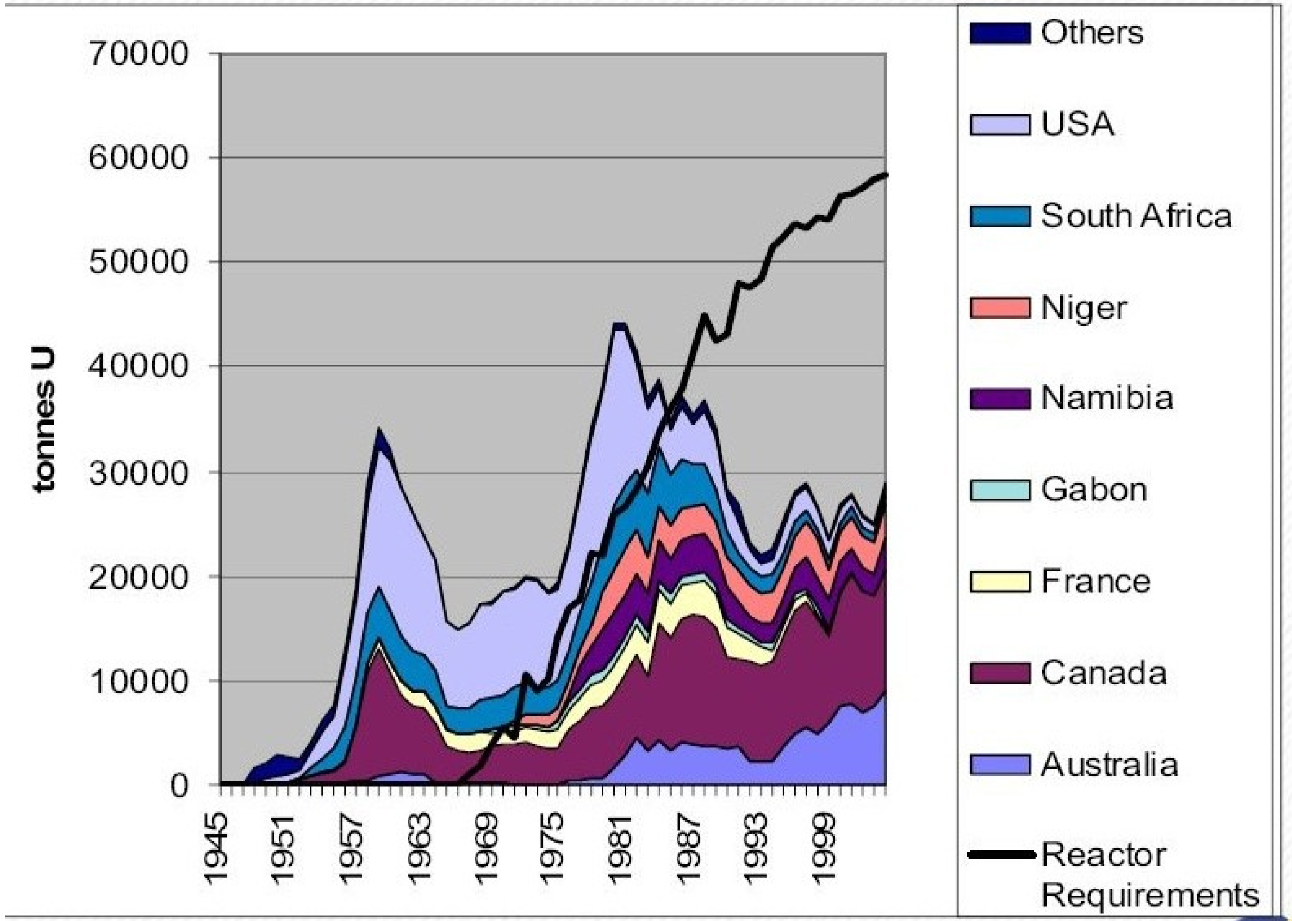


Limitations of current reactors

Uranium worldwide

F. Soso 2007

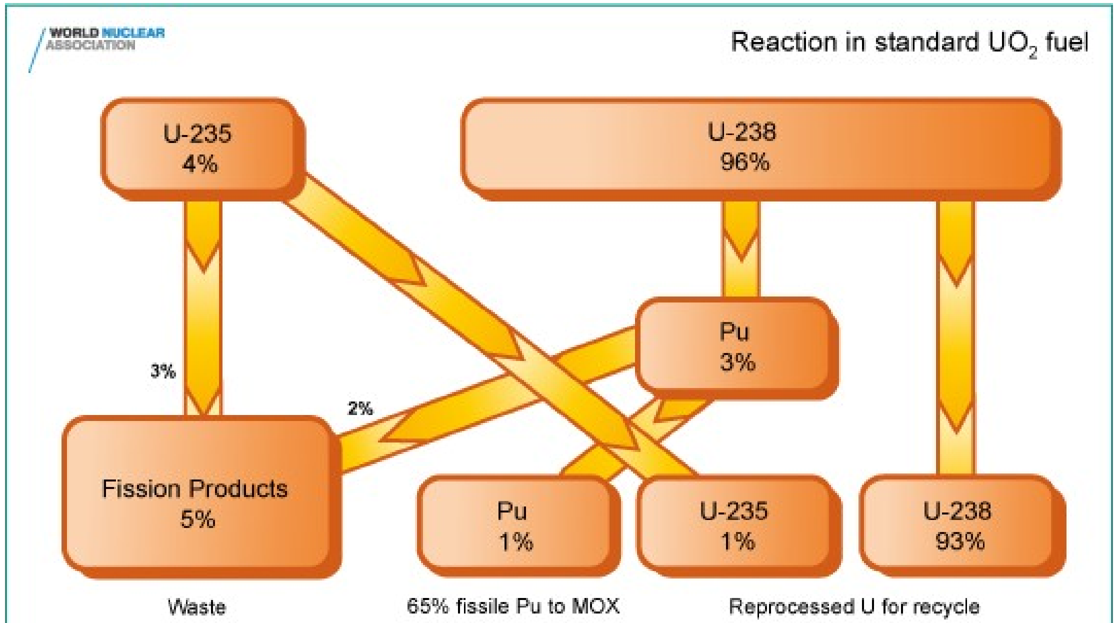
- Natural U produced 40.000 tons/yr
- Worldwide consumption : 65.000 tons/yr
- Different taken from stock done in the years 1960-80



World Nuclear Association

Uranium balance

- Starting from 100 atoms of Uranium, of which 4 of isotop 235 (fissile) and 96 of isotope 238.
  - Of the 4 initial ^{235}U, 3 undergo fission and 1 survives
  - Of the 96 initial ^{238}U, 3 are transformed into ^{239}Pu and 93 survive.
  - Of the 3 formed ^{239}Pu, 2 undergo fission and 1 survives
- Overall, there are 3 + 2 = 5 fissions : only 5 % of the heavy metal is actually used.
- Nuclear waste contain:
  - 5 fission products
  - 1 plutonium atom
  - 0.1 minor actinide atoms (high activity)



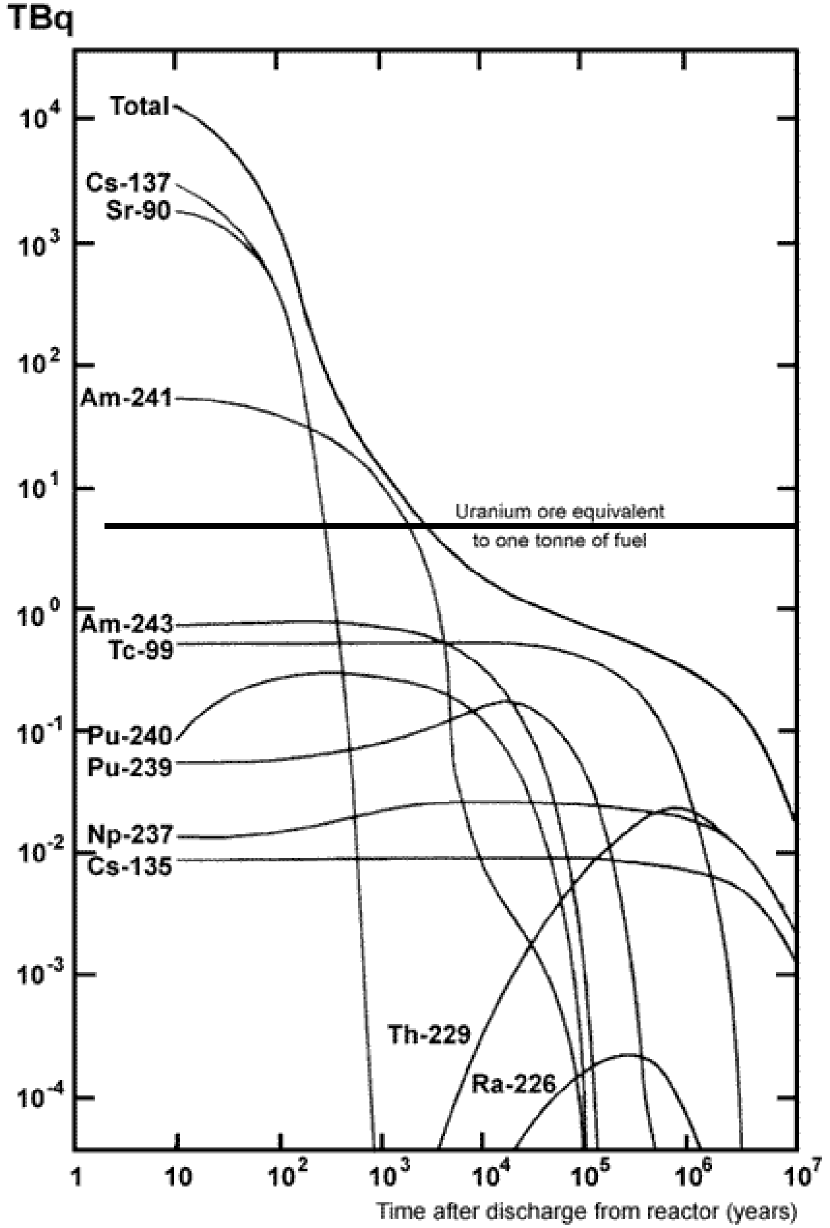
Uranium consumption – PWR

- Natural Uranium consumption in standard reactors could be reduced by a factor ~ 2:
  - Longer presence time in reactors
  - Treatment et re-enrichment of irradiated Uranium
- Even with these improvements, only 1% of natural Uranium is effectively used.

	/ (GWe . yr)
fissionned	1 t
enriched	30 t
natural	200 t

Waste activity

- Current generation of reactors accumulates radioactive waste
- Problem essentially comes from minor actinides, and moreover from Plutonium
- Implies storage (temporary and long-term)



Activity of high-level waste from one tonne of spent fuel

Source: IAEA, 1992 - radioactive waste management.

Lecture 5 – Nuclear Energy

I. Basics of nuclear physics

II. Fission Power Plants

III. Fast Breeders – Generation IV

IV. Fusion Energy, current status, challenges and outlook

V. Conclusions

Toward Generation IV

Neutron Capture – Fertilization – Breeding

- Neutron capture

$$ {}^{238}_{92}U + n \rightarrow {}^{239}_{92}U + \gamma\,, \qquad {}^{239}_{92}U \overbrace{\rightarrow}^{\beta^-(23\,\mathrm{mn})} \underset{\text{neptunium}}{{}^{239}_{93}Np} \overbrace{\rightarrow}^{\beta^-(2{,}3\,\mathrm{j})} {}^{239}_{94}Pu $$

  - No fission, but production of a fissile nucleus, potentially usable in a reactor
  - Similarly, fissile Uranium can be produced Thorium

$$ {}^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th + \gamma\,, \qquad {}^{233}_{90}Th \overbrace{\rightarrow}^{\beta^-(22\,\mathrm{mn})} \underset{\text{protactinium}}{{}^{233}_{91}Pa} \overbrace{\rightarrow}^{\beta^-(27\,\mathrm{j})} {}^{233}_{92}U $$

- This is called Fertilization: transformation of a fertile element into a fissile element (through neutron capture)
- Fast-breeder: production of at least the same amount of fissile material than consumed

Fast-breeder – Neutron Balance

- One neutron (if not absorbed by the moderator) has 3 possible futures:
  - Induced fission with probability P_F
  - Gamma capture with probability $P_A = \alpha P_F$
  - Fertilization with probability P_R
- Following relations are obtained:

$$\begin{cases} P_A + P_F + P_R = 1 & (\text{normalization}) \\ P_A + P_F = P_R & (\text{regeneration of fissile material}) \end{cases} \Rightarrow \begin{cases} P_A = \dfrac{\alpha}{2(1+\alpha)} \\ P_F = \dfrac{1}{2(1+\alpha)} \\ P_R = \dfrac{1}{2} \end{cases}$$

- The neutron balance reads

$$N = (\nu - 1) P_F - P_A - P_R = \nu P_F - 1 = \frac{\nu - 2(1+\alpha)}{2(1+\alpha)}$$

- The fast-breeder condition (N>0) reads then: $\boxed{\nu > 2(1+\alpha)}$

Fast-breeder – Neutron Balance (2)

- Fast neutrons are mandatory (for Uranium cycle)
- Thermal neutrons are possible when using Thorium cycle

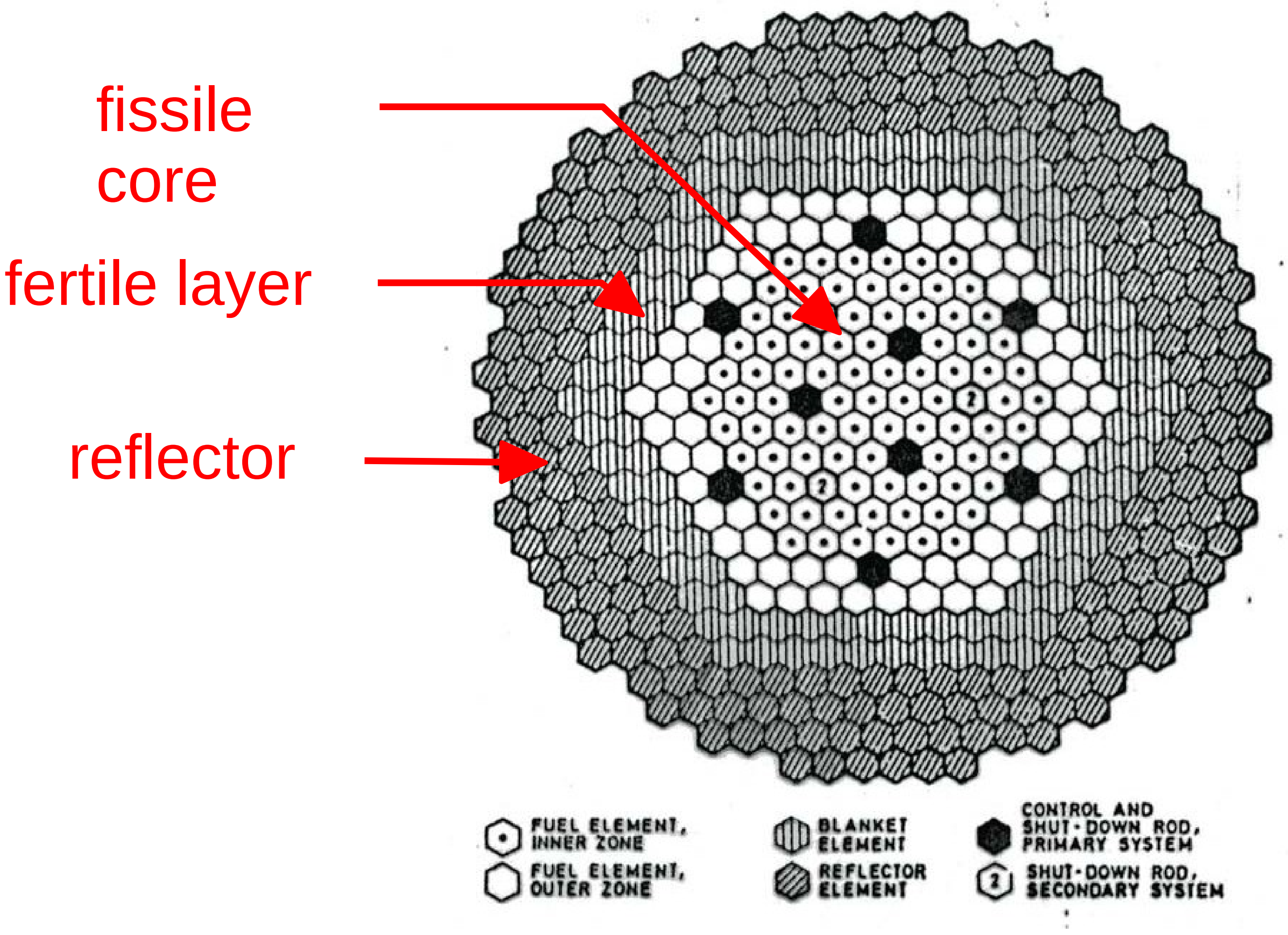
	Thermal Neutrons	Thermal Neutrons	Fast Neutron	Fast Neutron
	U/Pu	**Th/U**	**U/Pu**	**Th/U**
Fissile Material	^{239}Pu	^{233}U	^{239}Pu	^{233}U
σ (induced fission)	90	50	1,85	2.7
σ (gamma capture)	50	6	0.5	0.27
ν	2.9	2.5	2.9	2.5
	-0,2	**0,3**	**0,36**	**0,3**

Advantages of fast breeding

- All the heavy metal is used ⇒ multiplication by ~ 100 of the reserves
- Minor actinides can be recycled (incinerated) because they are fissile with fast neutrons ⇒ much less waste
- Waste accumulated in the last 50 years become ‘fuel’ !
- ^{232}Th, 4 times more abundant than Uranium, can be used. It does not produce any sub-products that could be used as nuclear weapons.

Structure of a Fast Breeder Reactor

- « onion skin » structure
- Reflector made of heavy element sends neutron back to the core



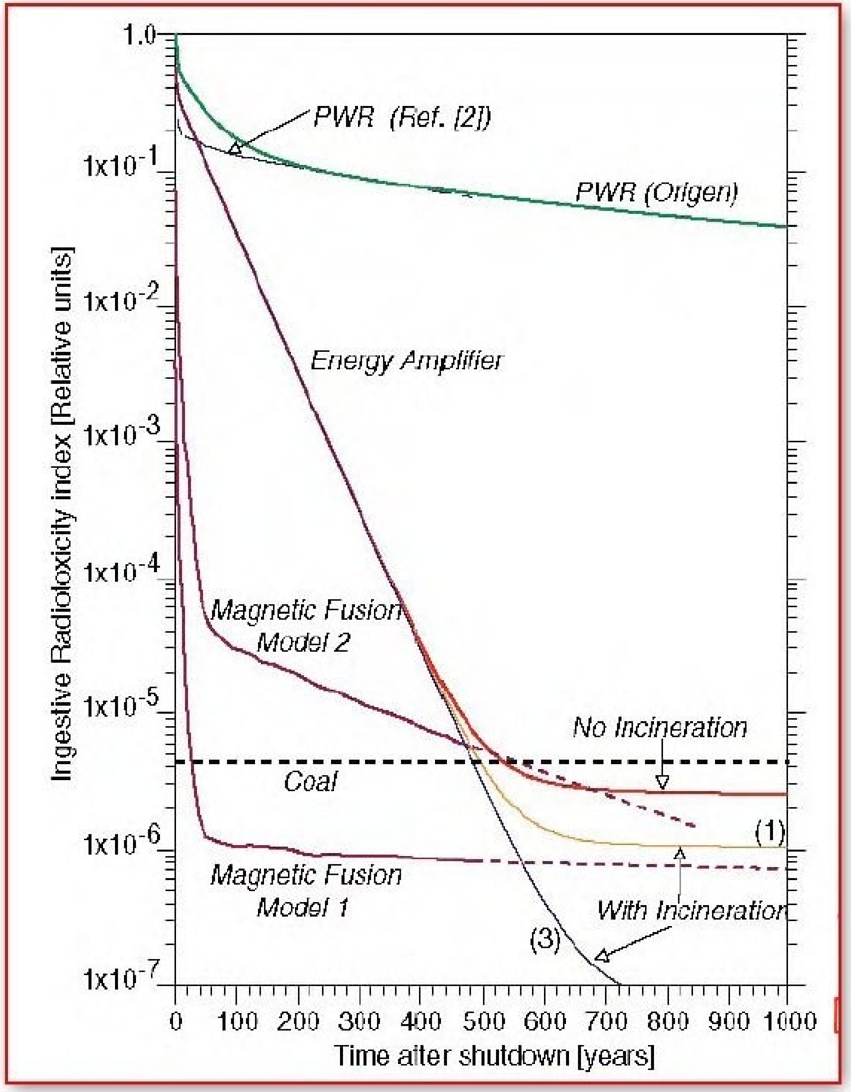
fissile core

fertile layer

reflector

Waste of a fast breeder reactor

- Almost nothing left after 500 yr, minor actinides are incinerated



Superphénix

- Follow-up of earlier Phenix prototype
- 1.4 GWe fast breeder reactor prototype, liquid sodium metal cooled
- Designed to use ^{239}Pu waste from PWR reactors
- Construction started 1974
- Power production started in 1985
- Various problems (liquid sodium cooling system suffered from corrosion and leaks)
- Nominal power reached only in 1996
- Closed in 1998 triggered by 3 incidents in the year
- In 11 years, only 53 month of normal operations, 25 months of outage and 66 months on halt due to political/administrative issues

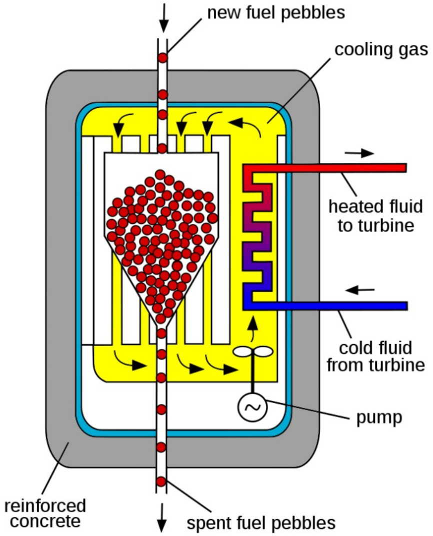
Generation IV Reactors

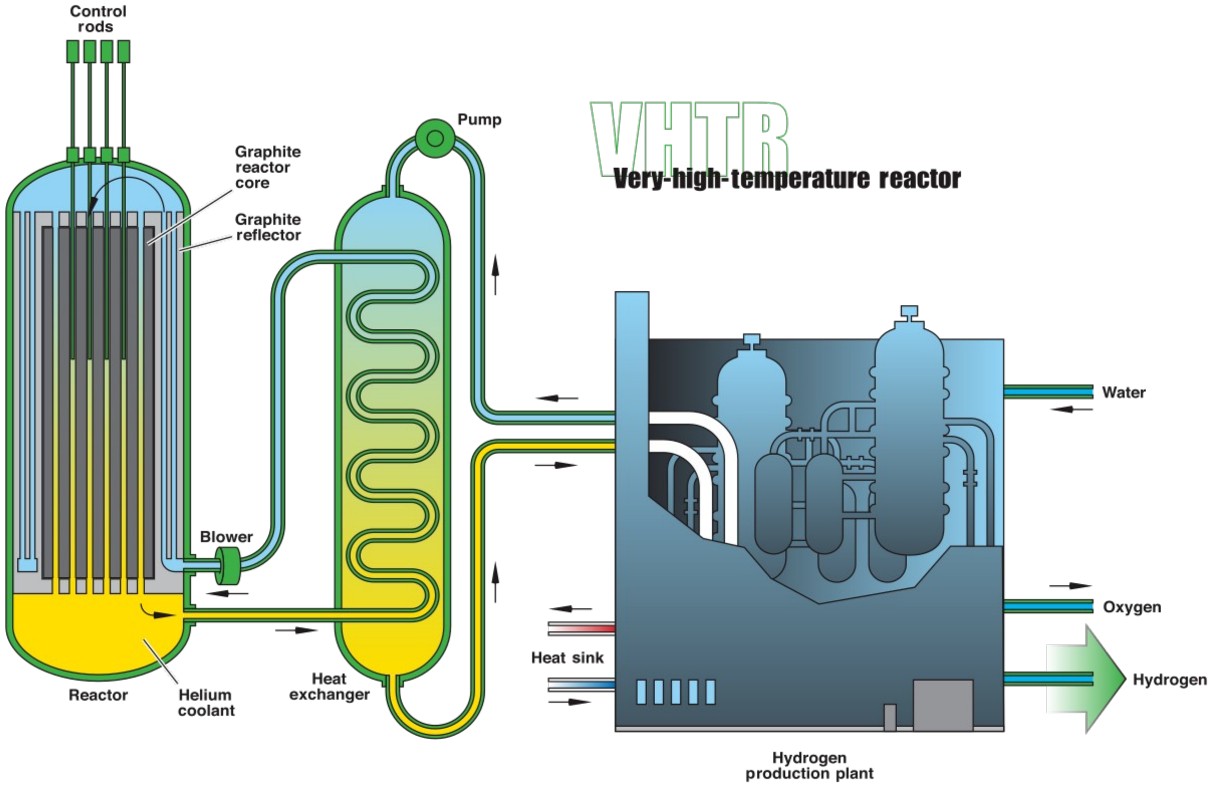
- 6 types of next generation reactors currently being designed.
- Promoted by the “Generation IV International Forum” (2001)
- 3 thermal reactor concepts
  - Very-high-temperature reactor (**VHTR**)
  - Molten-salt reactor (**MSR**)
  - Supercritical-water-cooled reactor (**SCWR**)
- 3 Fast breeder reactor concepts
  - Gas-cooled fast reactor (**GFR**)
  - Sodium-cooled fast reactor (**SFR**)
  - Lead-cooled fast reactor (**LFR**)

Very-high-temperature reactor – VHTR

- Graphite moderated core
  - prismatic block
  - or pebble bed reactor
- Helium or molten salt coolant
- Outlet temperature ~ 1000°C
  ⇒ **increased yield**
  ⇒ gateway to hydrogen
- First prototypes being constructed

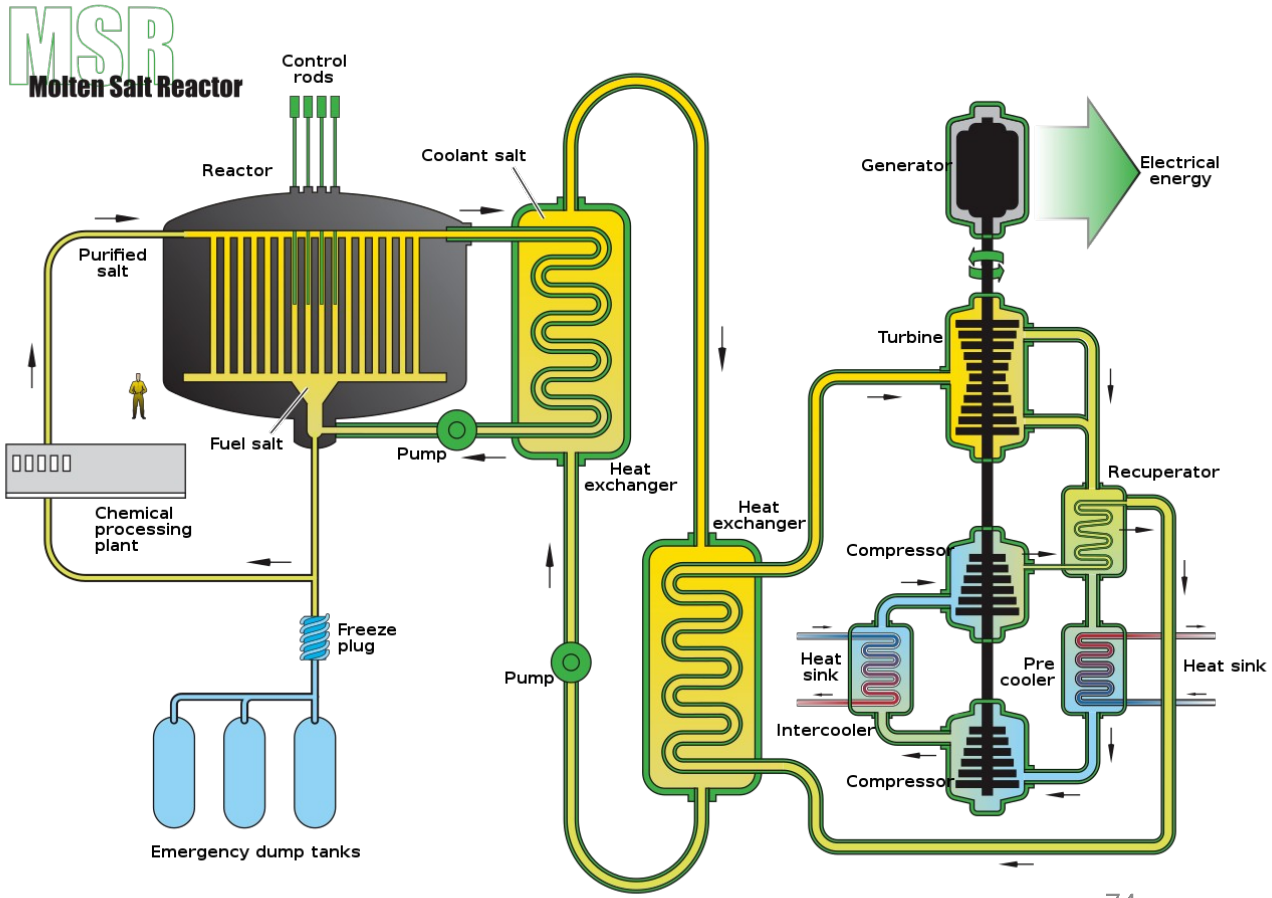
Pebble bed reactor scheme





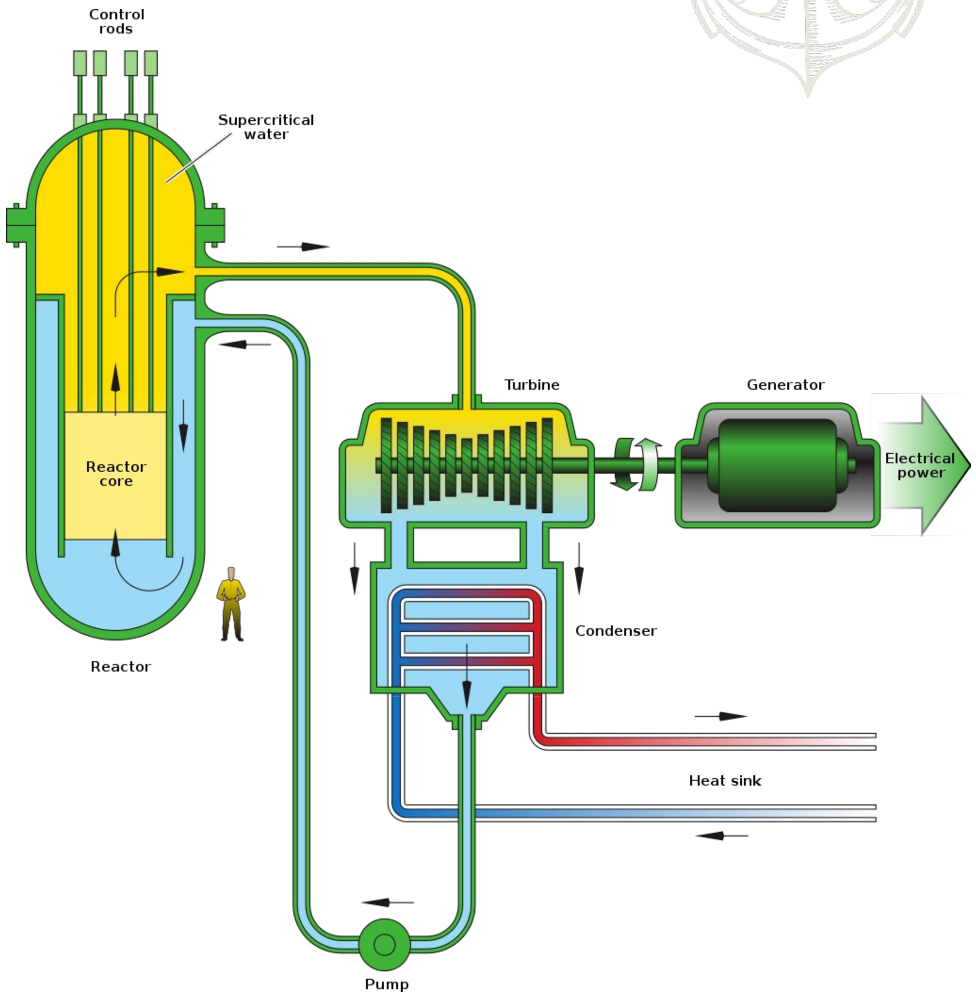
Molten-salt reactor – MSR

- Nuclear fuel dissolved in molten fluoride salt
- Criticality reached by flowing into a graphite moderator core
- Operate close to atmospheric pressure (no need for large containment structure)
- Do not produce radioactive fissions gases
- High temperature ⇒ high yield
- Several ongoing projects



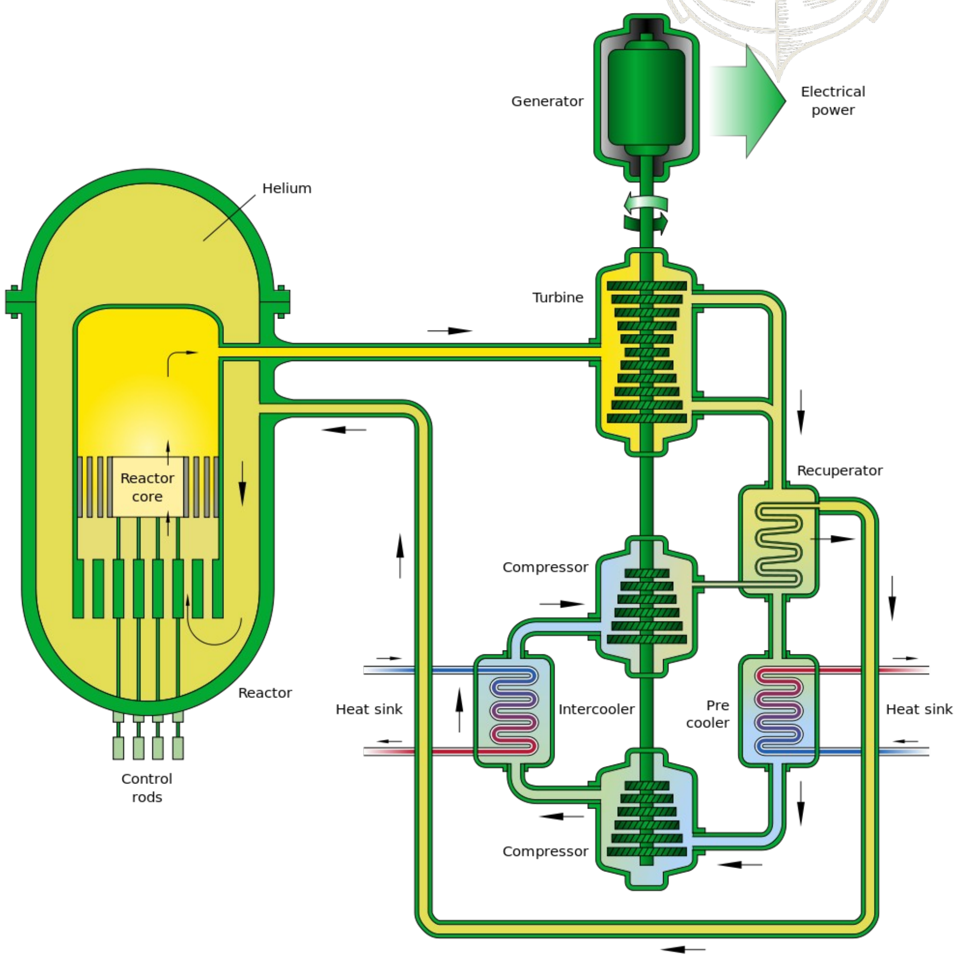
Supercritical-water-cooled reactor – SCWR

- Reduced moderation water reactor
- “Epithermal reactor” (faster neutrons than thermal neutrons)
- Uses supercritical water in a direct, once-through heat exchange cycle (like BWR), high pressure, high temperature
  ⇒ increased yield to ~ 45%
- But only one phase like PWR



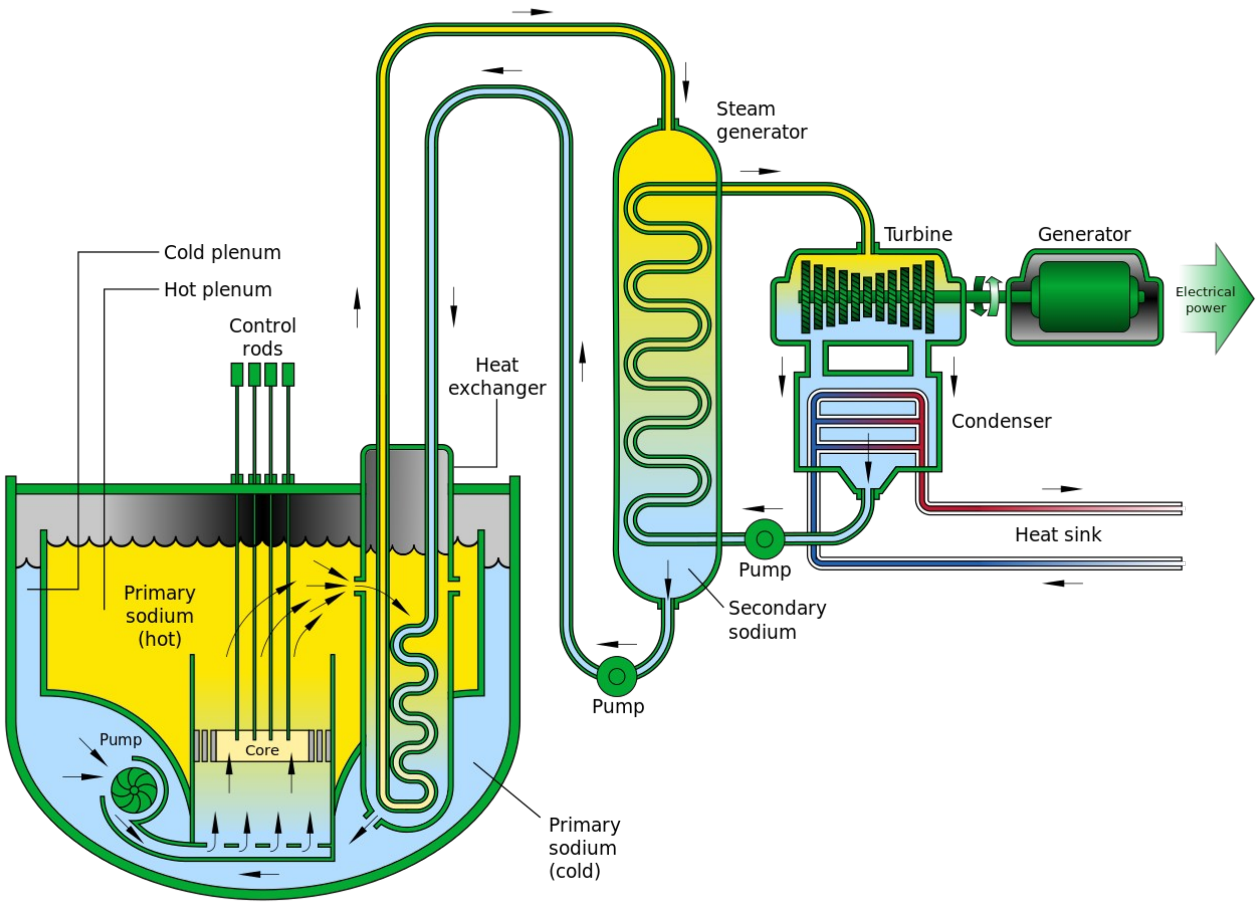
Gas-cooled fast reactor – GFR

- Fast neutron reactor for efficient conversion of fertile uranium and management of actinides
- Helium cooling
- High temperature (850°C)
- Uses direct Brayton cycle gas turbine (or combined cycle)
- One prototype in construction (Allegro)



Sodium-cooled fast reactor – SFR

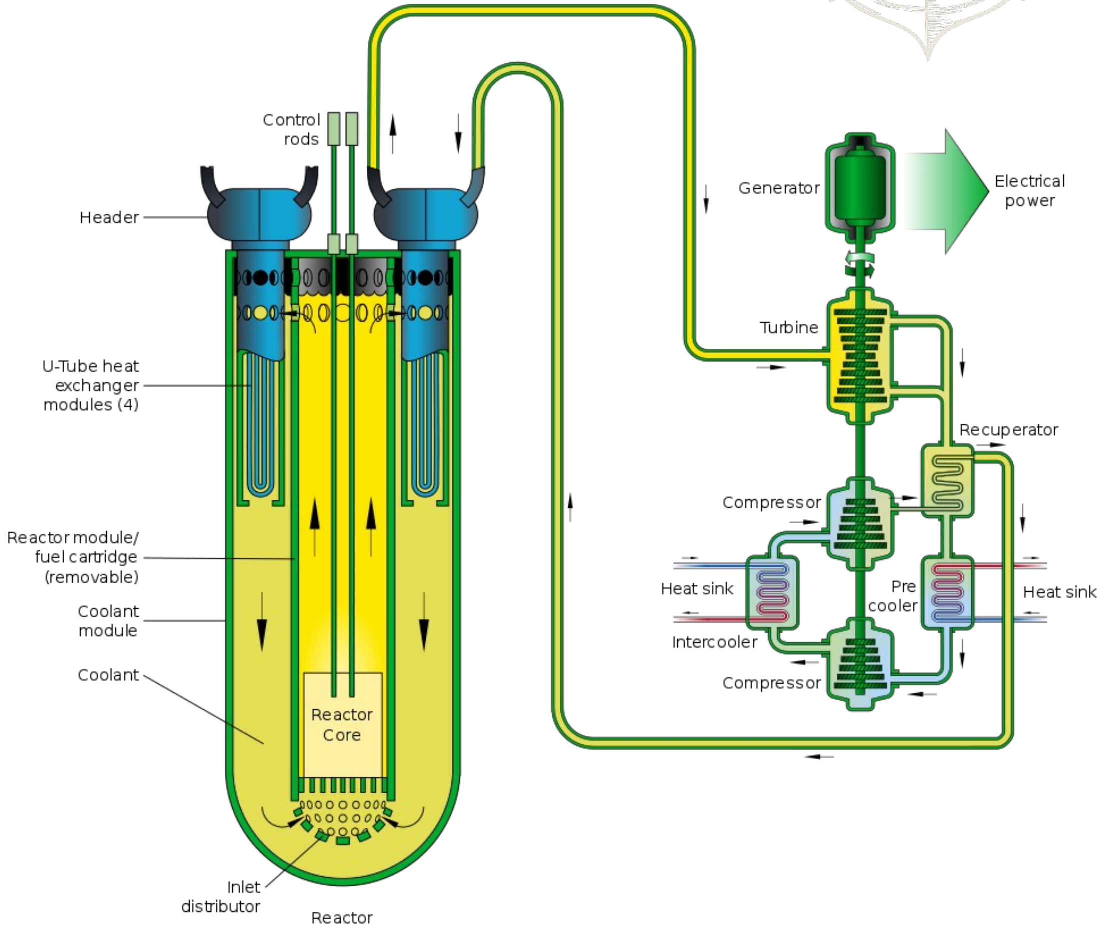
- Similar in concept to Superphénix
- Liquid sodium coolant
- Fueled by alloy of uranium and plutonium or spent nuclear fuel
- Working at atmospheric pressure



Lead-cooled fast reactor – LFR

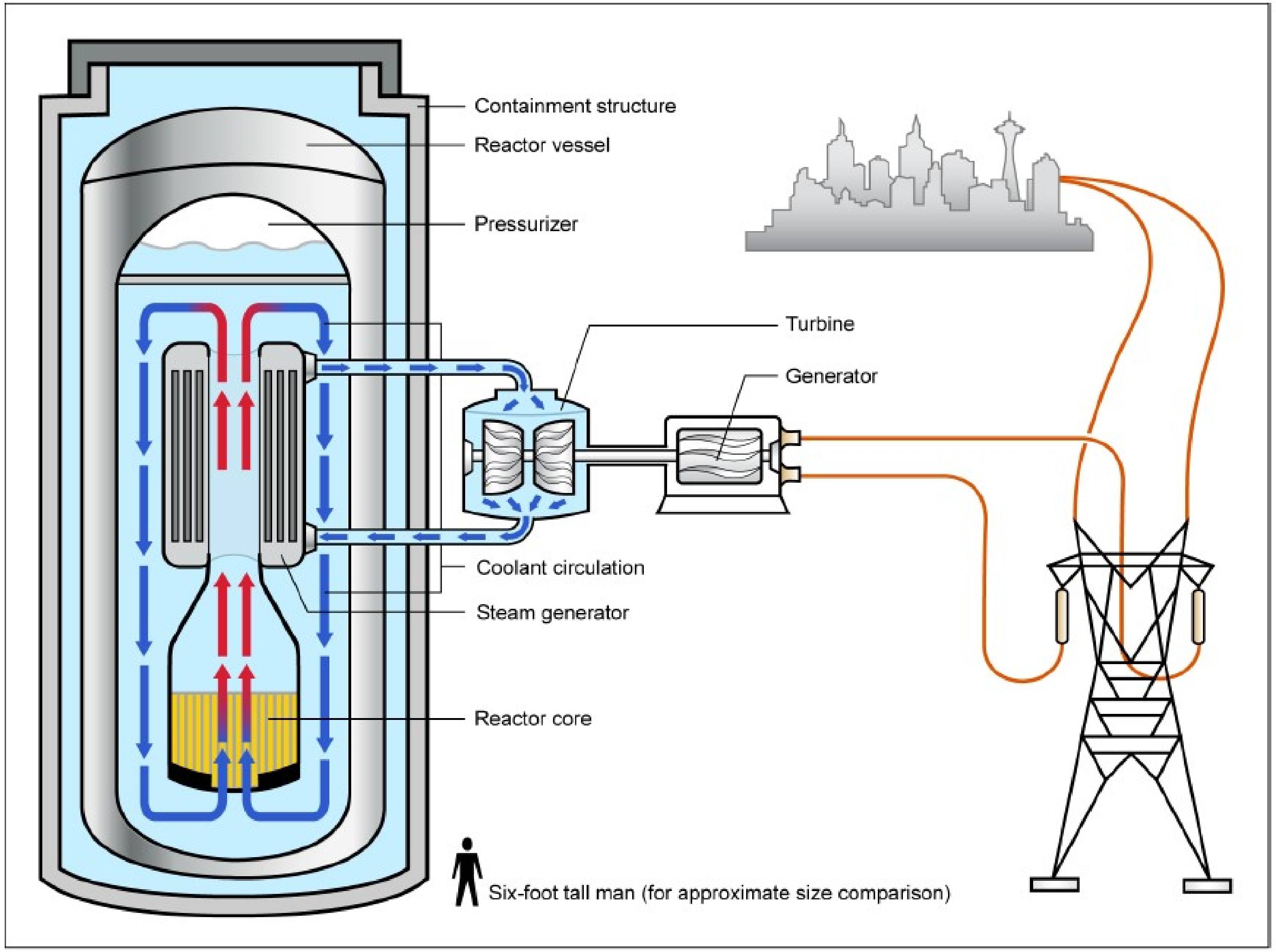
- Fast neutron reactor cooled by lead with a closed fuel cycle
- Cooled by natural convection
- Outlet temperature 550°C ⇒ 800°C

  ⇒ increased yield
  ⇒ gateway to hydrogen
- 3 funded projects



Small Modular Reactors – SMR

- Transportable
- Increased safety (avoiding active systems such as pumps)
- Little supervision
- Reduced wasted (using fertile materials)
- Adapted to remote locations
- Many designs
    - Pressurized Water Reactor
    - Sodium Cooled Fast Reactor
    - Molten Salt Reactor
    - Gas Cooled Reactor



Source: GAO, based on Department of Energy documentation. | GAO-15-652

Lecture 5 – Nuclear Energy

I. Basics of nuclear physics

II. Fission Power Plants

III. Fast Breeders – Generation IV

IV. Fusion Energy, current status, challenges and outlook

V. Conclusions

Short history of nuclear fusion

- 1930: energy source of the sun = nuclear fusion
  $p + p \rightarrow D + e^+ + \upsilon_e$ (BETHE)
- 1942: 1st American nuclear fission cell (FERMI)
- 1945: 1st American A bomb (fission) (OPPENHEIMER)
- 1949: 1st Russian A bomb (fission) (ZEL'DOVICH, KURCHATOV)
- 1952: 1st America H bomb (fusion) (TELLER): detonator = A bomb
- 1953: 1ère Russian H bomb (fusion) soviétique (SAKHAROV)
- from 1950's: experiments on controlled nuclear fusion
- 195X: Magnetic confinement: «Tokamak» (TAMM, SAKHAROV)
- 196X: Inertial confinement with ion beams
- 197X: Inertial confinement with power LASERs

Advantages & drawbacks of nuclear fusion

- ☺ fuel = light nuclei (deuterium, tritium, lithium)
  almost unlimited resources (D, Li) or regenerable (T, ^{3}He)
- ☺ no production of **long-lived** radioactive waste
- ☺ no chain reaction ⇒ **no risk of runaway**
- ☺ no generation of fissile products possible
  ⇒ **limited risk of nuclear weapons proliferation**
- ☺ **very low quantity** of radioactive products in the reactor
- ☹ **large installations** ⇒ centralized production
  not suitable for distributed production (emerging countries)
- ☹ **short-lived activation**
- ☹ advanced technologies (superconductivity, materials)
  - ➢ very high temperatures
  - ➢ high neutron flux
- ☹ **unstable** process, **difficult to sustain**
- ☹ risk of **contamination by tritium**

Fusion Energy E_F

- Several possible reactions:

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} \quad \mathbf{3.27}\ \mathrm{MeV}$$

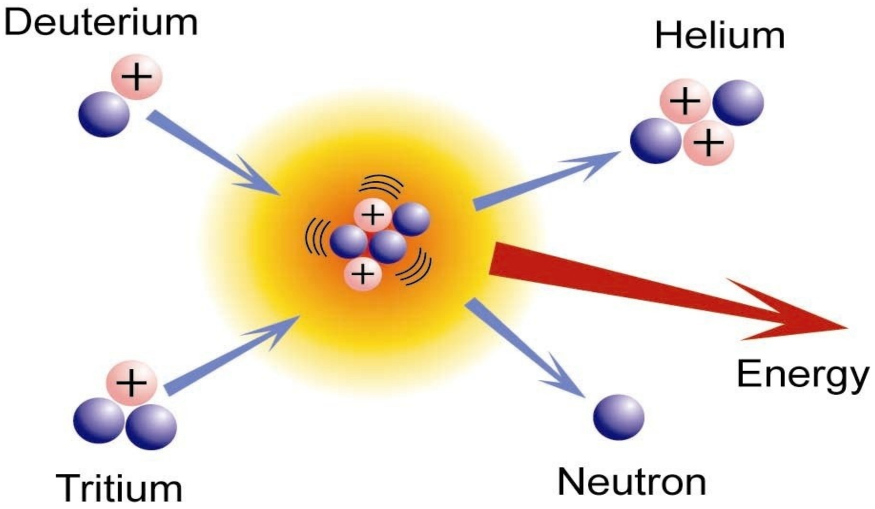
$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T} + \mathrm{p} \quad \mathbf{4.03}\ \mathrm{MeV}$$

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} \quad \mathbf{17.59}\ \mathrm{MeV}$$

$$\mathrm{D} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + \mathrm{p} \quad \mathbf{18.27}\ \mathrm{MeV}$$

- Most favourable (energy threshold & cross-section) : D + T
- 1 g D/T= 8 tons of oil

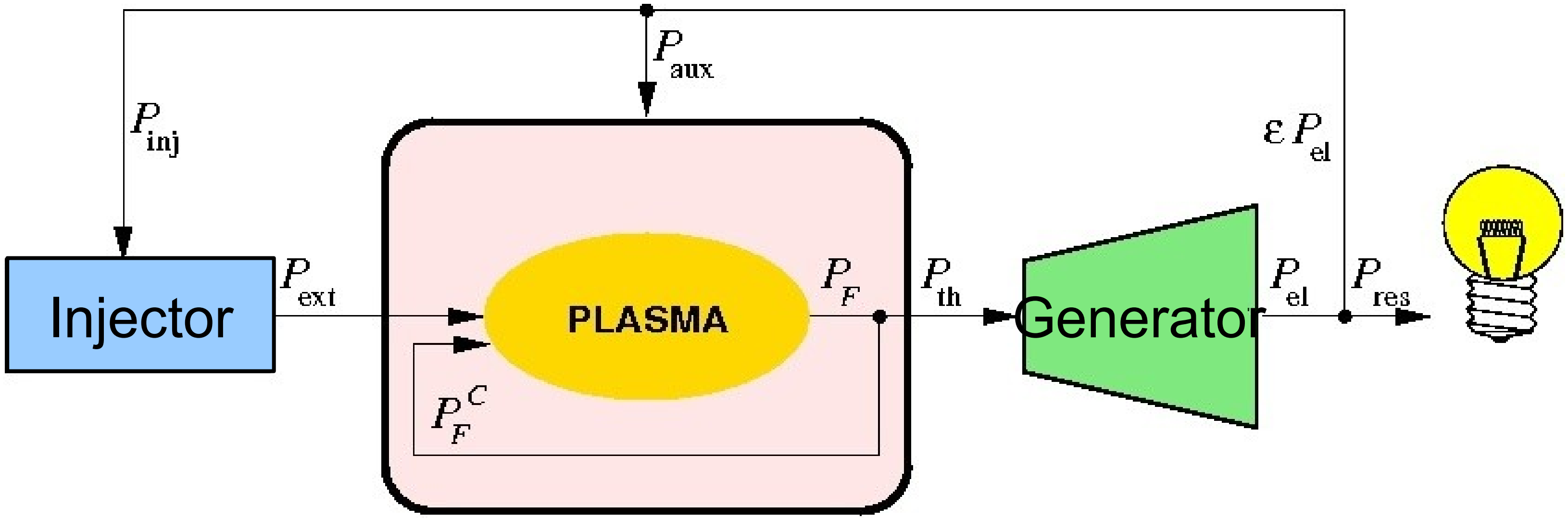
Energetic Balance of a fusion factory



$$E\left(^4\text{He}\right)=E_C=\alpha\, E_F$$

$$\alpha=1/5 \quad E_C=3.5\ \text{MeV}$$

$$E(\text{n})=(1-\alpha)\,E_F=14\ \text{MeV}$$



Fusion Production – Where are we?

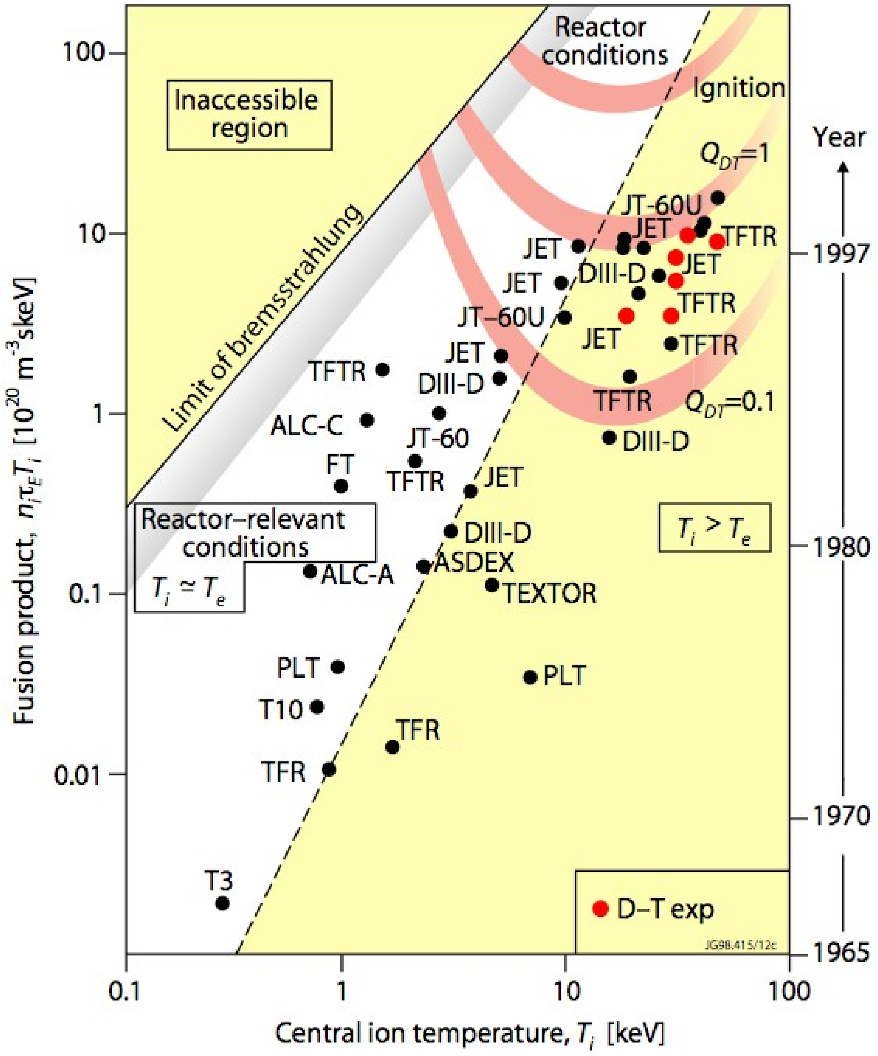
- Plasma looses energy by thermal radiation (mostly X-rays)
- Produced fusion energy is spread between neutrons (escaping the reactor) and nuclei (remaining confined)
- Fusion remains sustained if confined fusion power counteracts radiative cooling: “Lawson Criteria”

$$n\times\tau_E \;\geq\; 1.5\times10^{20}\,\mathrm{m}^{-3}\,s$$

$$\begin{aligned} n&: \quad \text{plasma density} \\ \tau_E&: \quad \text{confinement time} \end{aligned}$$

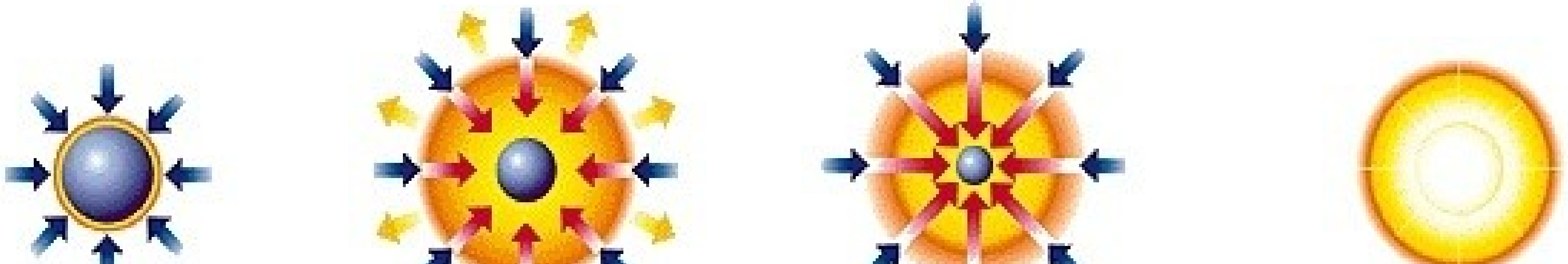
- Triple product (using optimal temperature)

$$n\times\tau_E\times T \;\geq\; 3\times10^{21}\,\mathrm{keV\,m}^{-3}\,s\left(3.5\times10^{28}\,\mathrm{K\,m}^{-3}\,s\right)$$



The two paths of thermonuclear fusion

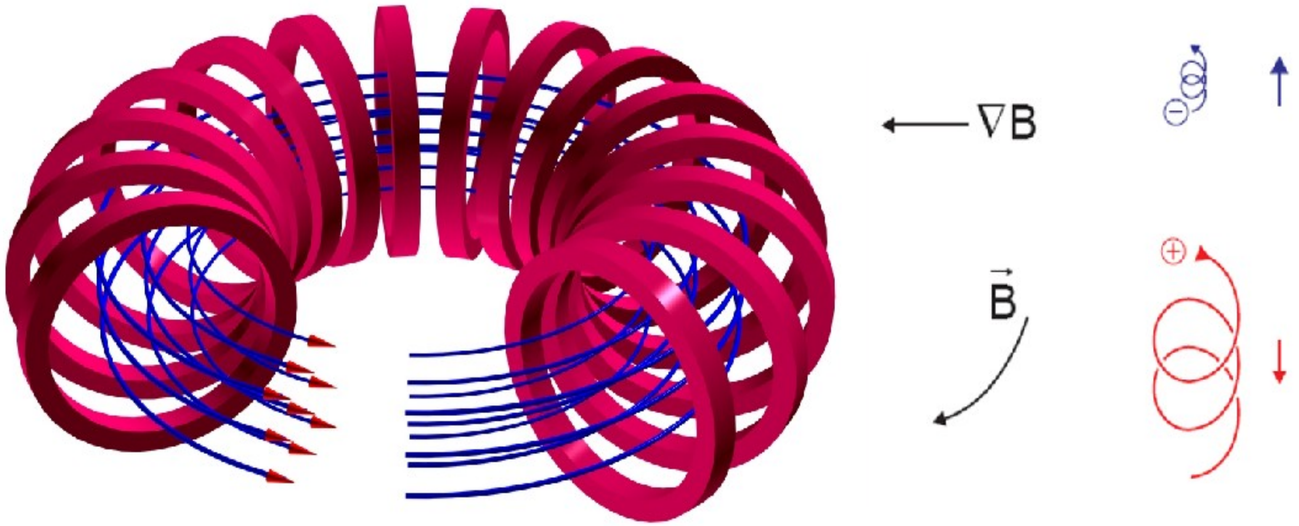
- LAWSON criteria : n × τ_E > 1.5 10^{20} m^{-3} s
- modest n, large τ_E : magnetic confinement
  External heating lowers the LAWSON criteria (Q factor)
  - open field lines configuration (solenoidal) « mirror machines »
  - closed field lines configuration (toroidal) « tokamaks »
    Tokamaks : Jet (EU), ToreSupra (F) , ITER (Int.), DEMO(?)
- large n, small τ_E: inertial confinement (laser fusion)
  external heating almost impossible → ignition mandatory
  - NOVA(US), NIF(US), MegaJoule Laser (F)
  - military interest (« simulation of a H bomb »)

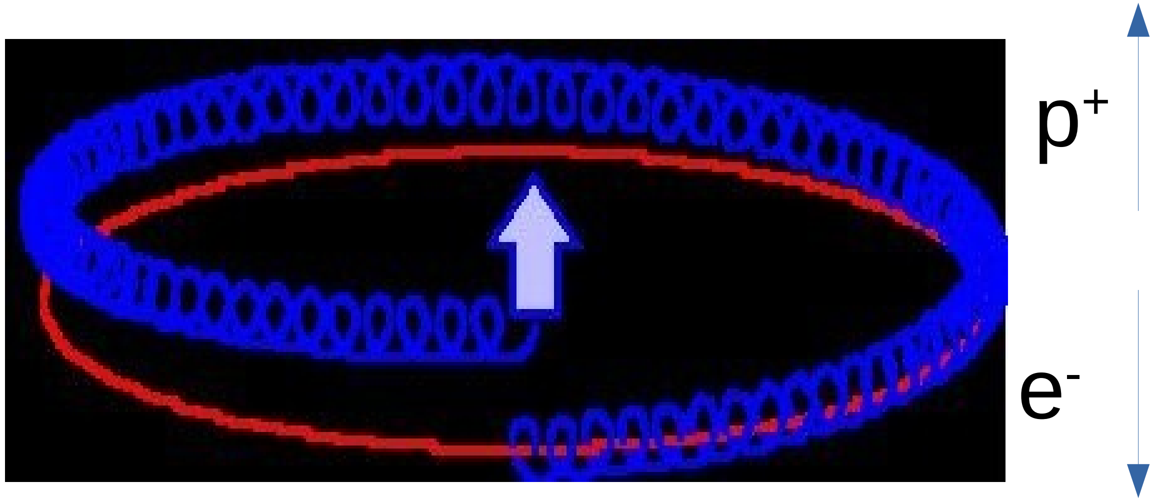


Magnetic confinement

- Trajectory of particles a toroidal field
- Transverse field gradient and centrifugal forcer induce a Drift of particles
  - Particles of opposite charge get separated

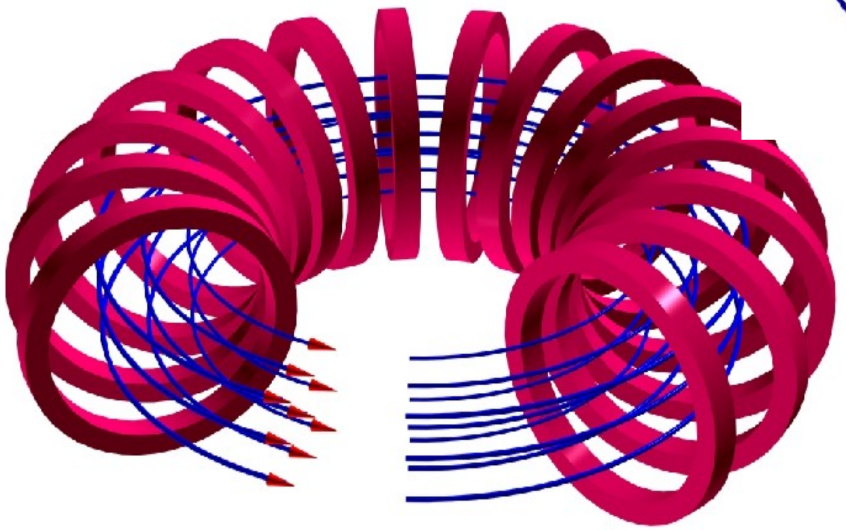
    ⇒ Induced electric field



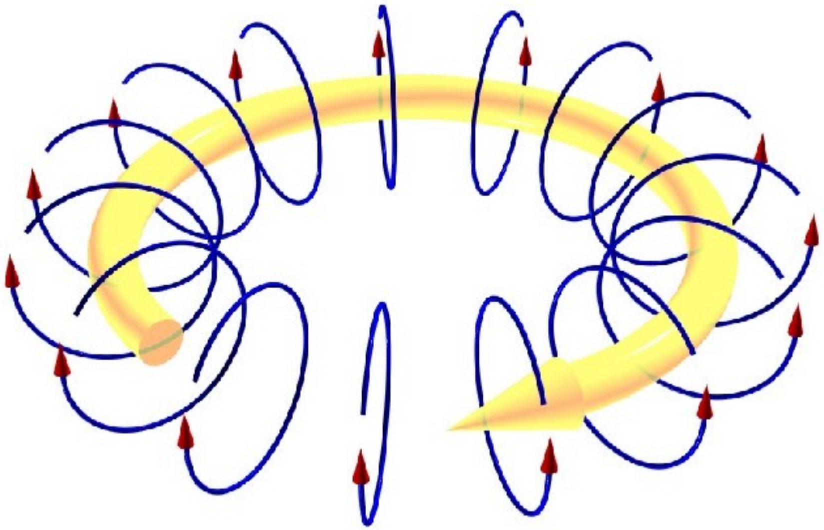


Tokamak Principle

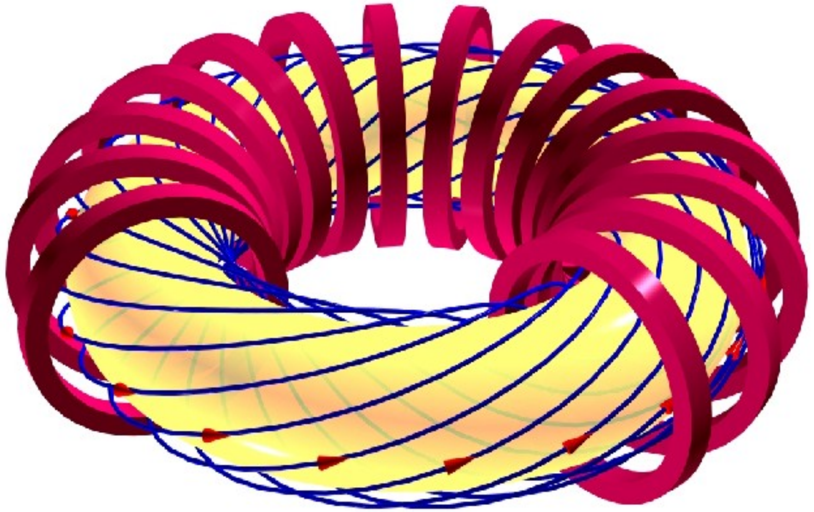
- Field configuration that avoids charge separation



Toroidal Field



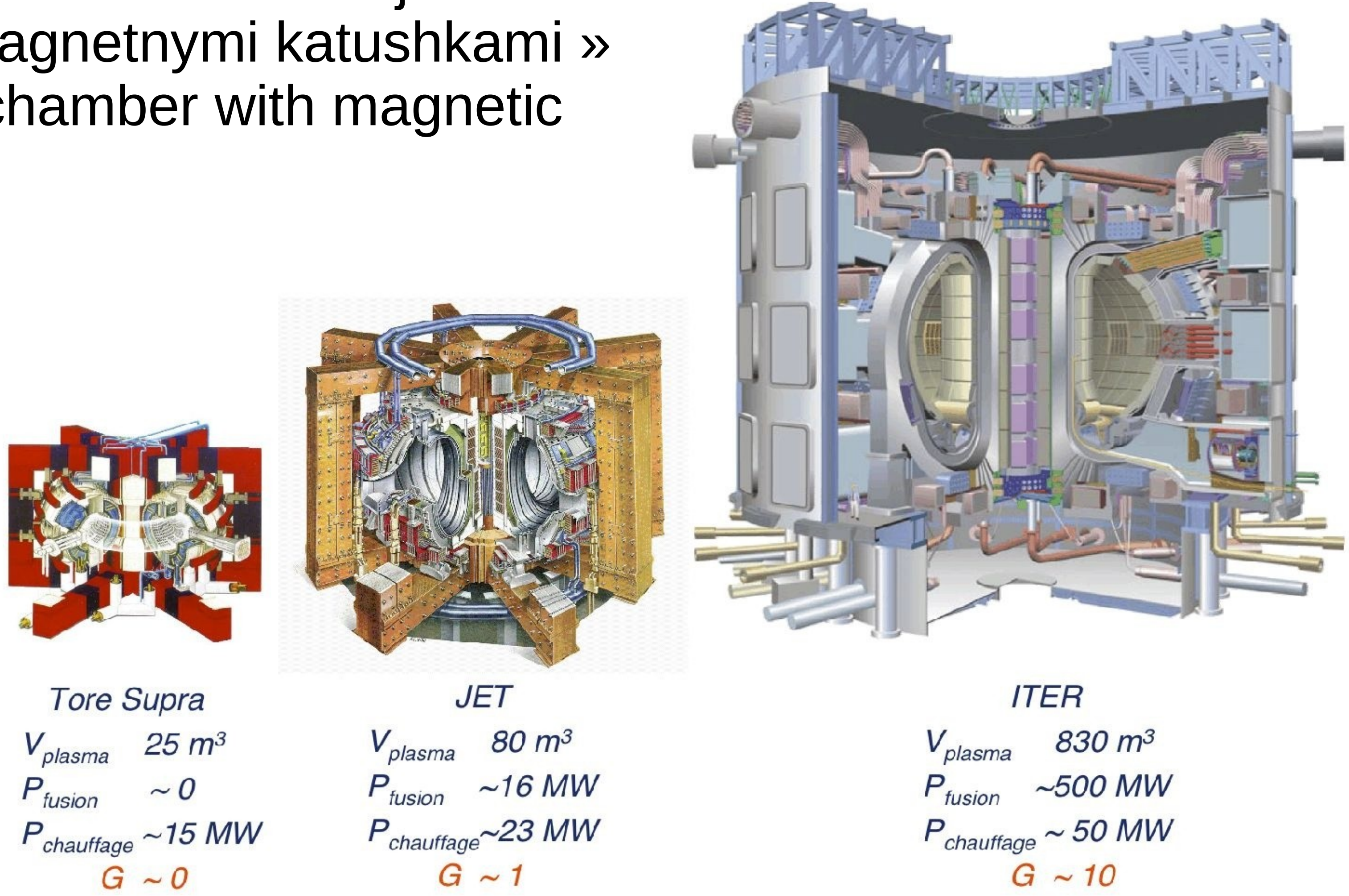
Poloidal field generated
by induction



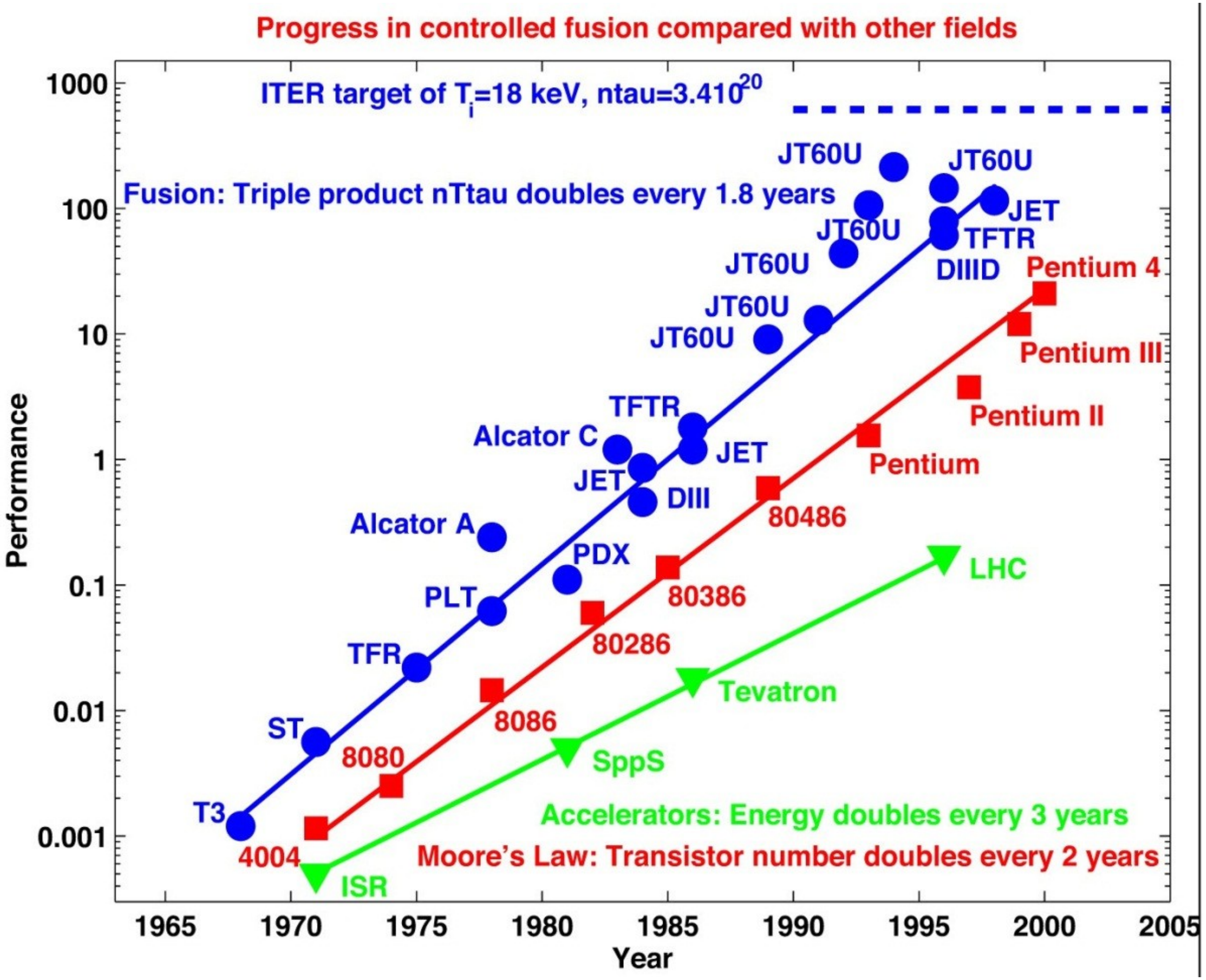
Total field

Magnetic Confinement : TOKAMAKs

- Russian word : toroidal'naja kamera magnetnymi katushkami » (Toroidal chamber with magnetic coils)

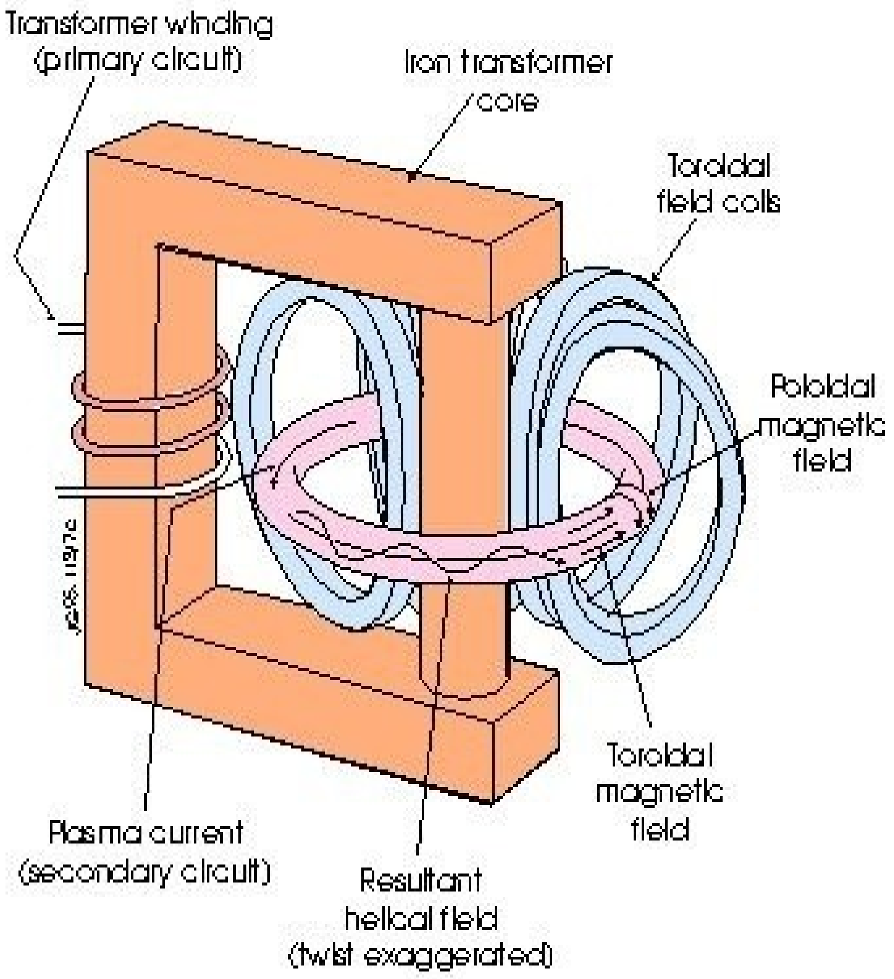


Moore’s law of Tokamaks

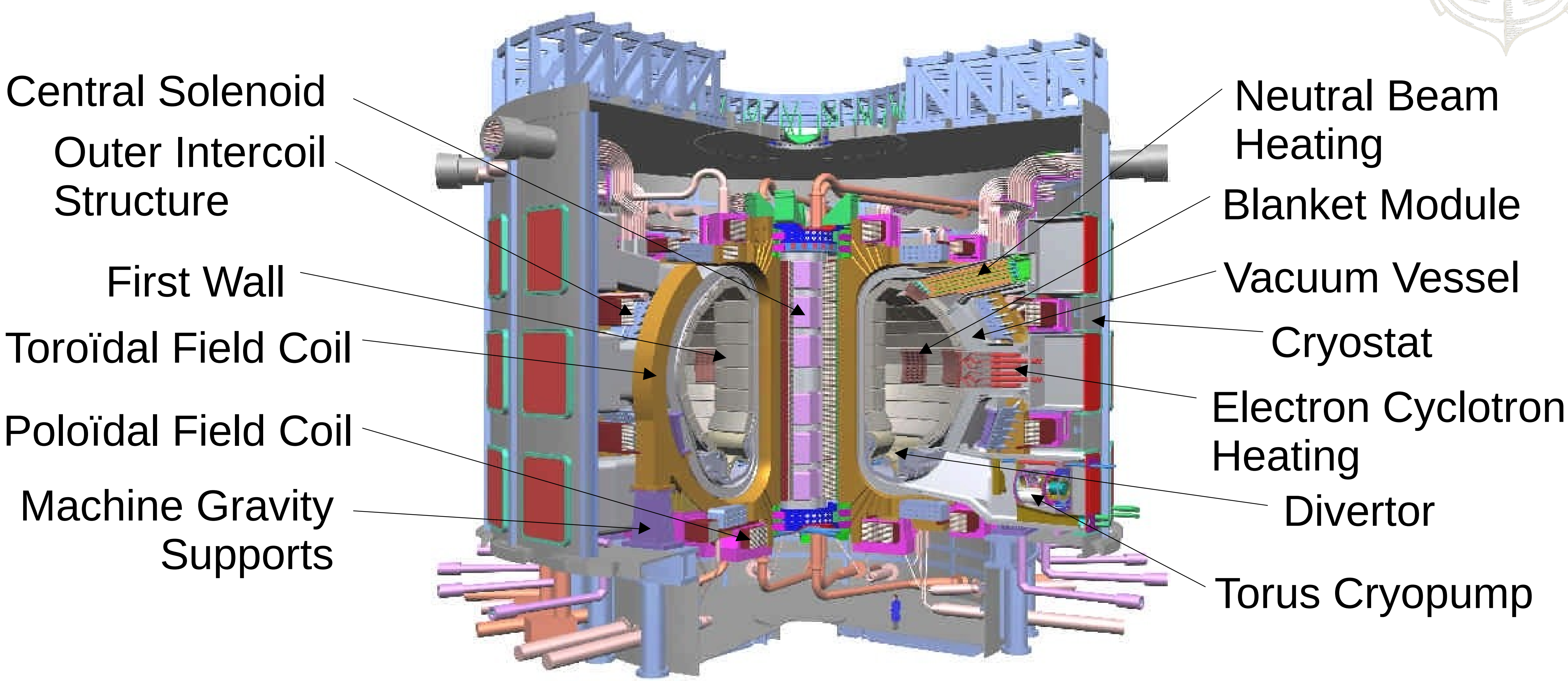


TOKAMAK operation

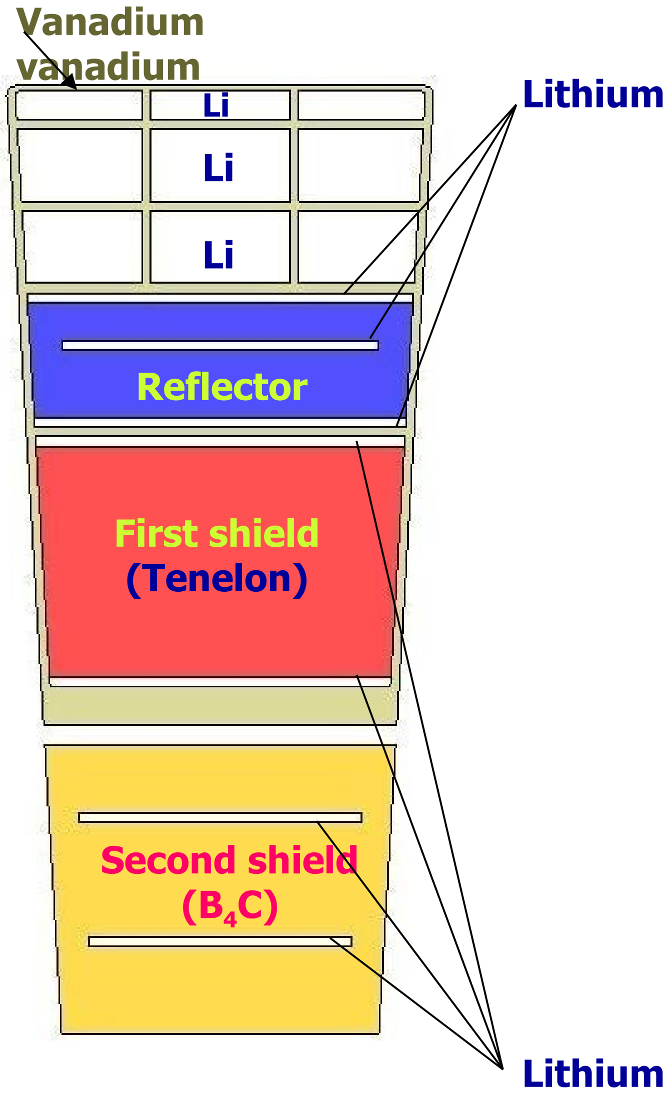
- a continuous current in the plasma generates the poloïdal field
- thus current needs to be created by induction
  - plasma = good conductor
  - plasma = (Single) secondary coil of a current transformer
  - current ramp in the primary coil around the transformer core
- Intermittent operation (if the plasma current can not be maintained by other means)
- In addition, it heats the plasma by Joule effect

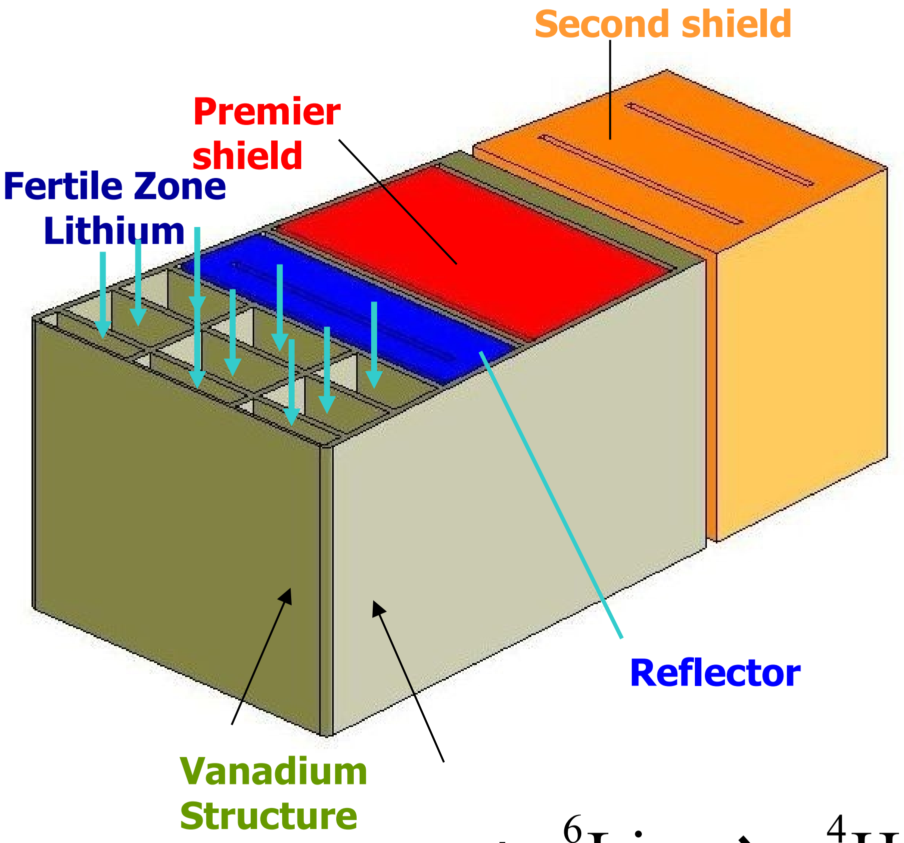


Elements of a TOKAMAK (cut)



Tritium generating cover: lithium / vanadium



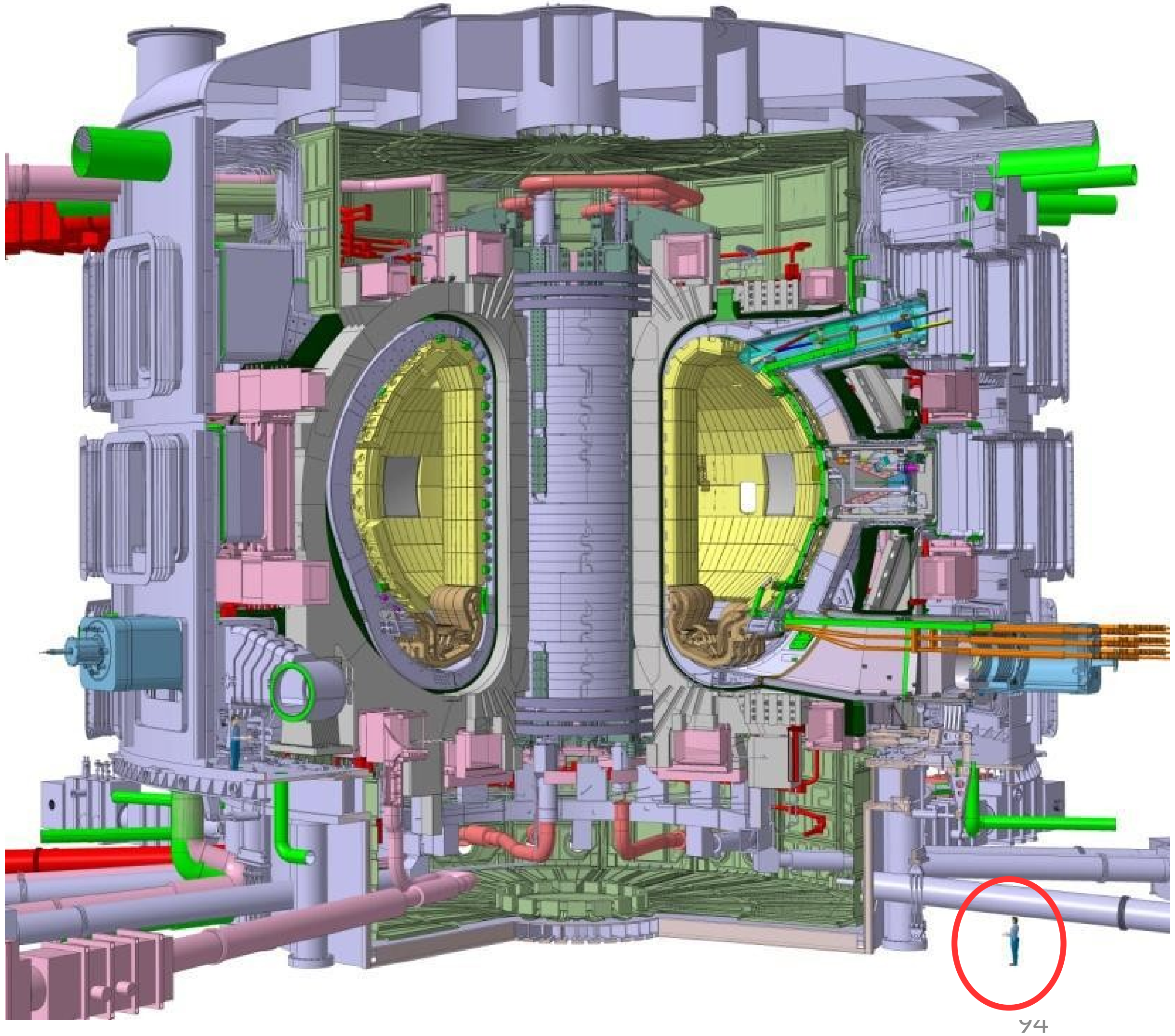


$$n + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{T} \qquad \mathbf{4.8}\,\mathrm{MeV}$$

$$n + {}^{7}\mathrm{Li} \rightarrow {}^{3}\mathrm{He} + {}^{3}\mathrm{T} + n \qquad -\mathbf{2.5}\,\mathrm{MeV}$$

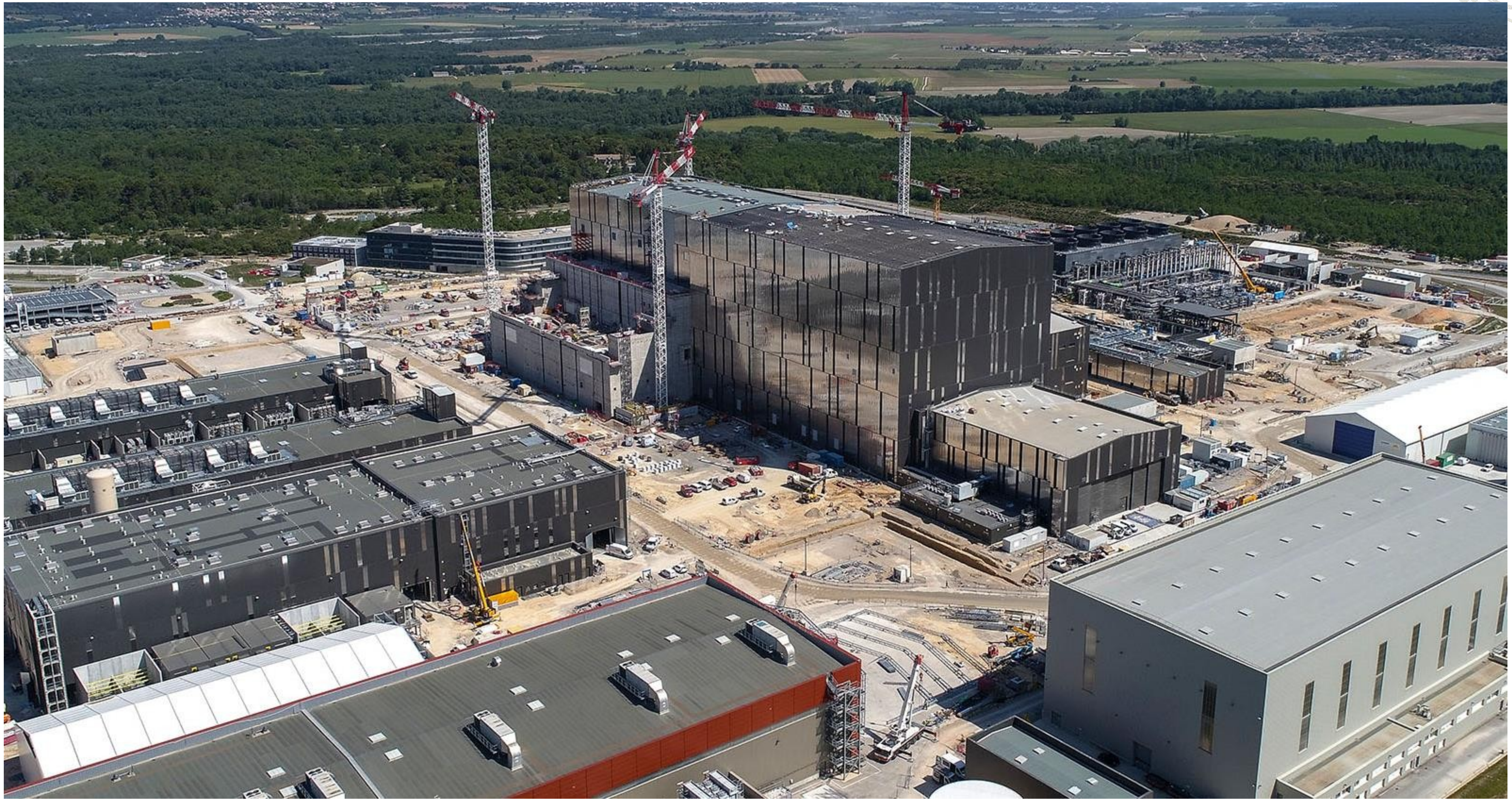
International Thermonuclear Experimental Reactor – ITER project

- Demonstrate self-burning tokamak reactor.
- 7 major partners (EU, USA, Russia, China, India, Korea, Japan), > 20G€ project
- R = 6.2 m, 500 MW fusion power, 73 MW heating

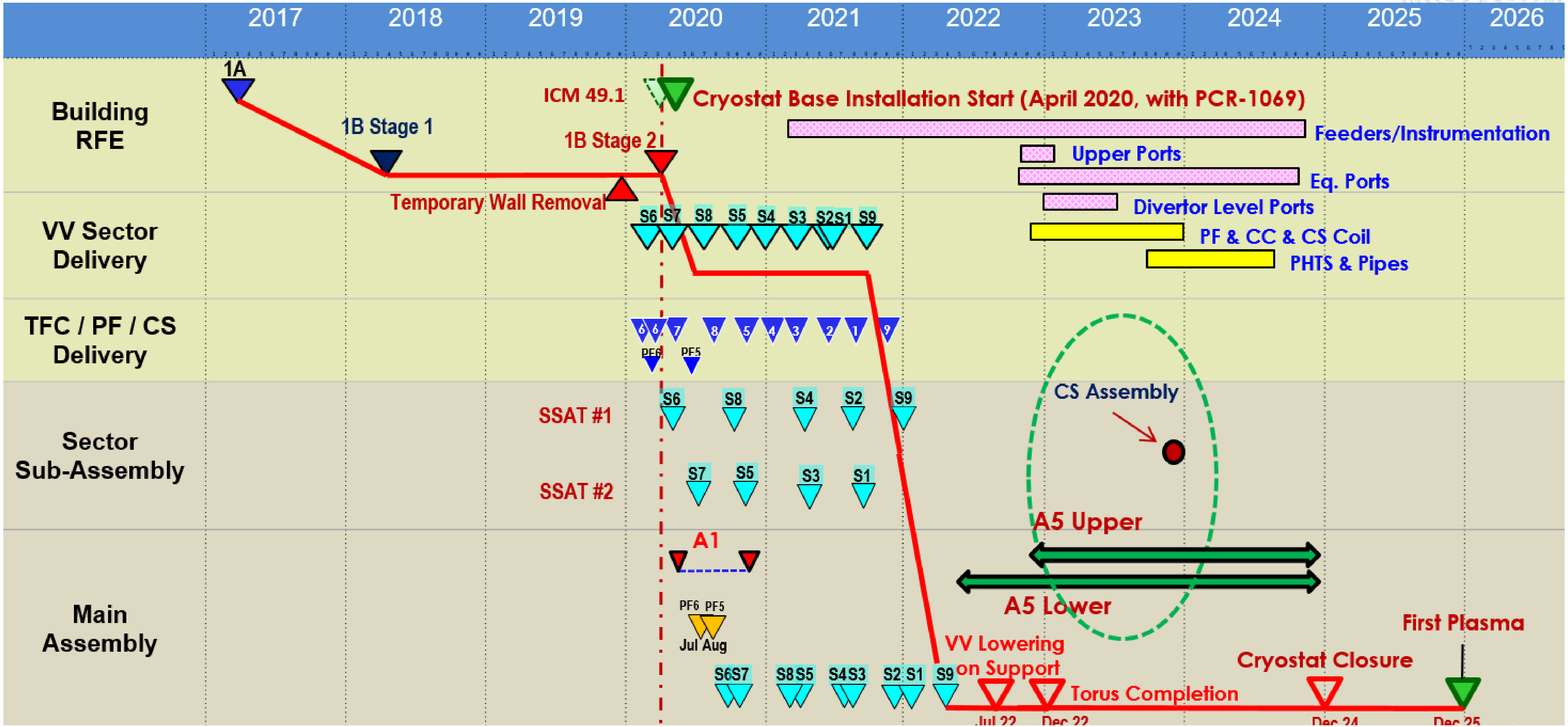


www.iter.org

ITER



ITER planning



ITER Assembly

- https://www.iter.org/construction/TokamakAssembly


Thermal Shields, 01/2021


Installation of lower cryostat part, 05/2020

ITER Assembly

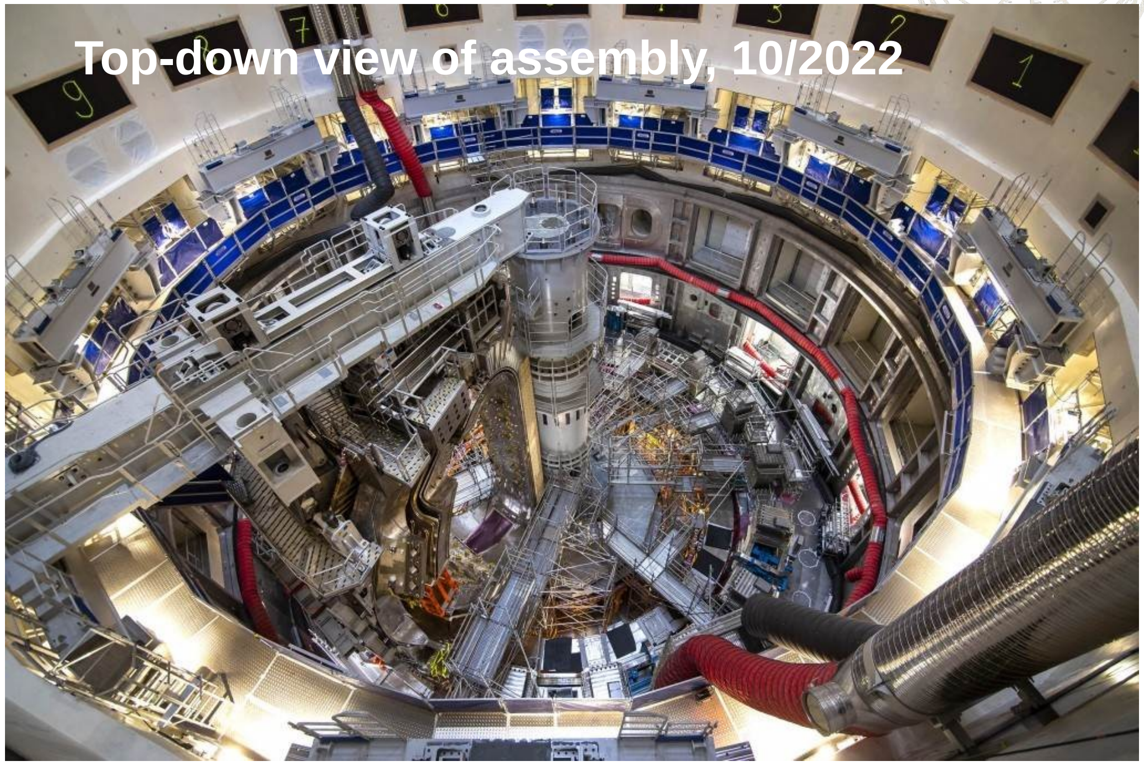
- https://www.iter.org/construction/TokamakAssembly


Las Vacuum Vessel, 09/2021

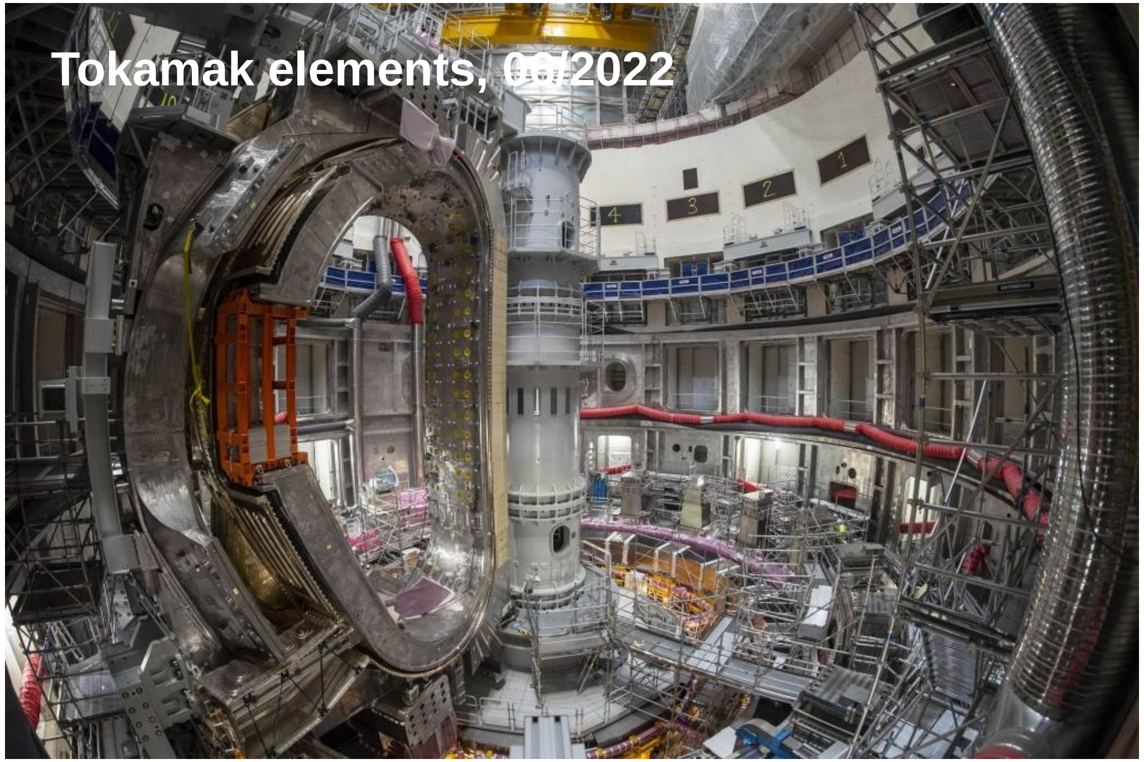

Poloidal Field coil #5, 09/2021

ITER Assembly

- https://www.iter.org/construction/TokamakAssembly



Top-down view of assembly, 10/2022



Tokamak elements, 06/2022

Comparison

Parameter	**Tore Supra**	**JET**	**ITER**
Plasma max radius (m)	2,25	3	6,21
Plasma small radius (m)	0,7	1,25	2
Plasma volume (m^3)	25	155	837
Plasma current (MA)	1,7	5-7	15
Magnetic Field (T)	4,5	3,4	5,3
Pulse duraction (s)	minute(s)	10	> 300
Plasma type	D-D	D-D/D-T	D-T
Fusion Power	~ kW	50kW/ 10MW	500 MV
$Q = P_{fus} / P_{ext}$	~ 0	~ 1	> 10
Output neutron power	20 W/m^2	60 kW/m^2	0.57 MW/m^2

Fusion energy in the news

- Very furnished news-feed, e.g.:
- https://www.newscientist.com/article-topic/nuclear-fusion/
- https://www.fusionindustryassociation.org/fusion-in-the-news
- Private funding now entering in the business

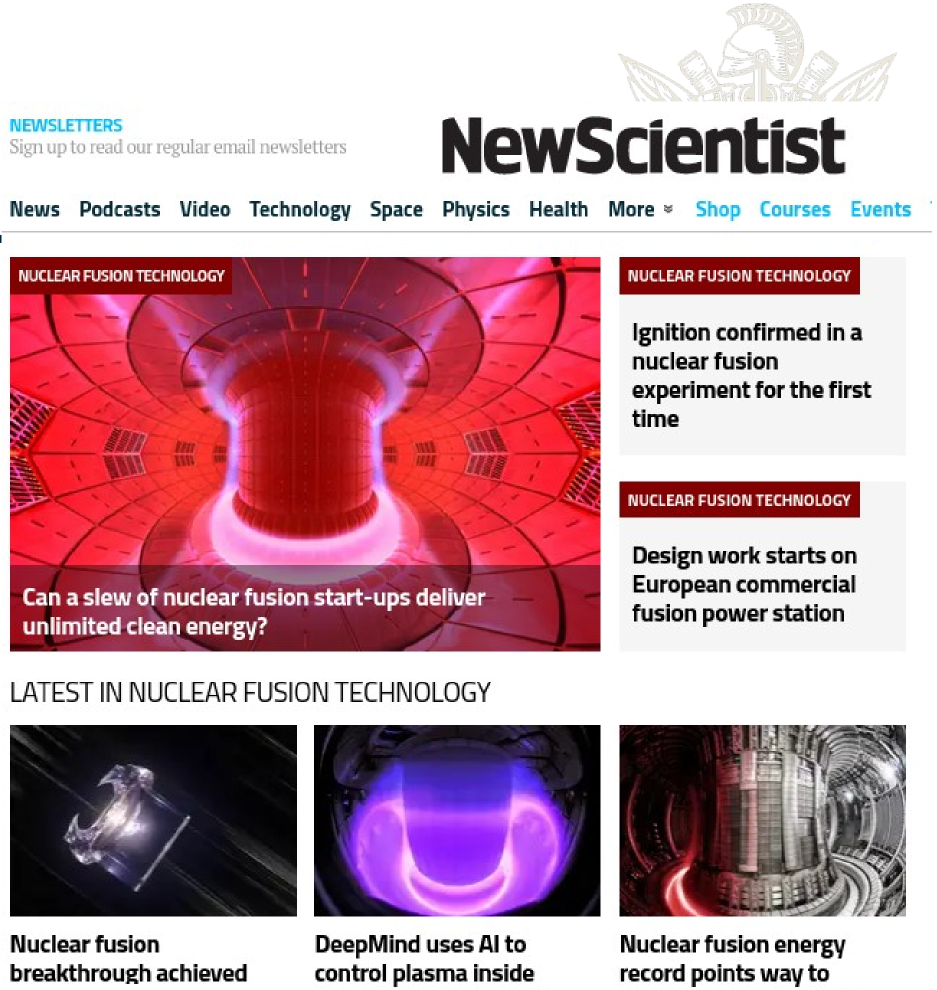
China's Artificial Sun Just Broke a Record for Longest Sustained Nuclear Fusion

Superheated plasma reached 126 million degrees Fahrenheit for 17 minutes

Elizabeth Gamillo

Daily Correspondent

January 10, 2022



NEWSLETTERS

Sign up to read our regular email newsletters

NewScientist

News Podcasts Video Technology Space Physics Health More Shop Courses Events

NUCLEAR FUSION TECHNOLOGY

Can a slew of nuclear fusion start-ups deliver unlimited clean energy?

NUCLEAR FUSION TECHNOLOGY

Ignition confirmed in a nuclear fusion experiment for the first time

NUCLEAR FUSION TECHNOLOGY

Design work starts on European commercial fusion power station

LATEST IN NUCLEAR FUSION TECHNOLOGY

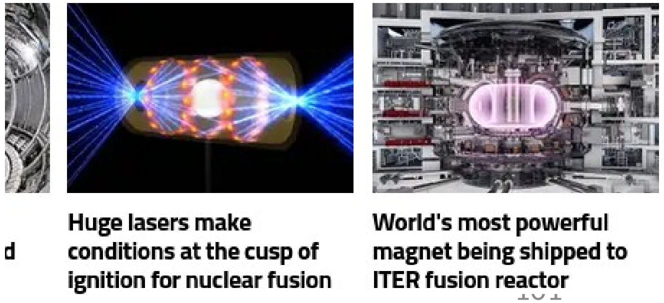
Nuclear fusion breakthrough achieved

DeepMind uses AI to control plasma inside tokamak fusion reactor

Nuclear fusion energy record points way to harnessing power of the sun

Nuclear fusion energy record points way to harnessing power of the sun

The nuclear fusion experiment at the Joint European Torus in Oxford on 21 December saw a ball of super-hot plasma sustained for 5 seconds, producing a record 59 megajoules of heat energy. JET's past record was 22 megajoules for less than a second, set in 1997.



d

Huge lasers make conditions at the cusp of ignition for nuclear fusion

World's most powerful magnet being shipped to ITER fusion reactor

Lecture 5 – Nuclear Energy

I. Basics of nuclear physics

II. Fission Power Plants

III. Fast Breeders – Generation IV

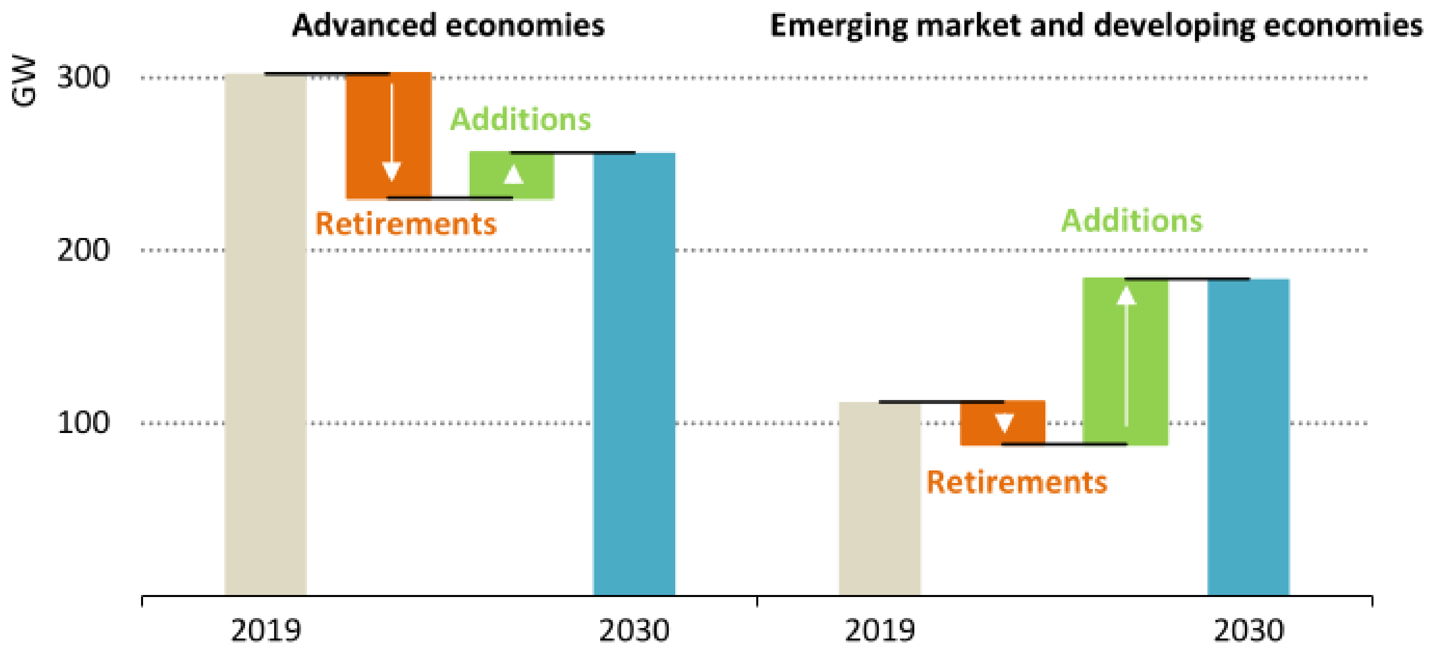
IV. Fusion Energy, current status, challenges and outlook

V. Conclusions

Evolution of nuclear share

- Shrinking in advanced economies, growing in developing countries
- Energy-crisis (COVID + War)
  ⇒ Renewed interest
  e.g.: 2022: announcement of construction of 6 new EPR2 reactors in France

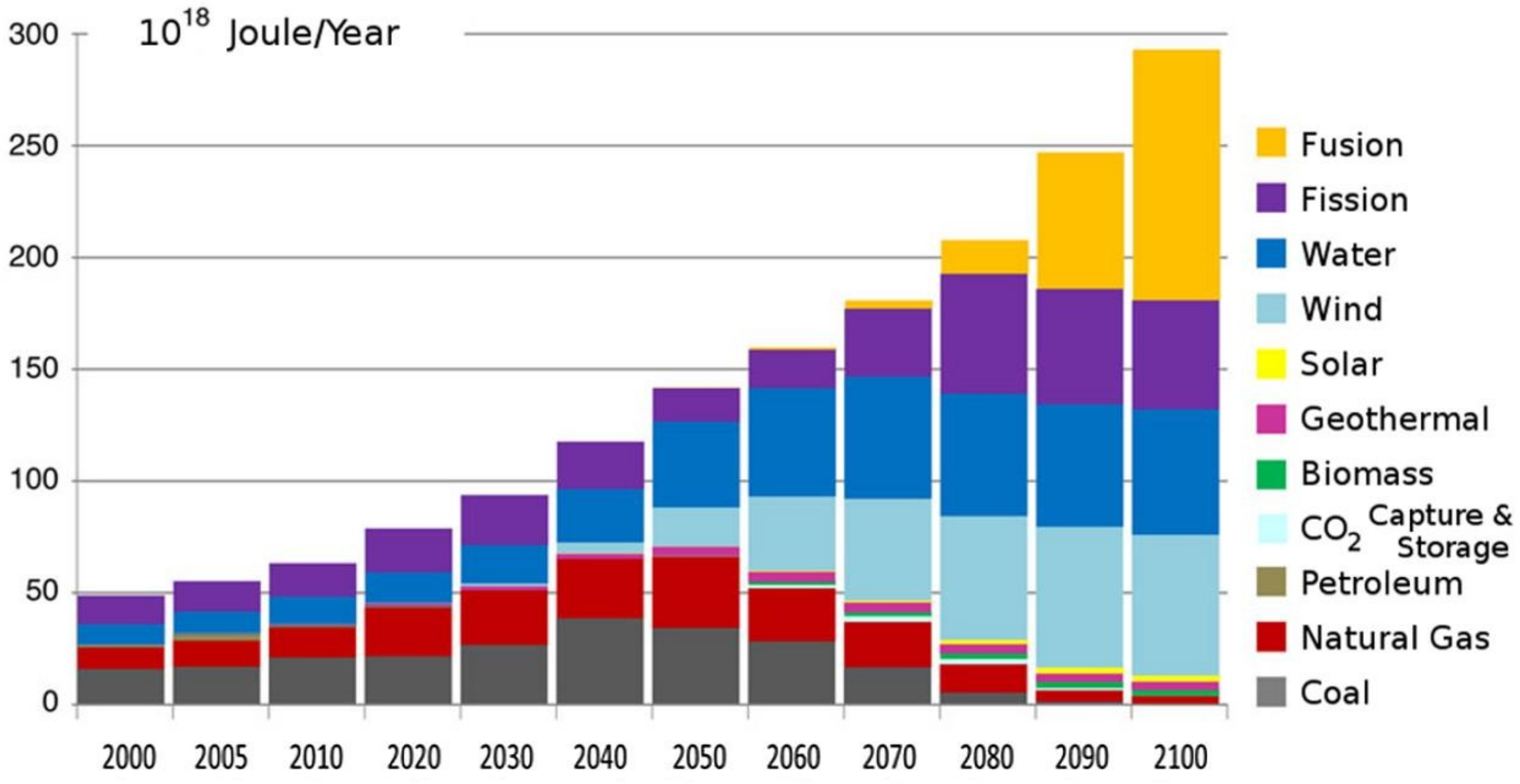
Figure 6.14 ▷ Nuclear power installed capacity, capacity additions and retirements in the Stated Policies Scenario, 2019-2030



Over the next decade, the fleet of nuclear reactors shrinks in advanced economies and most additional capacity is in emerging market and developing economies, led by China

Optimistic Outlook

- Fission expected to play a role in energy transition during a few decades
- Fusion making huge progresses
- Commercial fusion plants being deployed around 2070 and taking over



Take home message

- Fission nuclear reactors expected to play an important role in energy transition, providing large amounts of de-carbonated electricity
- Generation IV projects would increase energy efficiency, fuel availability and safety
- Fusion energy research making huge progresses, still very complicated and expensive devices, could take over by the end of the century

Last Word

“The problem I hope scientists will have solved by the end of the century is nuclear fusion. It would provide an inexhaustible supply of energy without pollution or global warming.”

Stephen Hawking, September 2010