nuclear energy: reactors and weapons

an introduction

Cyprus, April 2019

nuclear weapons

A nuclear weapon is a device with explosive energy derived from nuclear fission or a combination of fission and fusion processes.

Nuclear explosions cause catastrophic damage:

- immediate
  - high temperature thermal radiation
  - prompt ionizing radiation
  - destructive shocks
- long lasting
  - radioactive fall-out

nuclear weapons

remain the “real” arms of mass destruction for their unique concentration of power and destructive effects.

Since the 1940s they have been, and still are, a continuous threat to mankind

- they exist in large numbers
- they are deployed in several countries
- new countries in critical areas are considering their acquisition
- they substain military confrontation
- they stress the international relations

unique power

a highly inefficient weapon (≈ 1.3%) destroyed Hiroshima within a few seconds

a device tested at Bikini Atoll (1 March 1954) evaporated an island and caused substantial contaminations over an area of more of 18,000 square km

on 13 February 2013 a “small” nuclear device detonated underground in North Korea generated a ≈ 5 magnitude earthquake detected all over the world

the sources of nuclear energy

nuclear weapons are based on the most energetic processes existing in nature:

- the fission (splitting) of special heavy elements
- the fusion of light elements in heavier ones

these reactions take place between the nuclei of the relevant atomic elements

luckily, nuclear weapons are difficult to be produced

- the physics of the processes must be known in detail
- the fissile materials are rare or not-existing in nature and difficult and expensive to extract/produce
- fusion reactions are only possible in star-like conditions
- militarily operational weapons require sophisticated technologies

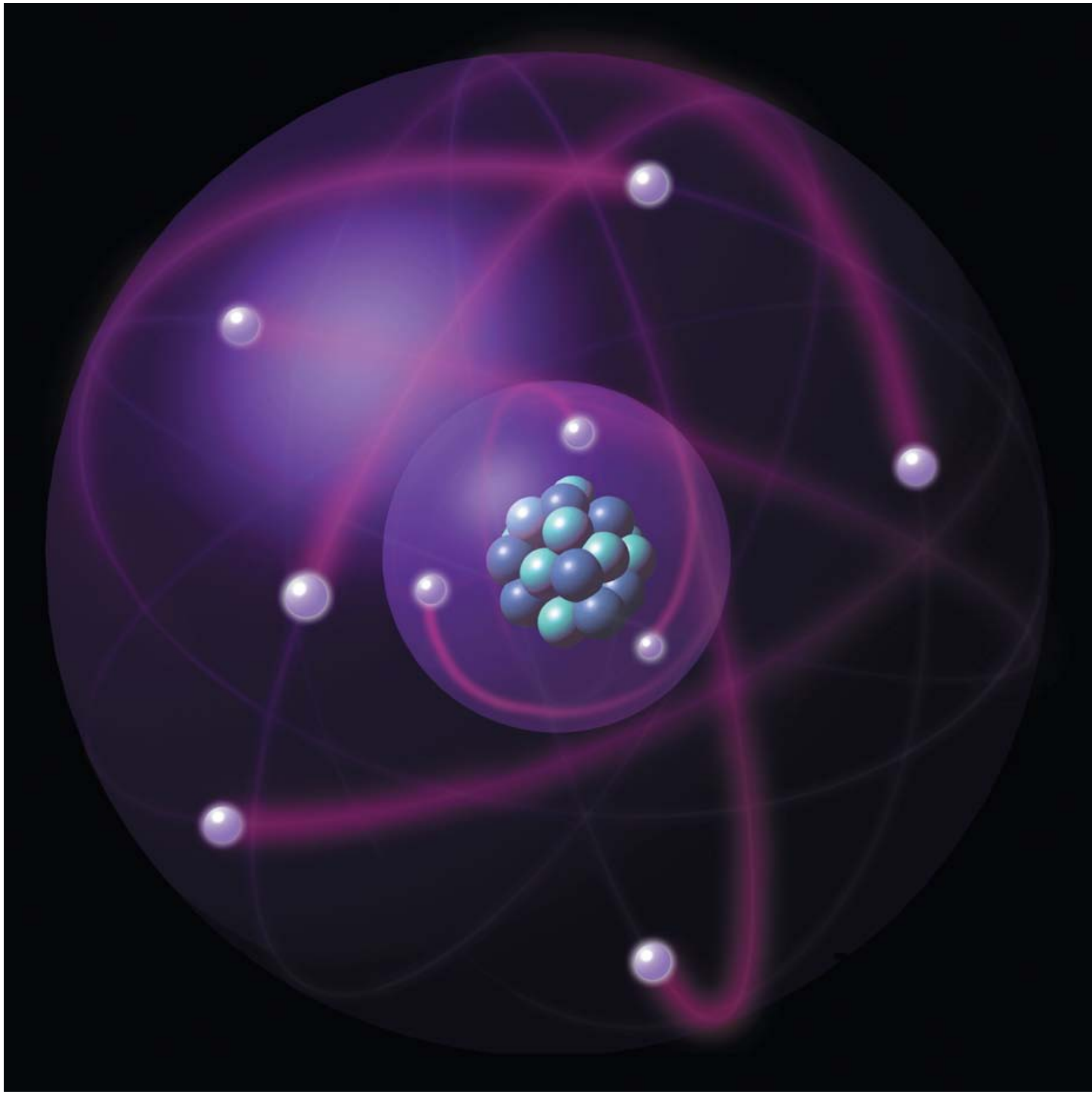
* pace for Ola Jonasson’s The Hundred-Year-Old Man Who Climbed Out the Window and Disappeared

the realm of relevant processes

an atom is composed by a central extremely small nucleus surrounded by a cloud of electrons;

nuclei are composed by two kinds of particles:

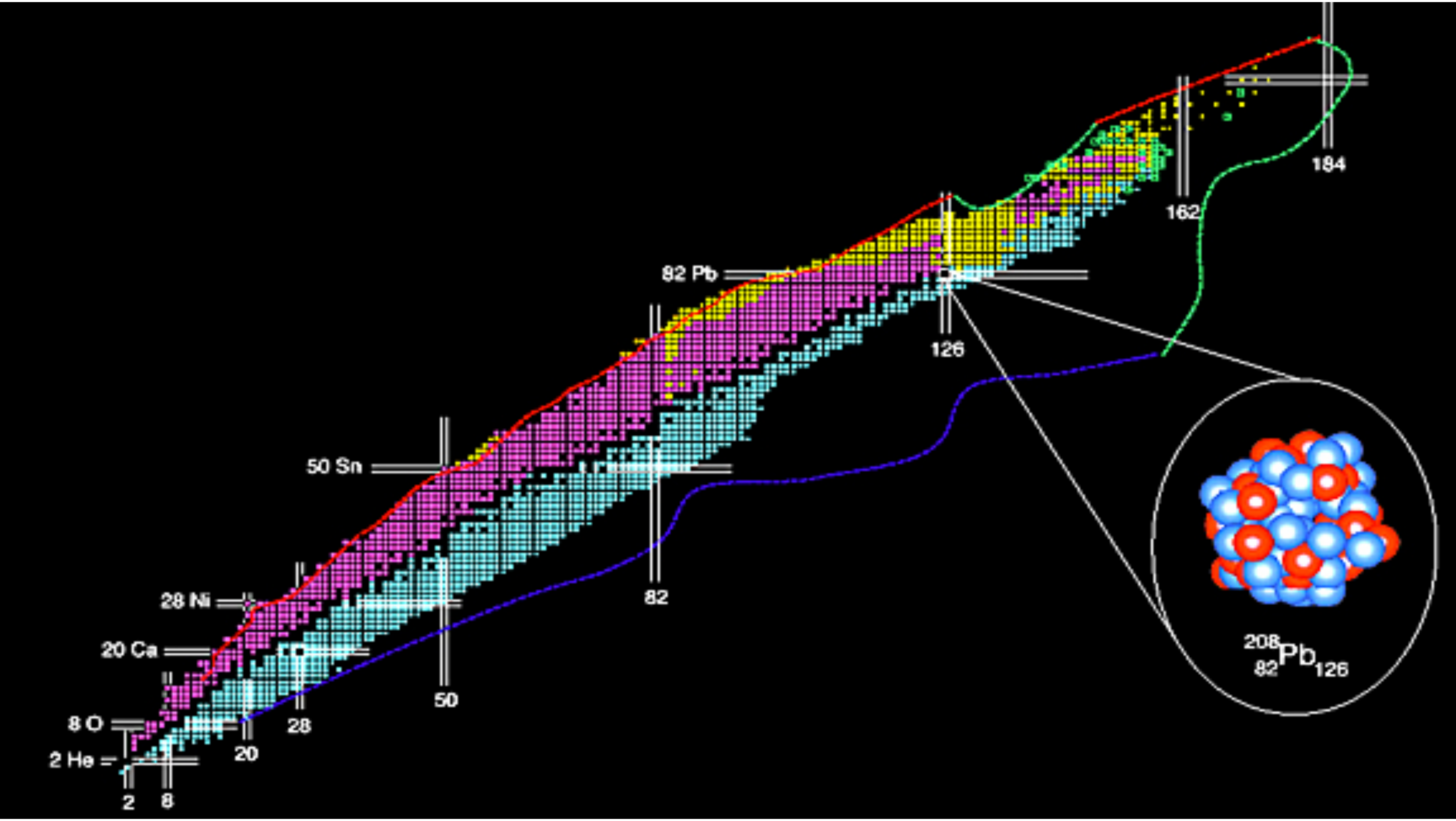
- electically charged protons and
- neutral neutrons



elements and isotopes

In nature 92 species of atoms exist (elements) of increasing mass from Hydrogen (H) to Uranium (U), characterized by a specific number of electrons
(1 for H and 92 for U).

The same element can exist with different nuclei, with a fixed number of protons (the same of the electrons) and a varying number of neutrons: the isotopes of the element



the isotopes are specified by the number of protons and the total number of particles in their nucleus

radioactivity

Several natural isotopes, and most of artificial ones, are radioactive: they transform into another species of nuclei with the emission of some kind of radiation.

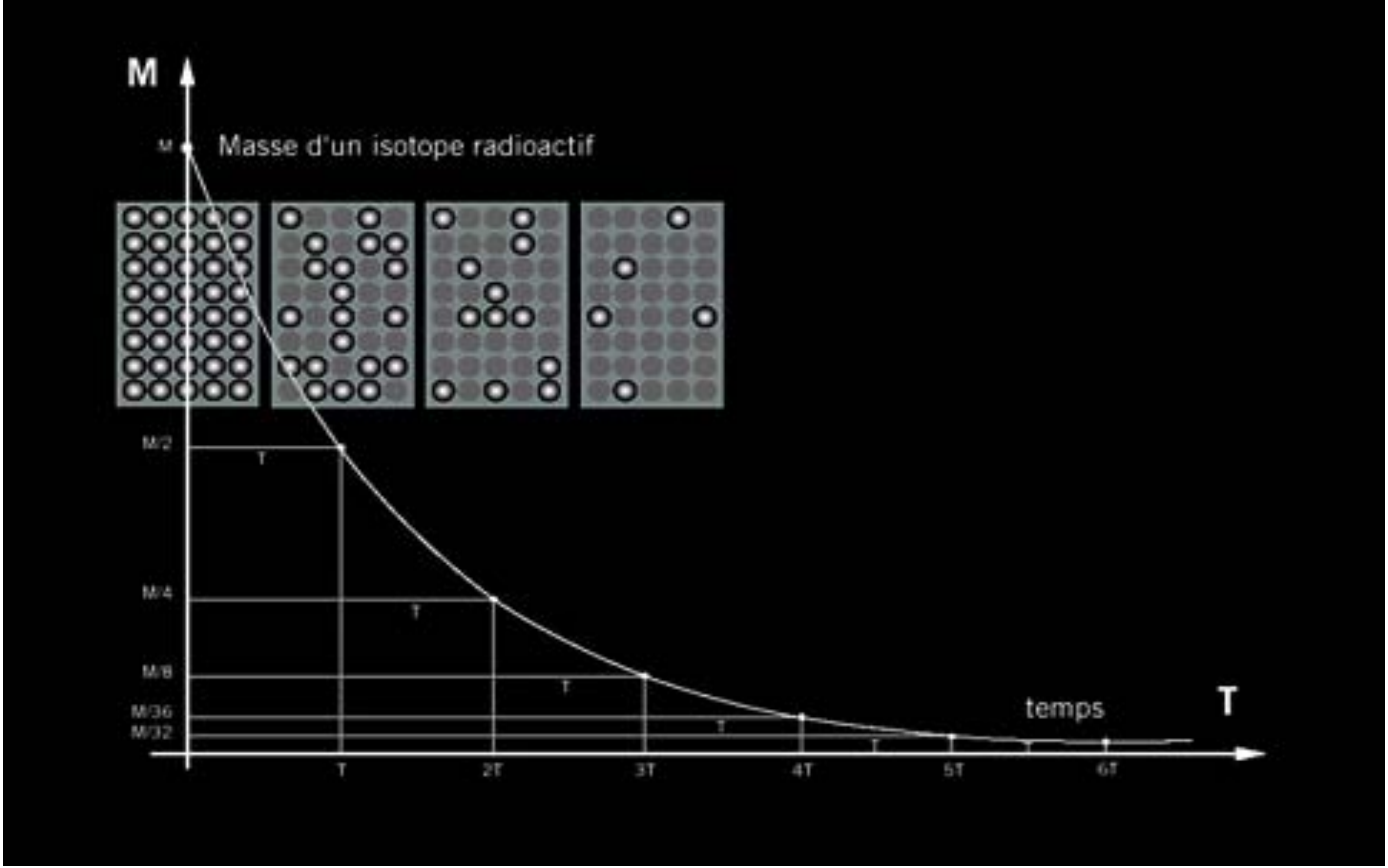
The process takes place with a constant characteristic probability. The half-life measures the time needed for the decay of one half of the radioactive nuclei present.

Measure of radioactivity

- ▻ Bequerel Bq = 1 decay per second
- ▻ Curie Ci = activity of 1 g of radium-226

  $1 \text{ Ci} = 3{,}7 \times 10^{10} \text{ Bq}$

The longer the half-life the smaller the activity



half-life: the time required for half of the material to undergo the specific process

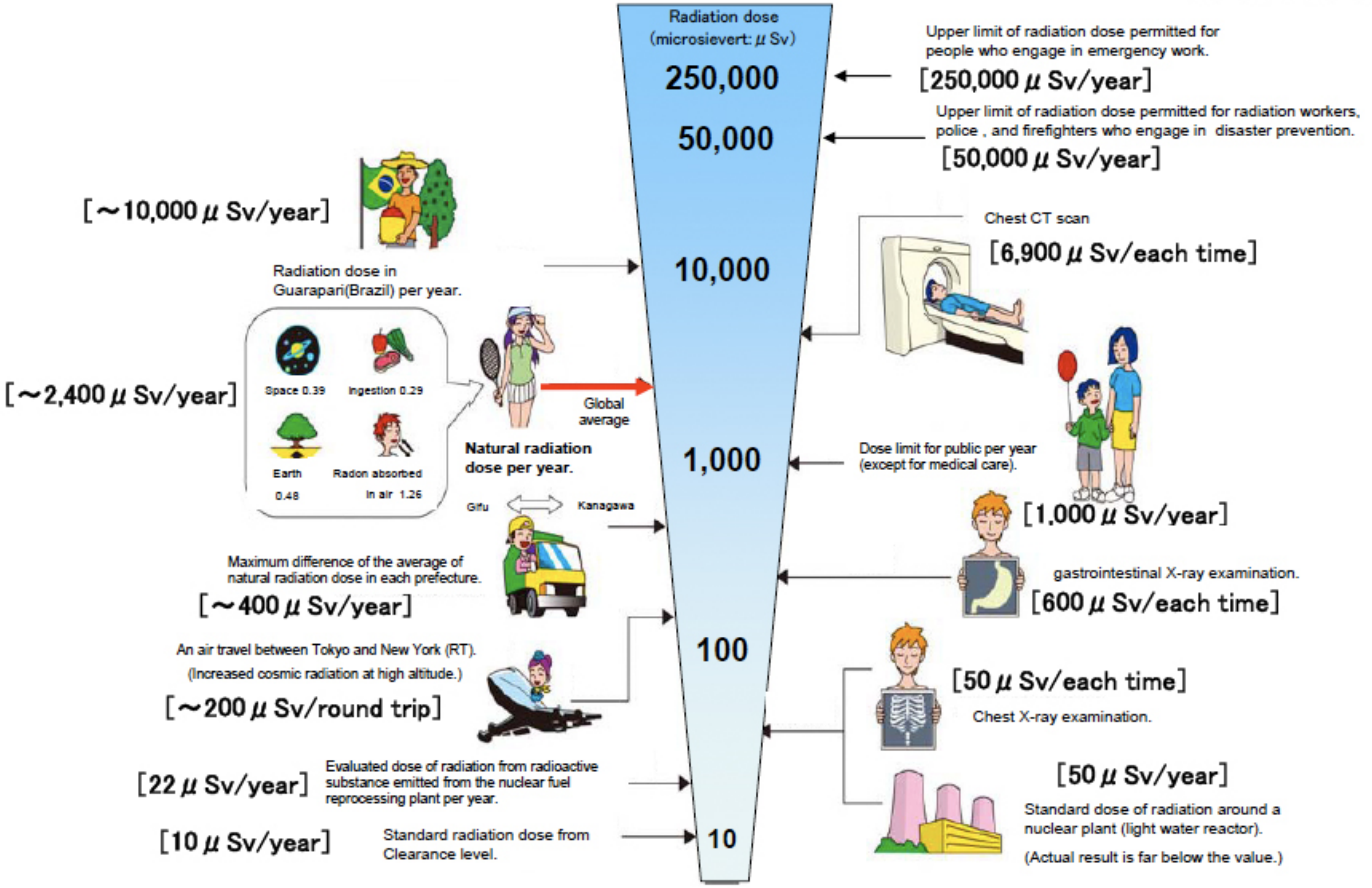
everything in nature is radioactive

human body contains radioactive potassium-40 and
radioactive carbon-14
in a person weighting 70 kg there are each second
3850 potassium disintegrations
4140 carbon disintegrations
about 8000 Bq

In addition, we receive radiations from the environment, the food, the working tools, the medical treatments, the sky (cosmic radiation) ...

Radiation in Daily-life

※Unit : μ Sv



Radiation dose (microsievert: μ Sv)

250,000

50,000

10,000

1,000

100

10

Upper limit of radiation dose permitted for people who engage in emergency work.
[250,000 μ Sv/year]

Upper limit of radiation dose permitted for radiation workers, police , and firefighters who engage in disaster prevention.
[50,000 μ Sv/year]

[～10,000 μ Sv/year]
Radiation dose in Guarapari(Brazil) per year.

Chest CT scan
[6,900 μ Sv/each time]

[～2,400 μ Sv/year]

Space 0.39

Ingestion 0.29

Earth 0.48

Radon absorbed in air 1.26

Global average

Natural radiation dose per year.

Dose limit for public per year (except for medical care).
[1,000 μ Sv/year]

Gifu ⟺ Kanagawa

Maximum difference of the average of natural radiation dose in each prefecture.
[～400 μ Sv/year]

gastrointestinal X-ray examination.
[600 μ Sv/each time]

An air travel between Tokyo and New York (RT).
(Increased cosmic radiation at high altitude.)
[～200 μ Sv/round trip]

[50 μ Sv/each time]
Chest X-ray examination.

[50 μ Sv/year]
Standard dose of radiation around a nuclear plant (light water reactor).
(Actual result is far below the value.)

[22 μ Sv/year] Evaluated dose of radiation from radioactive substance emitted from the nuclear fuel reprocessing plant per year.

[10 μ Sv/year] Standard radiation dose from Clearance level.

(Ref) Average dose rate at the monitoring post of Tokyo (3/17 9:00～3/18 9:00, March) : 0.050 μ Sv/h = 438 μ Sv/y

Table 2.1 Isotopes relevant to the nuclear arms race, together with some of their more important properties.[a]

Isotope	Half-life	Emissions	Major Properties
^{2}H	Stable	None	Fuel for the H-bomb
^{3}H	12.3 years	β: 18.6 keV; γ: 550 keV	Fuel for the H-bomb
^{6}Li	Stable	None	Produce T by $^{6}\mathrm{Li} + n \rightarrow {}^{3}\mathrm{H} + {}^{4}\mathrm{He}$
^{9}B	Stable	None	H-bomb tamper
^{14}C	5730 years	β: 156 kev	Produced from air by A-bombs
^{90}Sr	28 years	β: 546 keV; γ: 2.3 MeV	Fission product, bone seeker
^{131}I	8.05 days	β: 606 kev; γ: 364 keV	Fission product, thyroid seeker
^{137}Cs	30 years	β: 514 keV; γ: 662 keV	Fission product
^{233}U	165 kyrs	α: 5.3 MeV	Fissile material
^{235}U	710 Myrs	α: 4.4 MeV; γ: 185 keV	Fissile material, 0.7% of natural U
^{238}U	4500 Myrs	α: 4.2 MeV	"Contaminant" of ^{235}U
^{239}Pu	24.4 kyrs	α: 5.16 MeV	Fissile material
^{240}Pu	6580 yrs	α: 5.17 MeV	"Contaminant" of ^{239}Pu
^{242}Pu	380 kyrs	α: 4.9 MeV	"Contaminant" of ^{239}Pu

[a] The symbols kyrs and Myrs stand for 1000 and 1 million yr, respectively.

natural Uranium Z = 92

U-238 99.2745% $T_{1/2}$ 4.468×10^9 years

U-235 0.72% $T_{1/2}$ 7.038×10^8 years

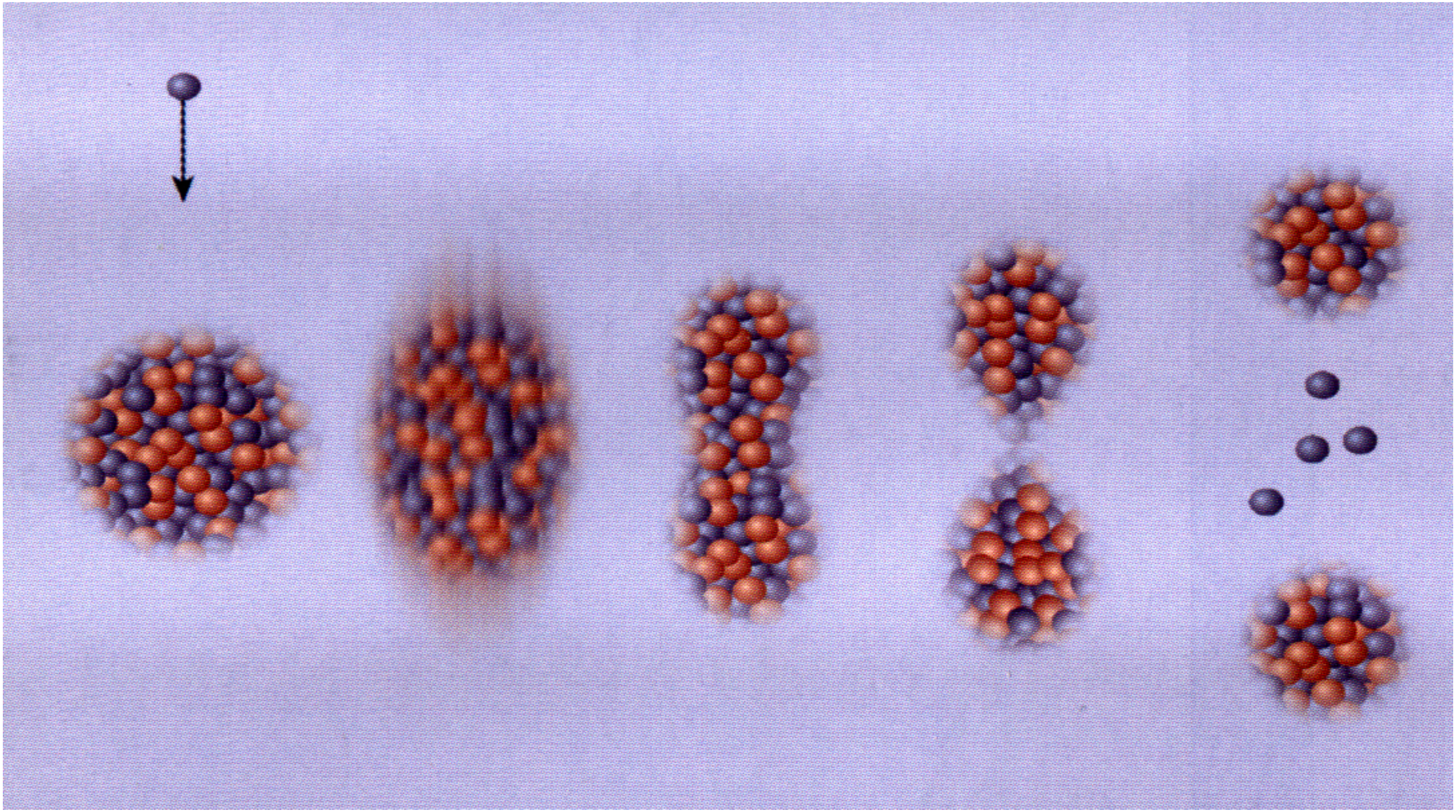
U-234 0.0055% $T_{1/2}$ 2.455×10^5 years

nuclear fission and fusion

fission occurs when a heavy isotope, after absorbing a neutron, transforms in a new isotope in an excited state and undergoes distortions and vibrations up to a complete splitting in two smaller nuclei; these are also instable and emit some neutrons to stabilize

fusion consists in the merging of two light nuclei to produce a new one; it is the process of the energy of the stars and of the synthesis of the elements starting from Hydrogen up to Iron; a relevant example

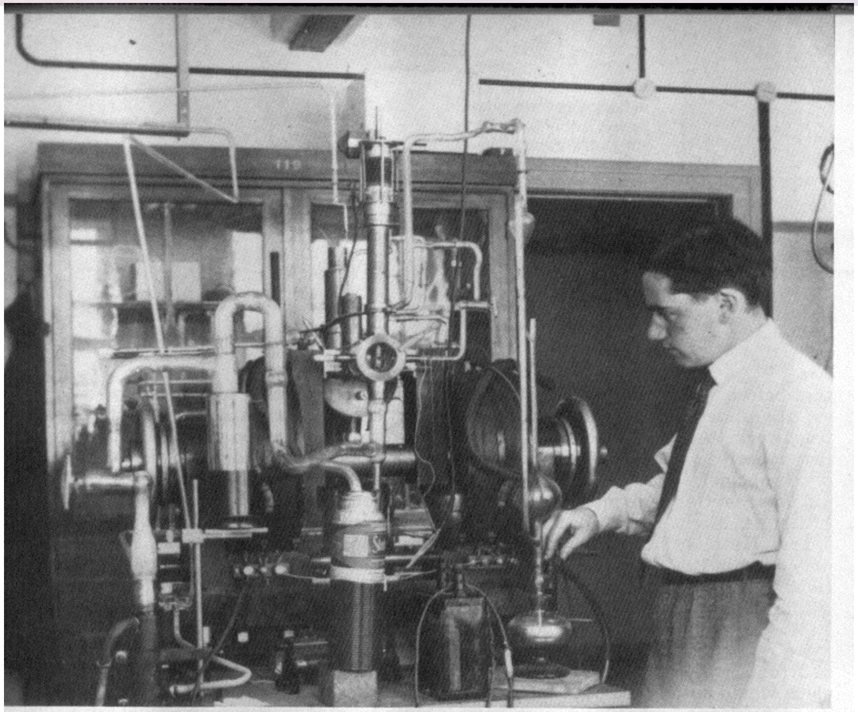
$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He\text{-}4} + \mathrm{n} + 17.6\ \mathrm{MeV}$$



nuclear fission

two characteristic fission reactions, among a large variety of possible outcomes

$$\left.\begin{aligned} U^{235} + n &\rightarrow \mathrm{Ba}^{139} + \mathrm{Kr}^{95} + 2n \\ &\rightarrow \mathrm{La}^{144} + \mathrm{Br}^{89} + 3n \end{aligned}\right\}$$



nuclear fission

the discovery of fission happened when the world was starting the second world war and its potential military relevance was immediately considered

- free basic research started in France, Germany, Japan, Russia and USA
- research programs with military objectives were first pursued in France and Germany, subsequently in UK and USA and finally in Japan and Russia
- only the Anglo-American program succeeded in achieving a fission weapon and in using it

the energy unit for atomic and nuclear processes
is the electronvolt eV
it is extremely small
1 eV = 1.6×10^{-19} joule = 3.822×10^{-20} calories

a wing-beat of a butterfly
requires an energy of
1 GeV (1 billion eV)

characteristic energies

combustion of one carbon atom	4.2 eV
explosion of one TNT molecule	11 eV
alpha radioactivity	4 MeV
nuclear fusion	20 MeV
nuclear fission	200 MeV

energy from the fission of 1 kg of U-235

the energy released in each process is small at macroscopic level, but the number of nuclei involved is extremely large

$$
\begin{aligned}
E &= 2.58 \times 10^{24} \text{ atoms} \times 200 \text{ MeV} \\
&= 2.58 \times 10^{24} \times 200 \times 10^{6} \times 1.6 \times 10^{-19} \text{ J} \\
&= 8.256 \times 10^{13} \text{ J} \approx 20 \text{ GWh} \\
&\approx 18 \text{ kton}
\end{aligned}
$$

an electro-nuclear plant of 1GWe power “burns”
U-235 at the rate of
around 47 mg every second
1.3 ton in a year

a coal electric plant of 1GWe power “burns” coal at the rate of
around 100 kg every second
3.2 million ton in a year

Problem 1:

only the rare isotope U-235 fissions after interaction with neutrons
→ the extraction of U-235 from natural uranium is extremely difficult and requires special technologies and huge quantities of energy

Problem 2:

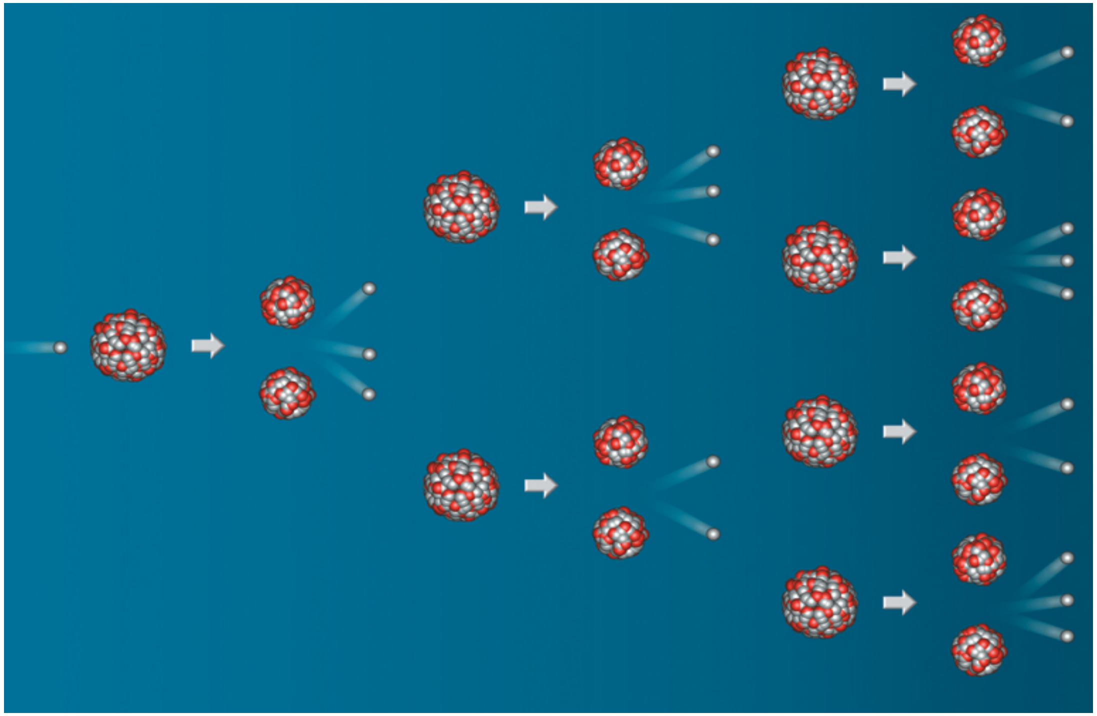
in order to fission 1 kg of U-235 as many neutrons are necessary as the number of nuclei of U-235, at least
$n > 2.58 \times 10^{24}$

→ no device exists able to produce such a flux of neutrons

Enrico Fermi and Frédéric Joliot:

the fission process itself can produce the needed neutrons in a “chain” reaction.

If every fission produces 2 neutrons and each of them induces a new fission, after 80 “generations” the number of neutrons is $n = 2^{80} \approx 1.2 \times 10^{24}$

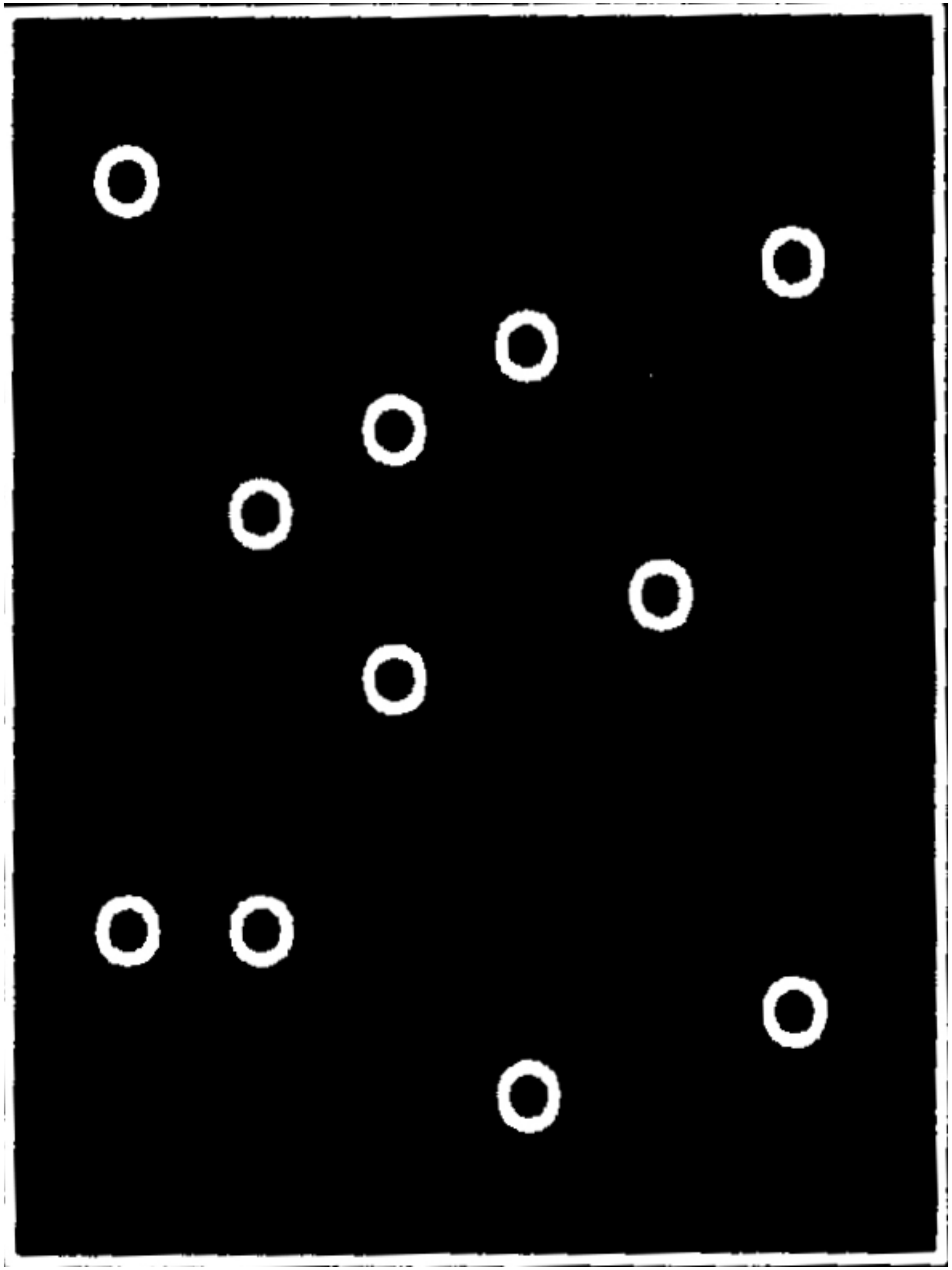


conditions for a chain reaction

- in each fission at least 2 neutrons have to be produced
- the neutrons must interact with the fissile uranium nuclei
  - ▹ a sufficiently quantity of U-235 is necessary
  - ▹ high purity of the materal
- the neutron-Uranium interaction has to lead to fission, not to competing processes
  - ▹ neutrons must have an optimal energy

Uranium is a dense material but the nuclei are very small and most of the material is empty space

→ neutrons can escape without interacting

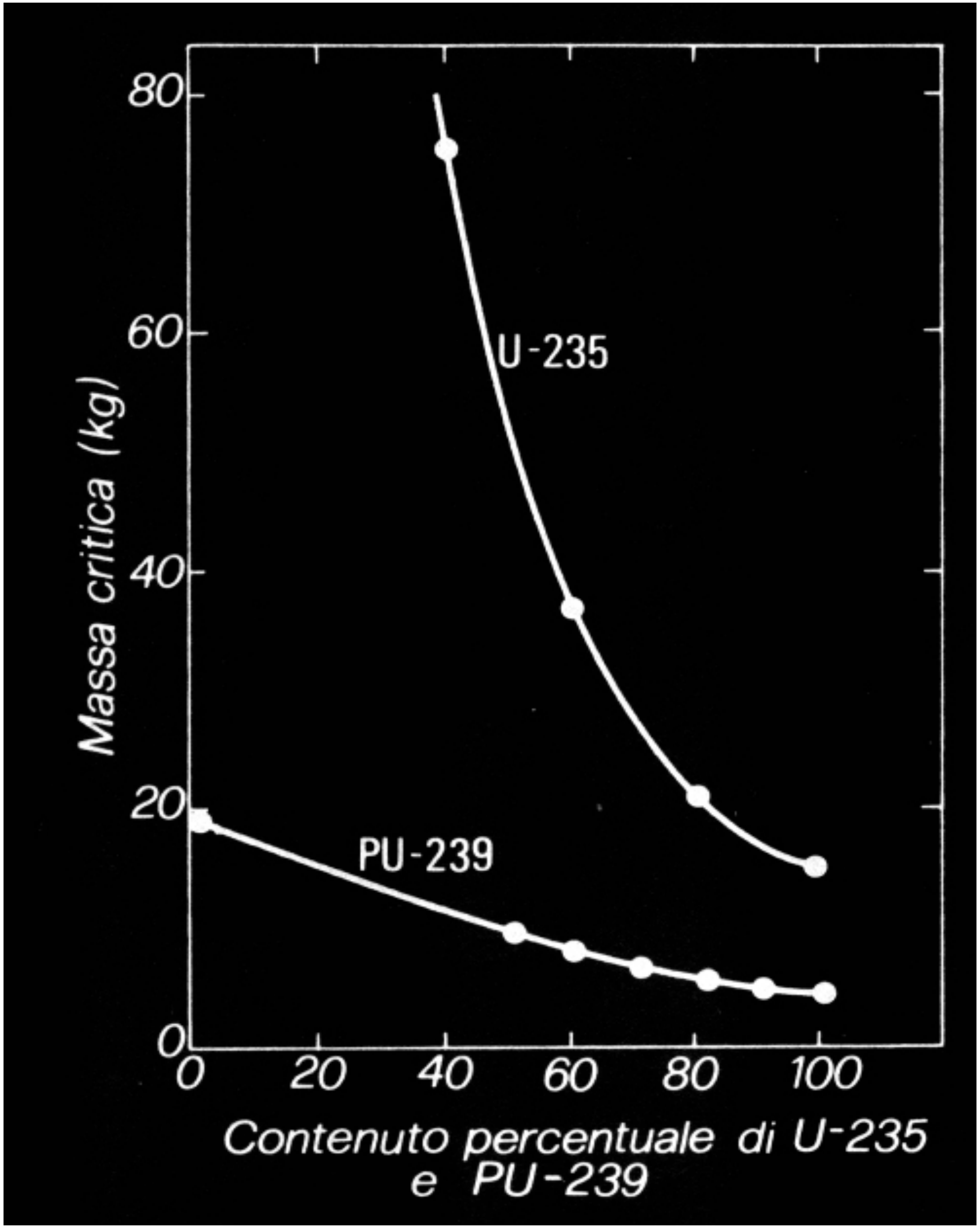


critical mass

in order to make the neutrons interact with the Uranium nuclei instead of escaping, or being captured, a minimum quantity of fissile material is necessary: the “critical mass”

the critical mass depends on the kind of fissile material and its density and on the structure of the device (neutron reflectors, tampers …)

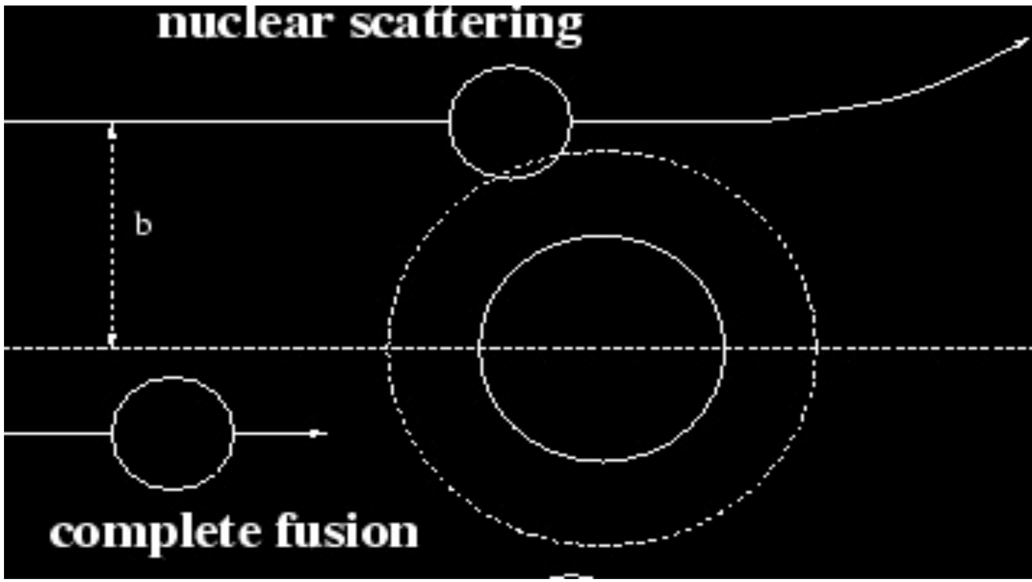
critical mass for Uranium and Plutonium of different purities



main competing processes in n-U interaction

- elastic or anelastic scattering
- absorption without fission

the relative frequency of competing processes depends on the energy of the neutrons

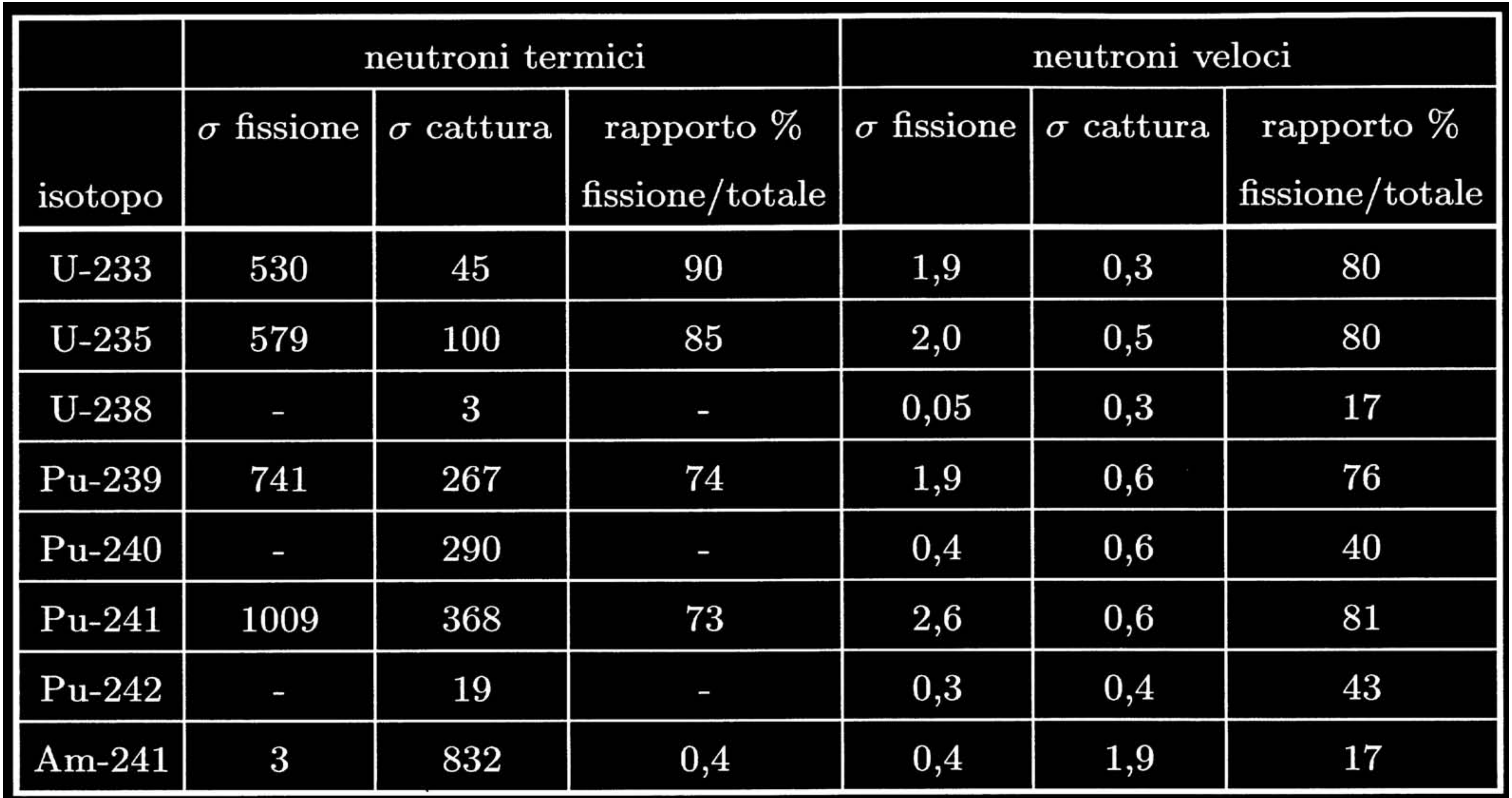


fast and thermal neutrons

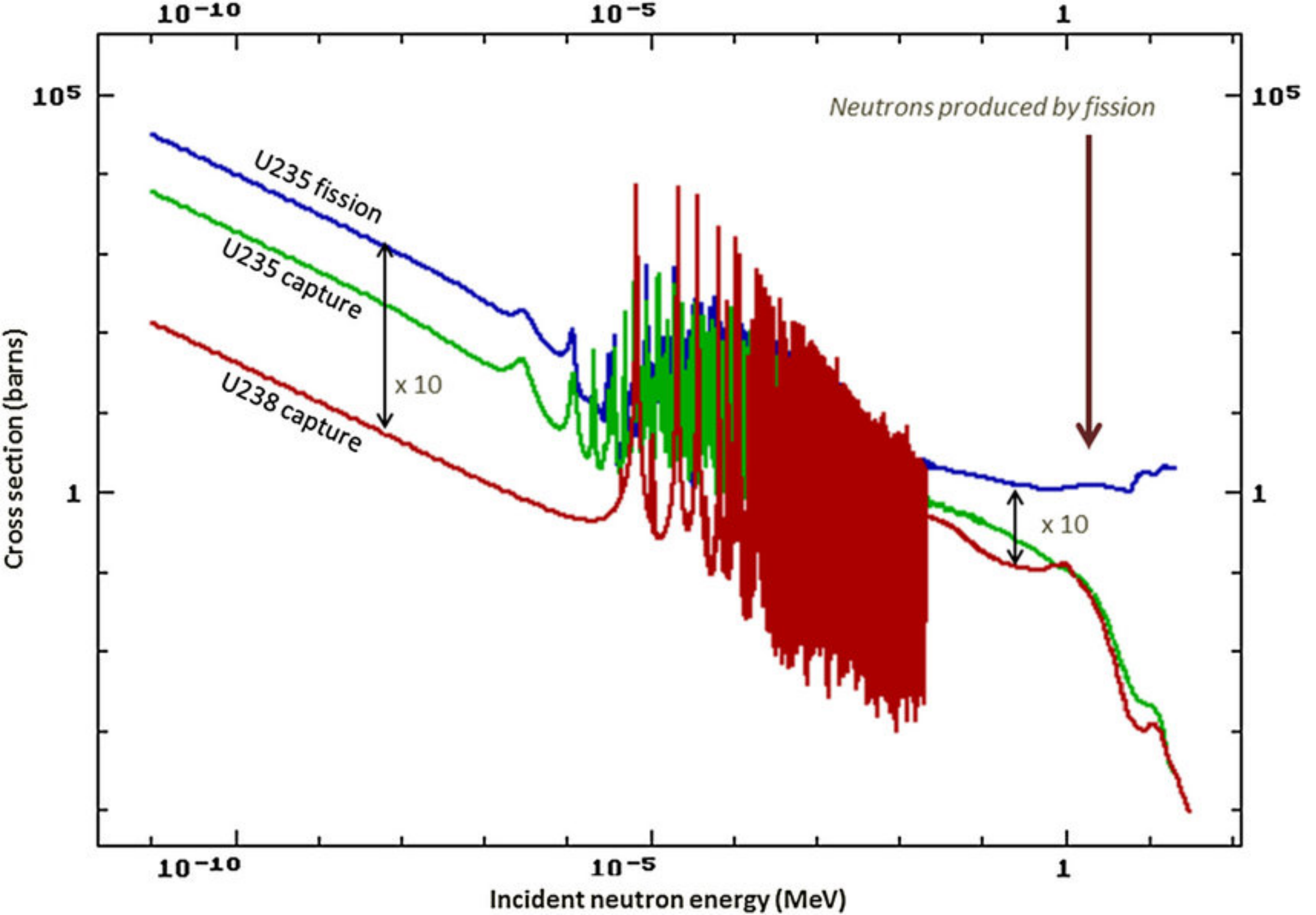
- the neutrons emitted in the fission process are “fast”
  - ▻ average energy 2 MeV
  - ▻ average velocity 20,000 km/s

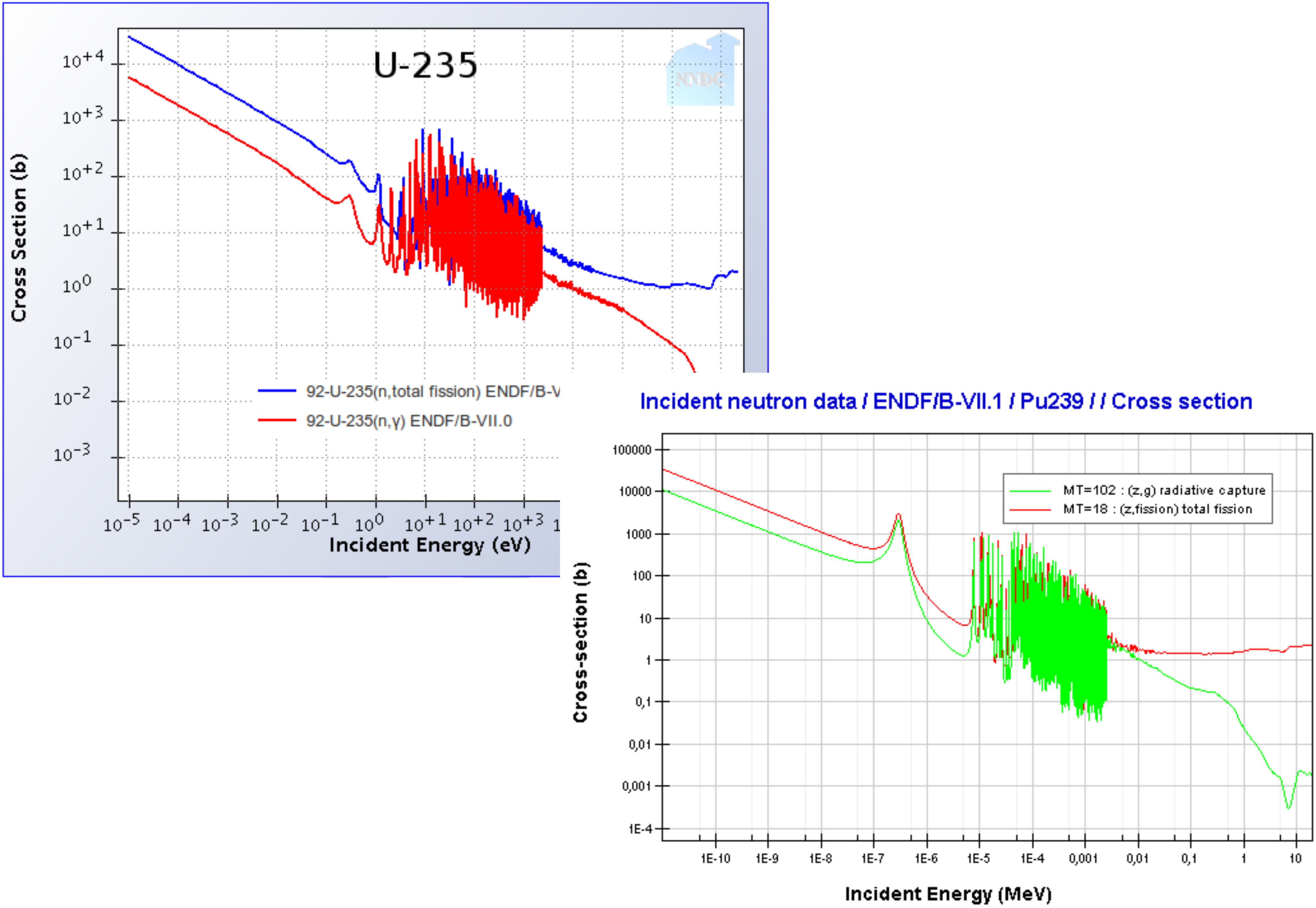
- thermal neutrons have the energy of the environment temperature
  - ▻ average energy 0.025 eV
  - ▻ average velocity < 2 km/s

relative probability of fission and capture in different fissile isotopes for slow and fast neutrons

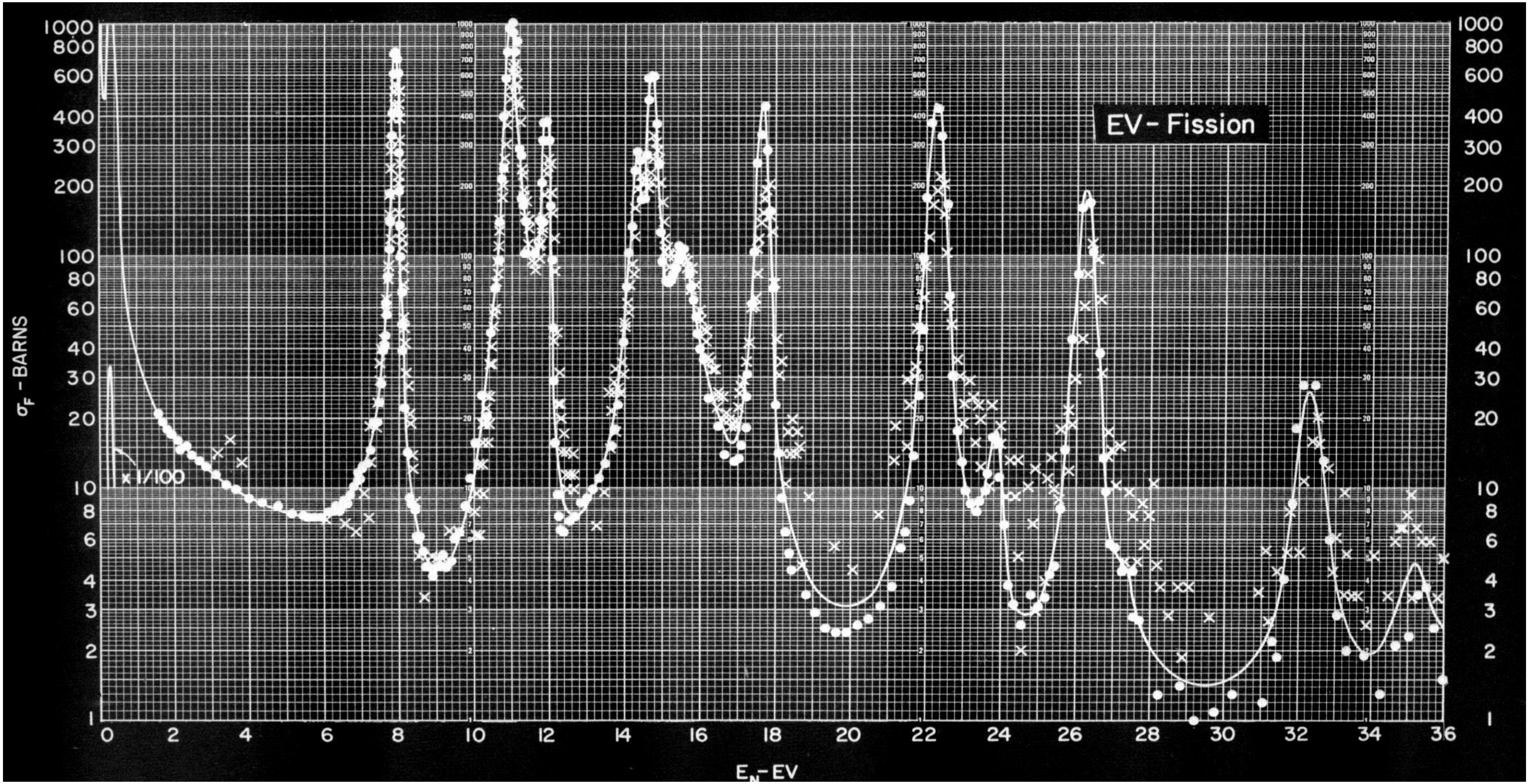


	neutroni termici			neutroni veloci		
isotopo	σ fissione	σ cattura	rapporto % fissione/totale	σ fissione	σ cattura	rapporto % fissione/totale
U-233	530	45	90	1,9	0,3	80
U-235	579	100	85	2,0	0,5	80
U-238	-	3	-	0,05	0,3	17
Pu-239	741	267	74	1,9	0,6	76
Pu-240	-	290	-	0,4	0,6	40
Pu-241	1009	368	73	2,6	0,6	81
Pu-242	-	19	-	0,3	0,4	43
Am-241	3	832	0,4	0,4	1,9	17

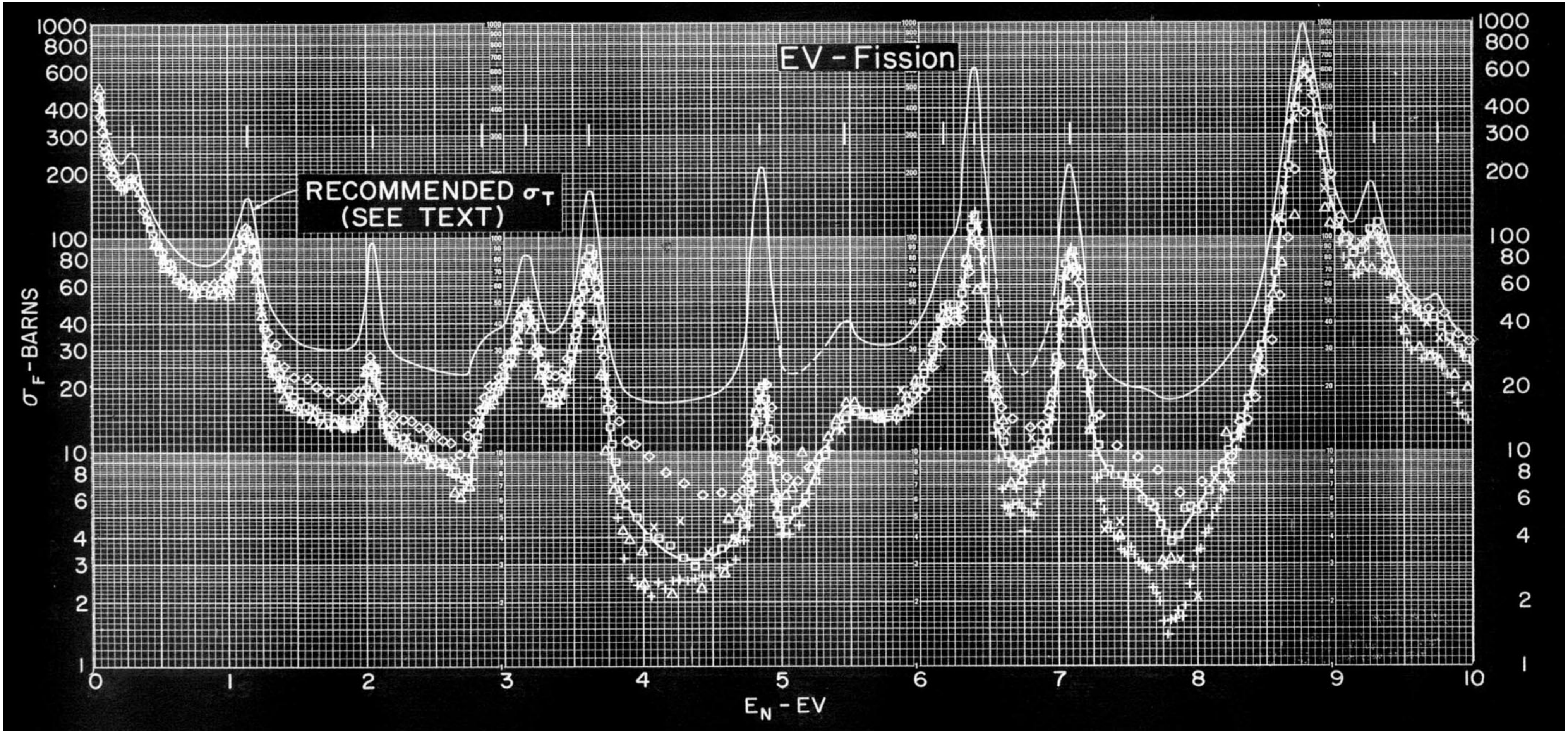

10^-10
10^-5
1
10^5
1
Neutrons produced by fission
U235 fission
U235 capture
U238 capture
x 10
x 10
Cross section (barns)
Incident neutron energy (MeV)


U-235
NNDC
Cross Section (b)
10^{+4}
10^{+3}
10^{+2}
10^{+1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
92-U-235(n,total fission) ENDF/B-V
92-U-235(n,γ) ENDF/B-VII.0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{+1}
10^{+2}
10^{+3}
1
Incident Energy (eV)
Incident neutron data / ENDF/B-VII.1 / Pu239 / / Cross section
MT=102 : (z,g) radiative capture
MT=18 : (z,fission) total fission
Cross-section (b)
100000
10000
1000
100
10
1
0,1
0,01
0,001
1E-4
1E-10
1E-9
1E-8
1E-7
1E-6
1E-5
1E-4
0,001
0,01
0,1
1
10
Incident Energy (MeV)

fission cross section for Pu as a function of neutron energy



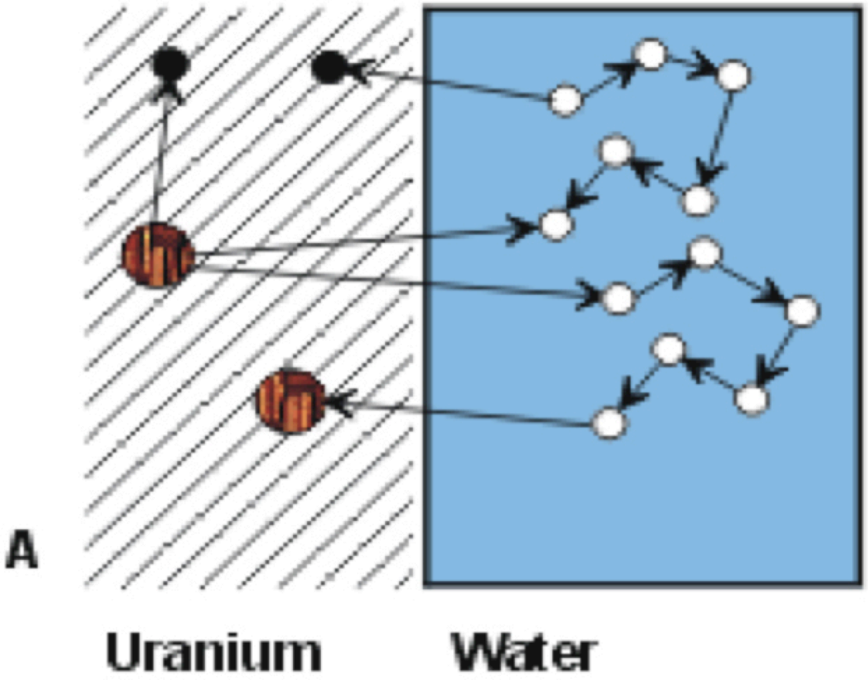
fission cross section for U-235 as a function of neutron energy

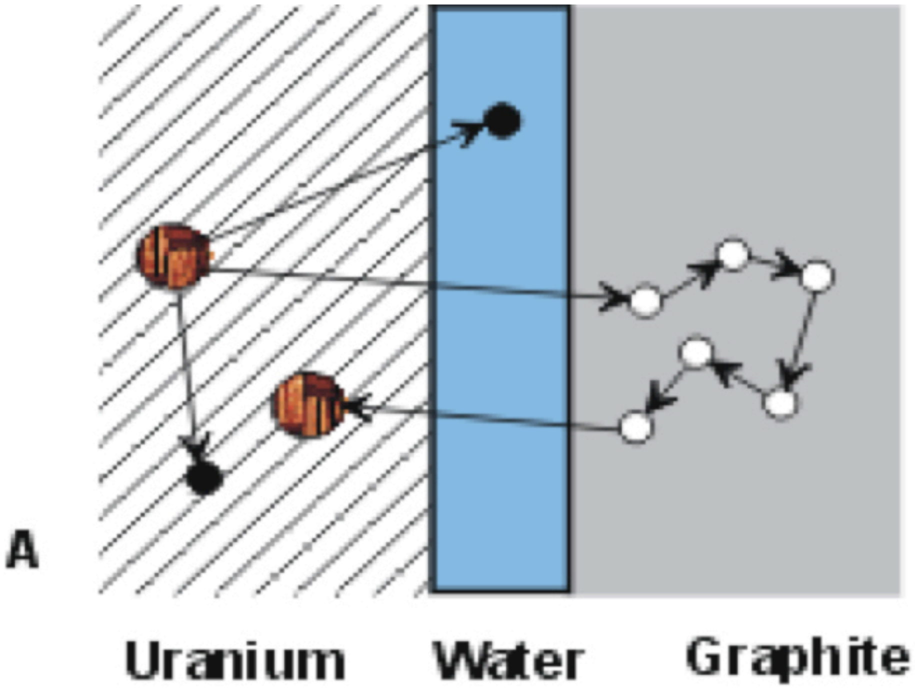


the probability of fission for thermal neutrons is near 300 times the probability for fast neutrons

- it is possible reduce the neutron velocity to thermal velocity by diffusion with light nuclei (Hydrogen, Deuterium, Boron, Carbon)
- Uranium elements have to be separated by a “moderator”, where neutrons loose energy (water, heavy water, graphite)
- thermalization takes time, several tens of microseconds

neutron moderation





in the case of graphite moderation, water is present as a coolant

properties of moderator elements

- the lighter the element, the more effective the transfer of energy of the neutron in the collision
  - ▻ the number of necessary collisions is proportional to (A +1)/2
- elements can absorb colliding neutrons
  - ▻ Hydrogen absorbs much more than Deuterium

	H_2O	Be	D_2O	C	Fe	Pb
α	-	0.64	-	0.72	0.93	0.98
ξ	0.93	0.21	0.51	0.16	0.04	0.01
Σ_s (1/cm)	1.50	0.87	0.37	0.38	0.96	0.37
Collisions to 1 eV	16	69	28	91	414	1450
Time to 1 eV (μs)	1.5	8.5	9.7	25	43	390

the moderation with graphite or heavy water allows a chain reaction in natural Uranium

natural reactors in Oklo (Gabon)

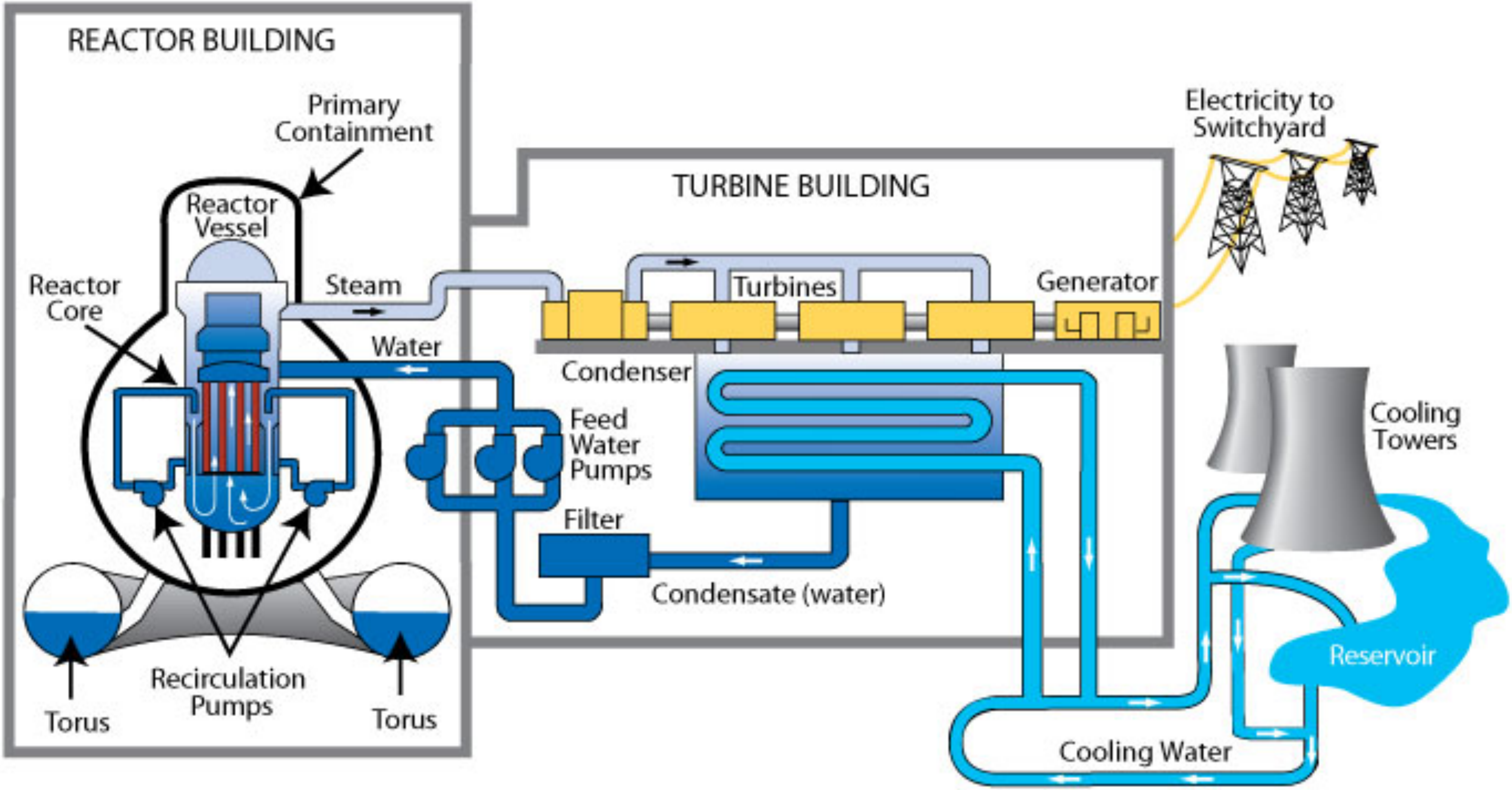
- 1950 milion years ago
- 17 natural reactors operating intermittently over a 150,000 year long period
- some 5 to 6 tons of Uranium burnt
- some 500 gigajoule energy produced (as a 1000 MWe reactor in 5 years)

the chain reaction parameter k

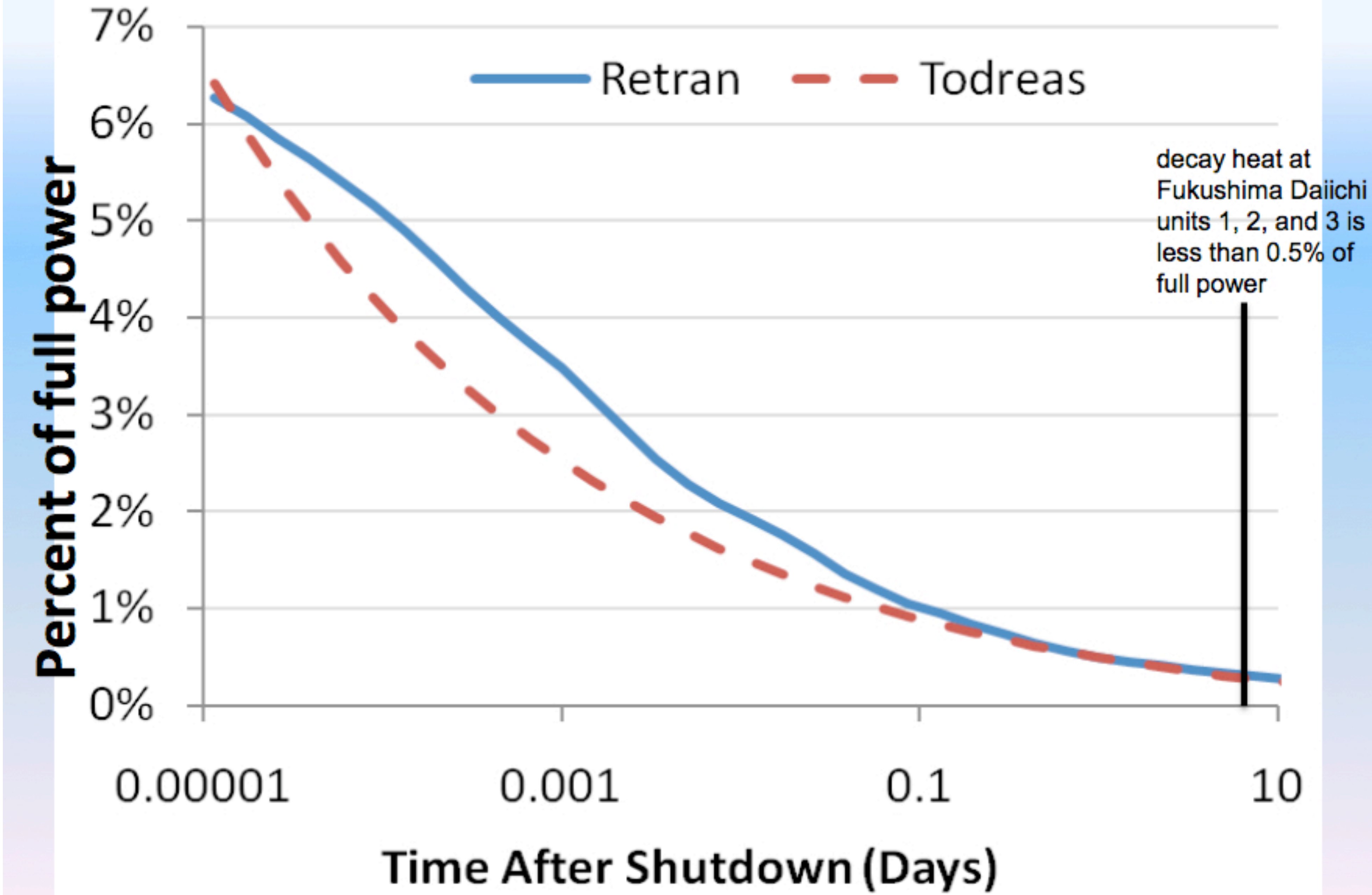
k, the "neutron multiplication numer",
gives the ratio between the number of neutrons in the current generation and the number of neutrons in the previous one
$k < 1$ sub-critical condition
$k = 1$ critical condition
$k > 1$ hypercritical condition
the chain reaction is only possible for k equal or larger then 1

the twofold way

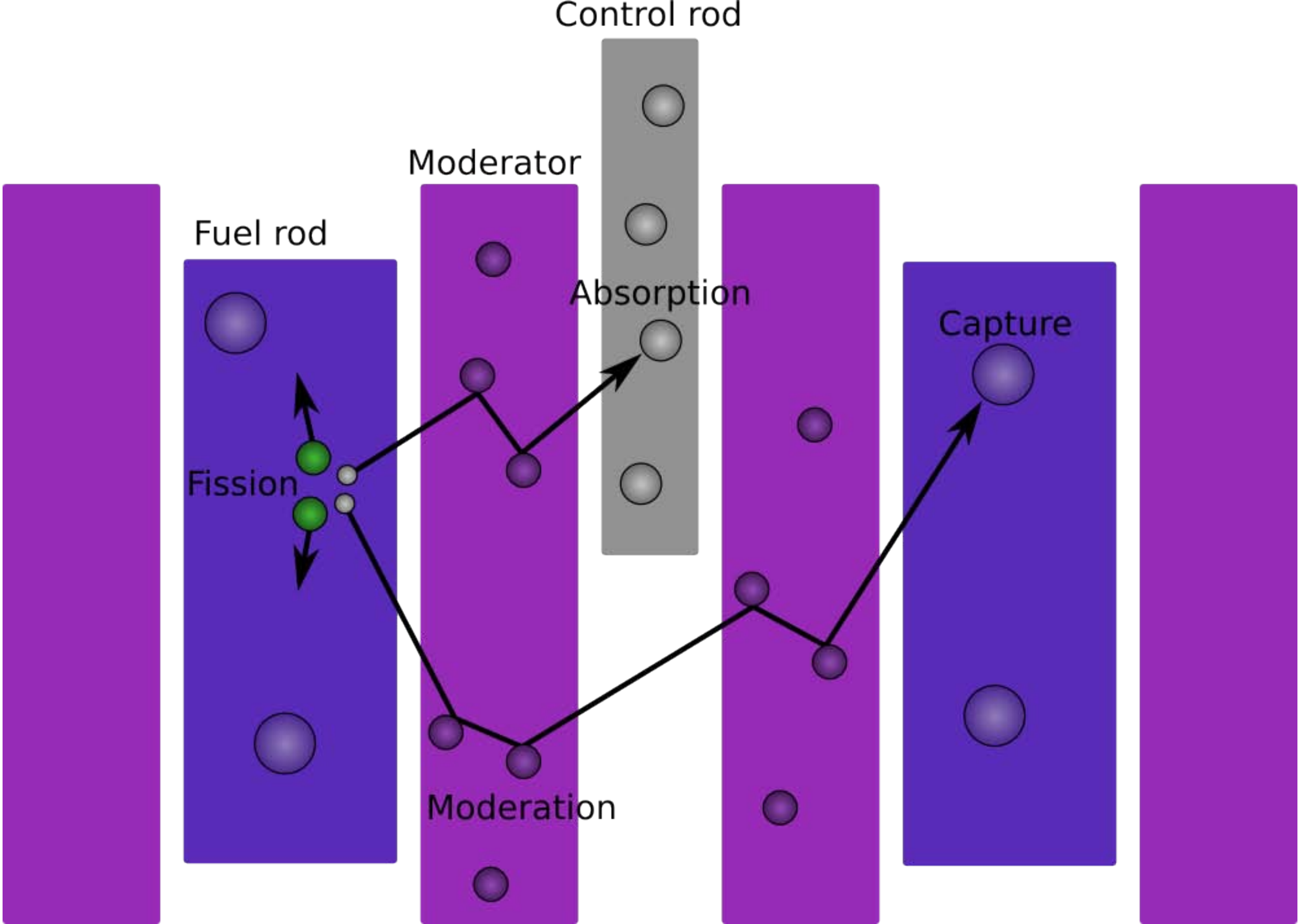
- thermal neutrons with moderator
  - ▻ high probability of fission and efficiency
  - ▻ Uranium oxide with a limited fraction of U-235
  - ▻ slow and controlled reaction $k \leq 1$
  - ▻ large dimension
  - ⇒ reactor
- fast neutrons without moderator
  - ▻ low probability of fission and efficiency
  - ▻ near pure U-235, U-233 or Plutonium-239
  - ▻ fast free reaction $k \gg 1$
  - ▻ compact dimension
  - ⇒ weapon


REACTOR BUILDING
Primary Containment
Reactor Vessel
Reactor Core
Steam
Water
Recirculation Pumps
Torus
Torus
TURBINE BUILDING
Turbines
Generator
Condenser
Feed Water Pumps
Filter
Condensate (water)
Electricity to Switchyard
Cooling Towers
Reservoir
Cooling Water

Decay Heat Generation After Shutdown



decay heat at Fukushima Daiichi units 1, 2, and 3 is less than 0.5% of full power


Control rod
Moderator
Fuel rod
Absorption
Capture
Fission
Moderation

fuel elements

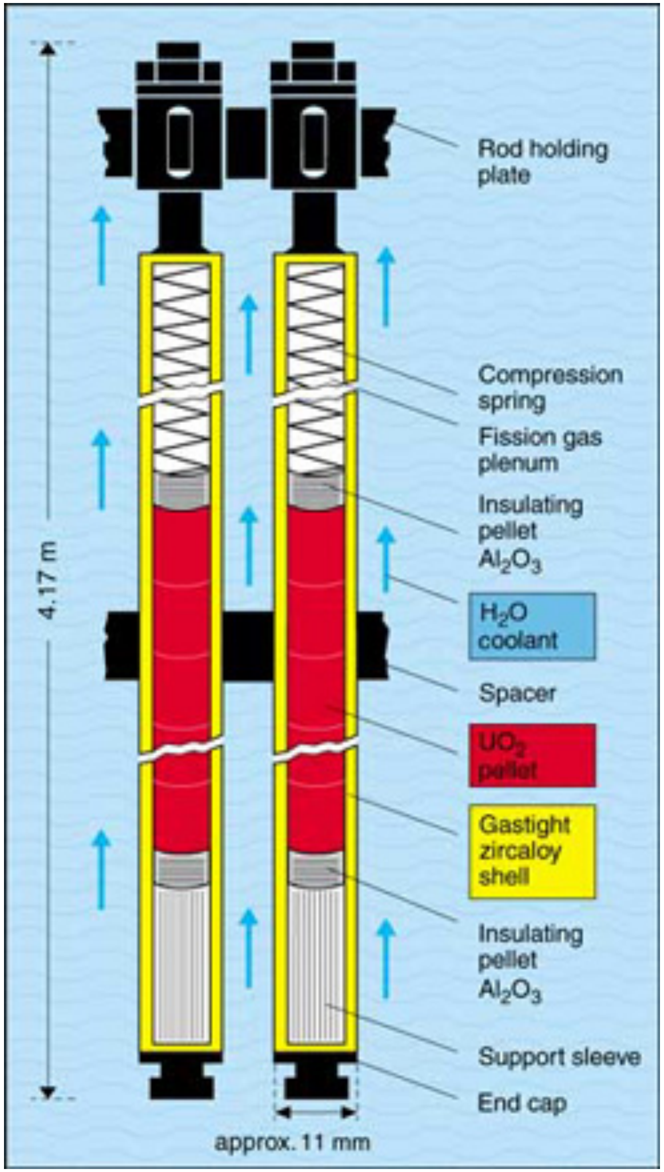
ceramic pellets of Uranium oxide UO_2

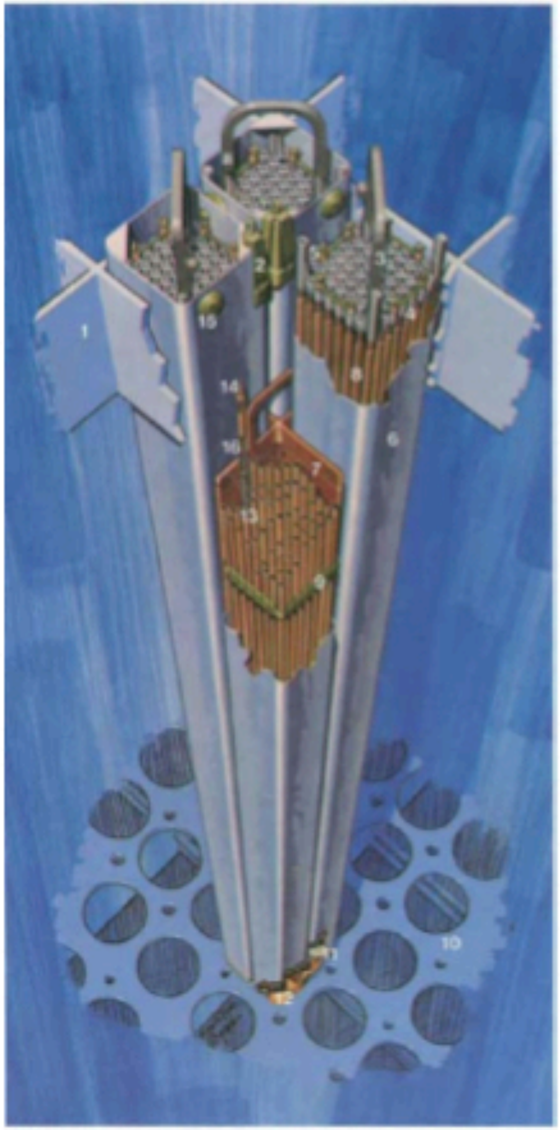
1cm diameter and 1.5 cm high

⇒ fuel rods a few meter long with a zirconium alloy cladding, permeable to neutrons and corrosion resistant

⇒ fuel elements of hundreds of fuel rods contain from 200 to 500 kg of uranium

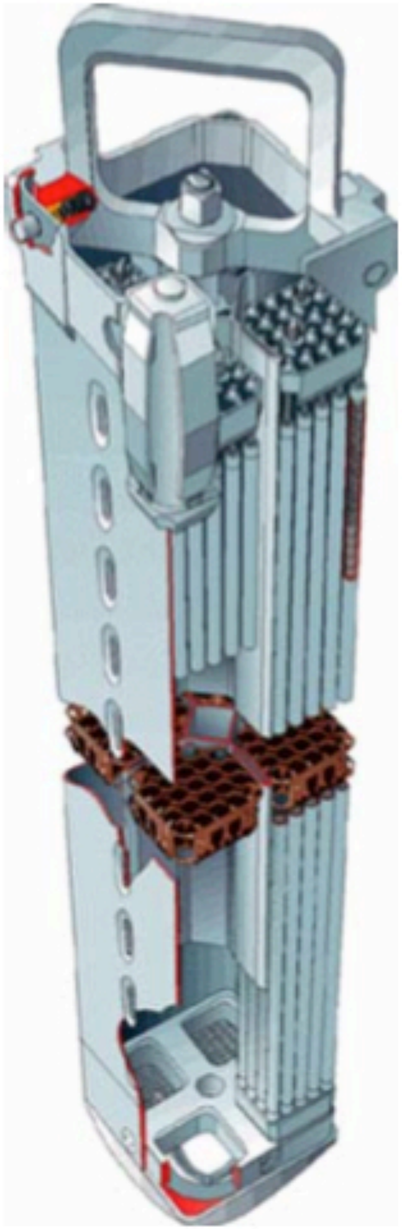
⇒ the core contain from 200 to 800 fuel elements



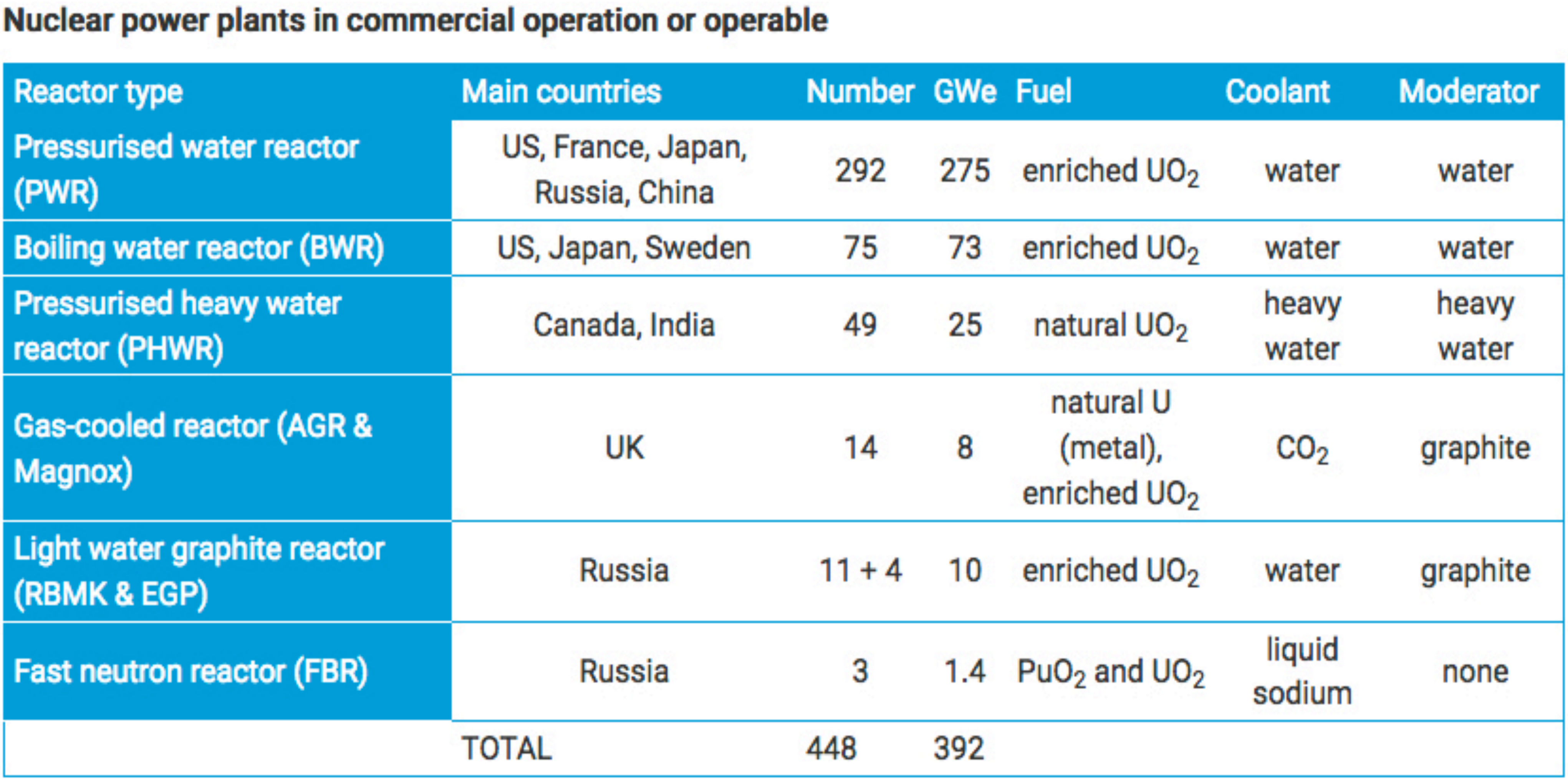


Modulo di combustibile

Barra di controllo



Elemento di combustibile



Nuclear power plants in commercial operation or operable

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	US, France, Japan, Russia, China	292	275	enriched UO_2	water	water
Boiling water reactor (BWR)	US, Japan, Sweden	75	73	enriched UO_2	water	water
Pressurised heavy water reactor (PHWR)	Canada, India	49	25	natural UO_2	heavy water	heavy water
Gas-cooled reactor (AGR & Magnox)	UK	14	8	natural U (metal), enriched UO_2	CO_2	graphite
Light water graphite reactor (RBMK & EGP)	Russia	11 + 4	10	enriched UO_2	water	graphite
Fast neutron reactor (FBR)	Russia	3	1.4	PuO_2 and UO_2	liquid sodium	none
	TOTAL	448	392			

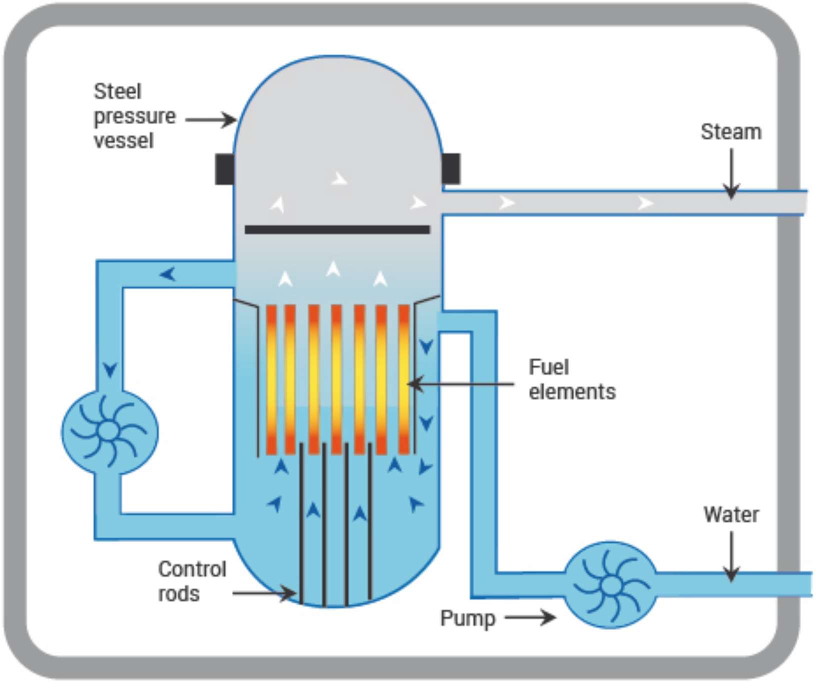
(2% to 5%)-enriched Uranium reactors:

BWR – boiling water reactor

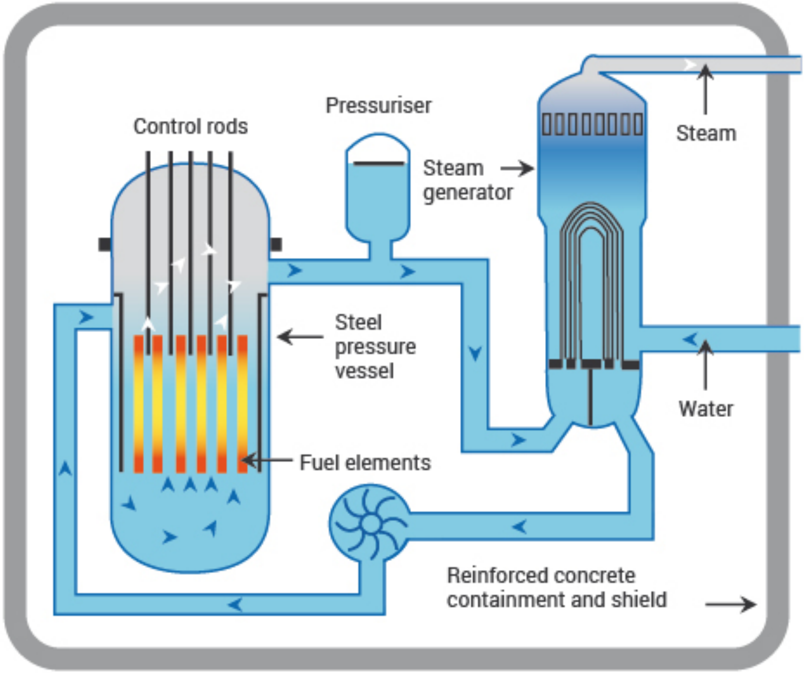
PWK – pressurized water reactor

- operate at high pressures
- containment is needed
- fuel is renewed after a few years

A Boiling Water Reactor (BWR)



A Pressurized Water Reactor (PWR)



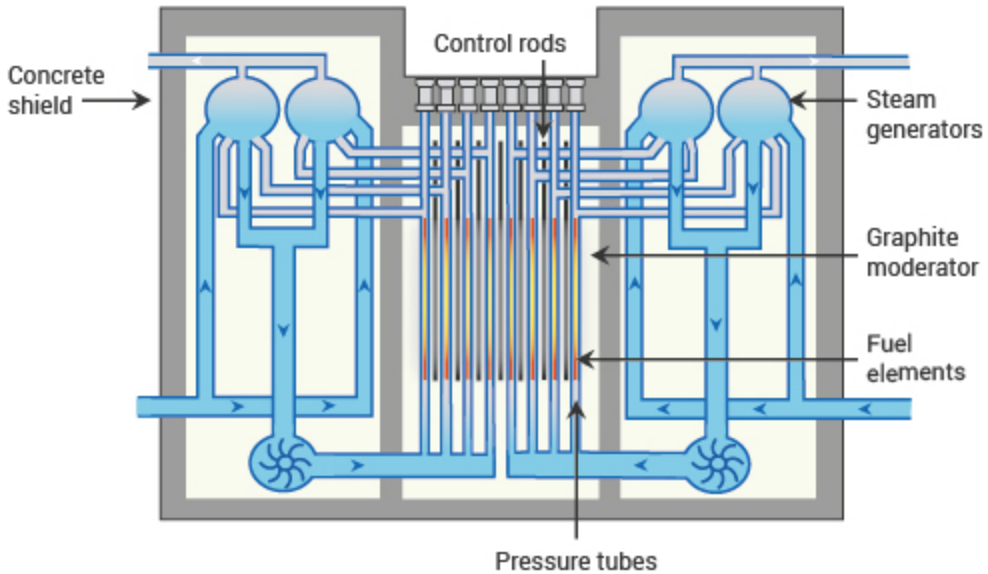
natural Uranium reactors:

Candu – heavy water moderated

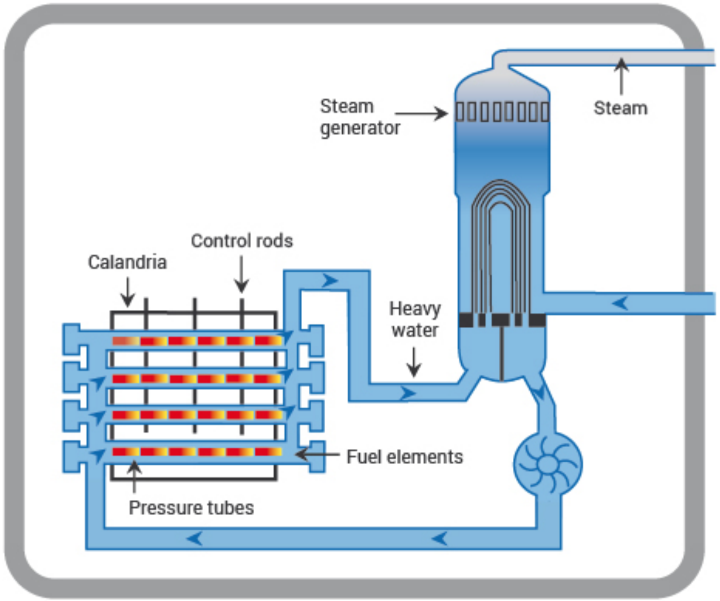
RBMK – graphite moderated

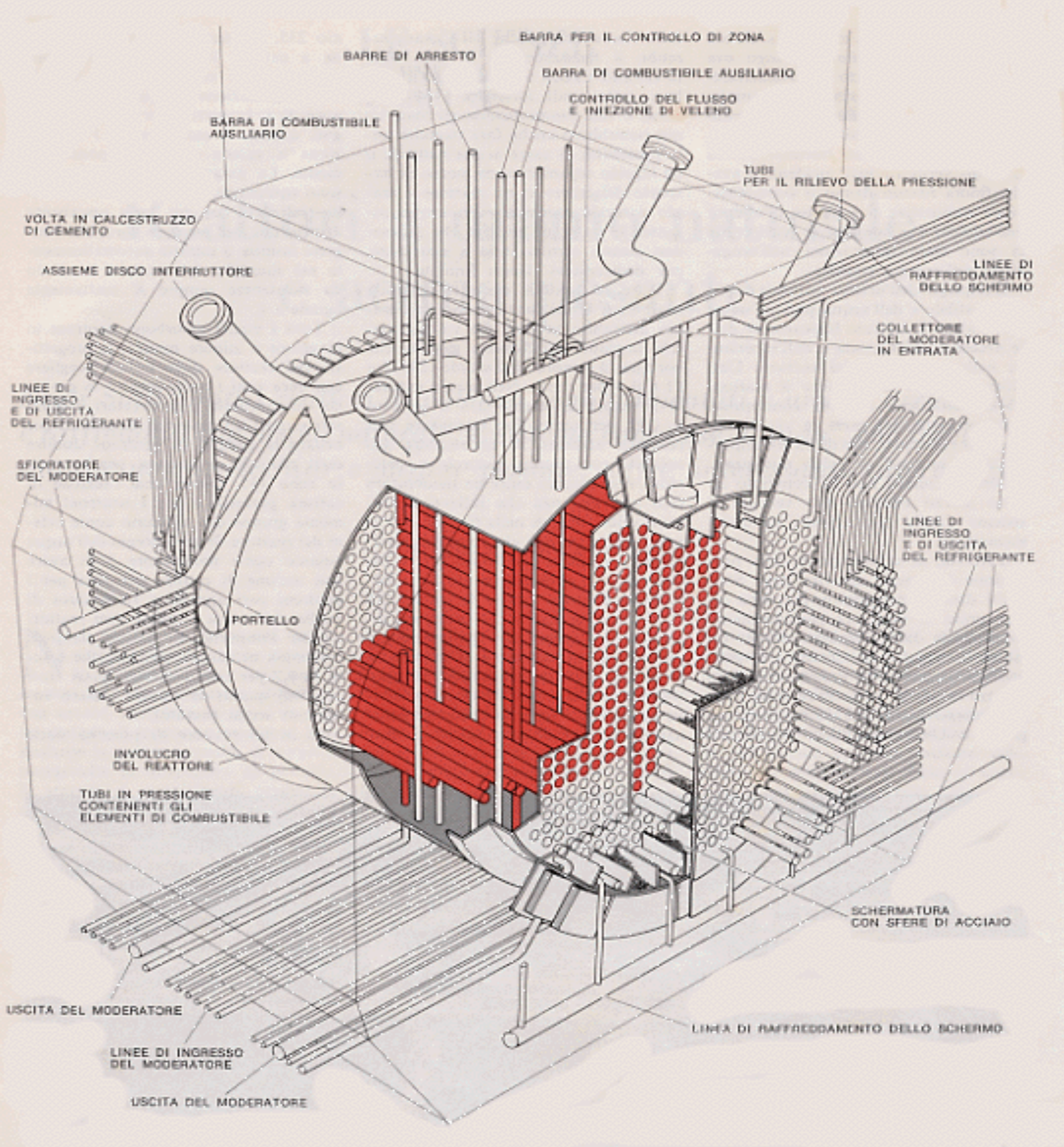
- operate at atmospheric pressure
- individual fuel channels
  - ▻ fuel rods can be extracted during operation
- water cooling in pressure tubes

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

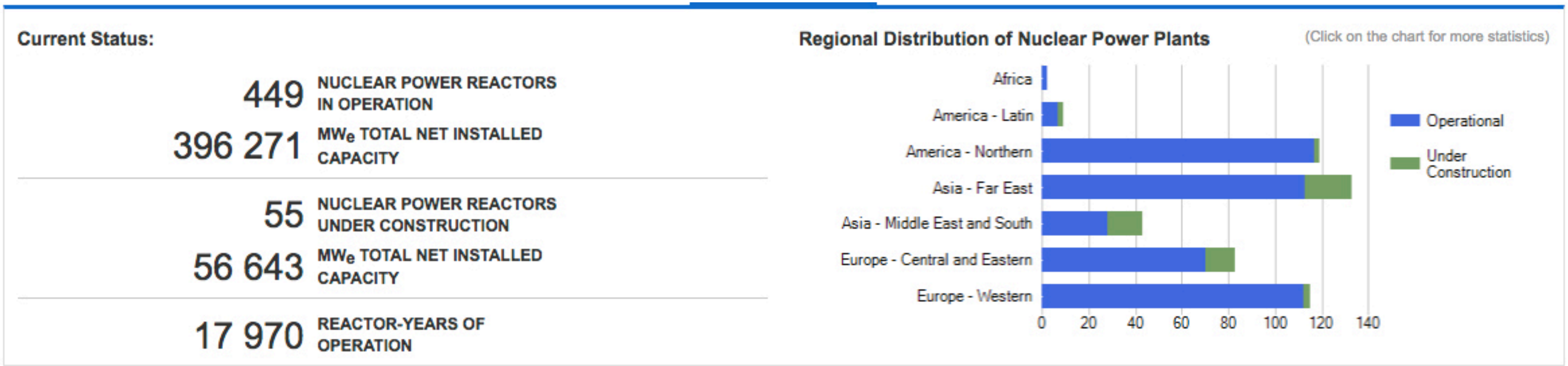


A Pressurized Heavy Water Reactor (PHWR/Candu)





a symphony of pipes



Current Status:

449 NUCLEAR POWER REACTORS IN OPERATION

396 271 MW$_e$ TOTAL NET INSTALLED CAPACITY

55 NUCLEAR POWER REACTORS UNDER CONSTRUCTION

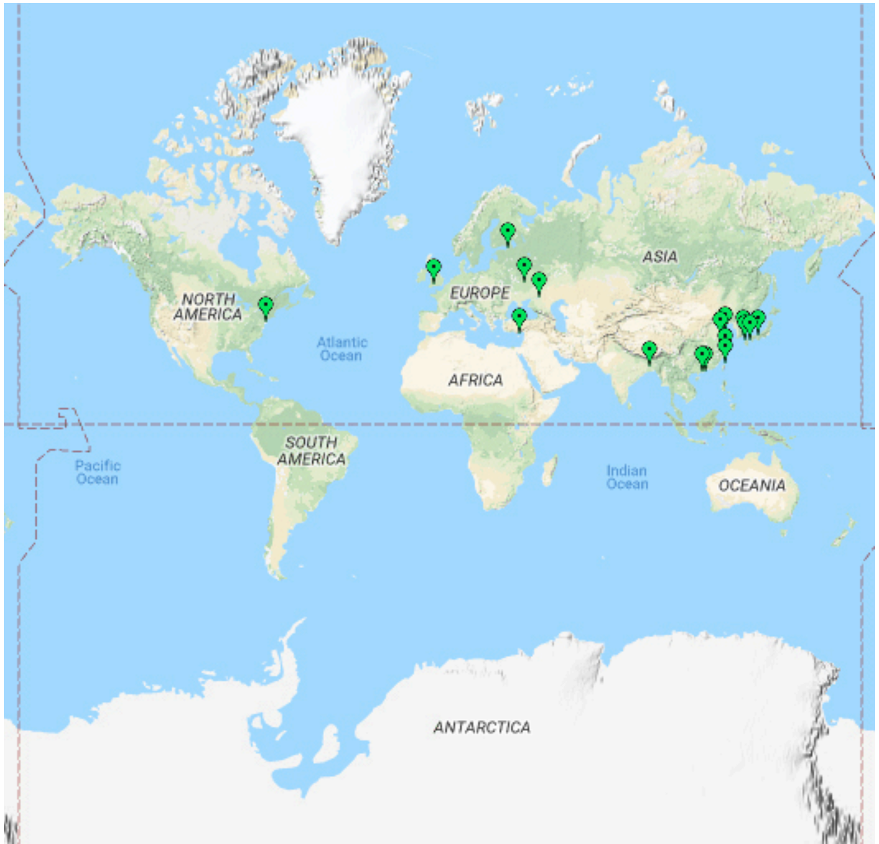
56 643 MW$_e$ TOTAL NET INSTALLED CAPACITY

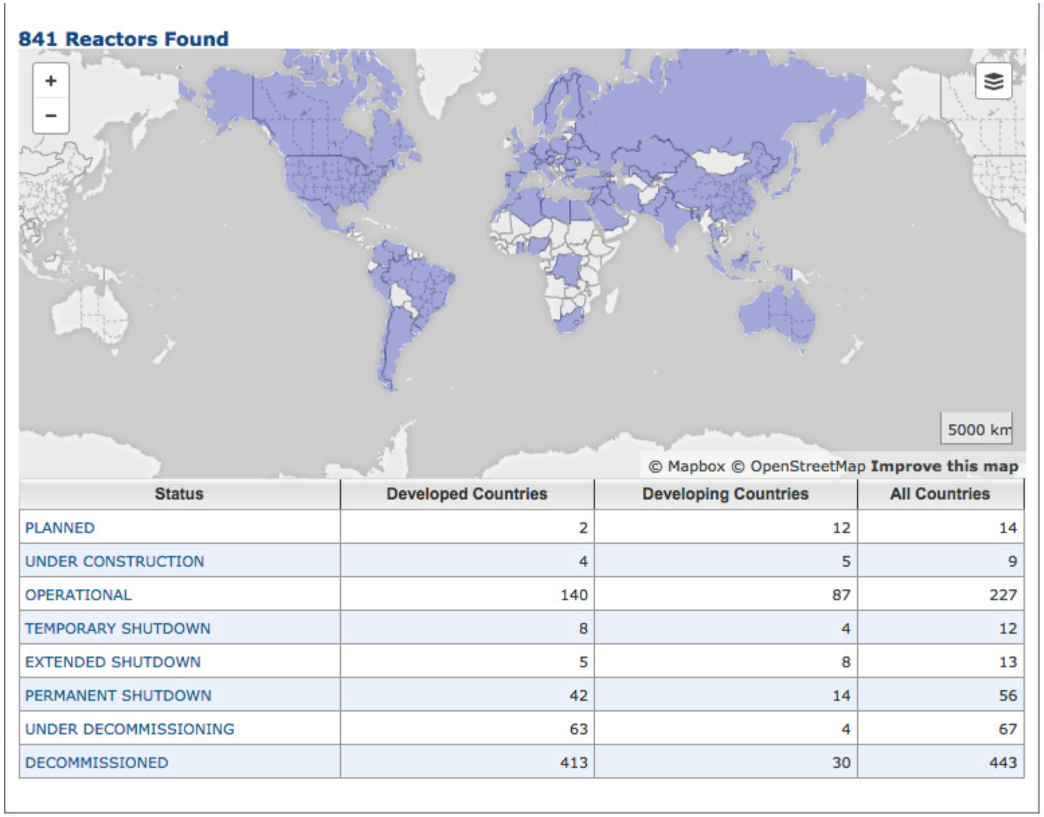
17 970 REACTOR-YEARS OF OPERATION

Regional Distribution of Nuclear Power Plants

(Click on the chart for more statistics)

HIGHLIGHTS



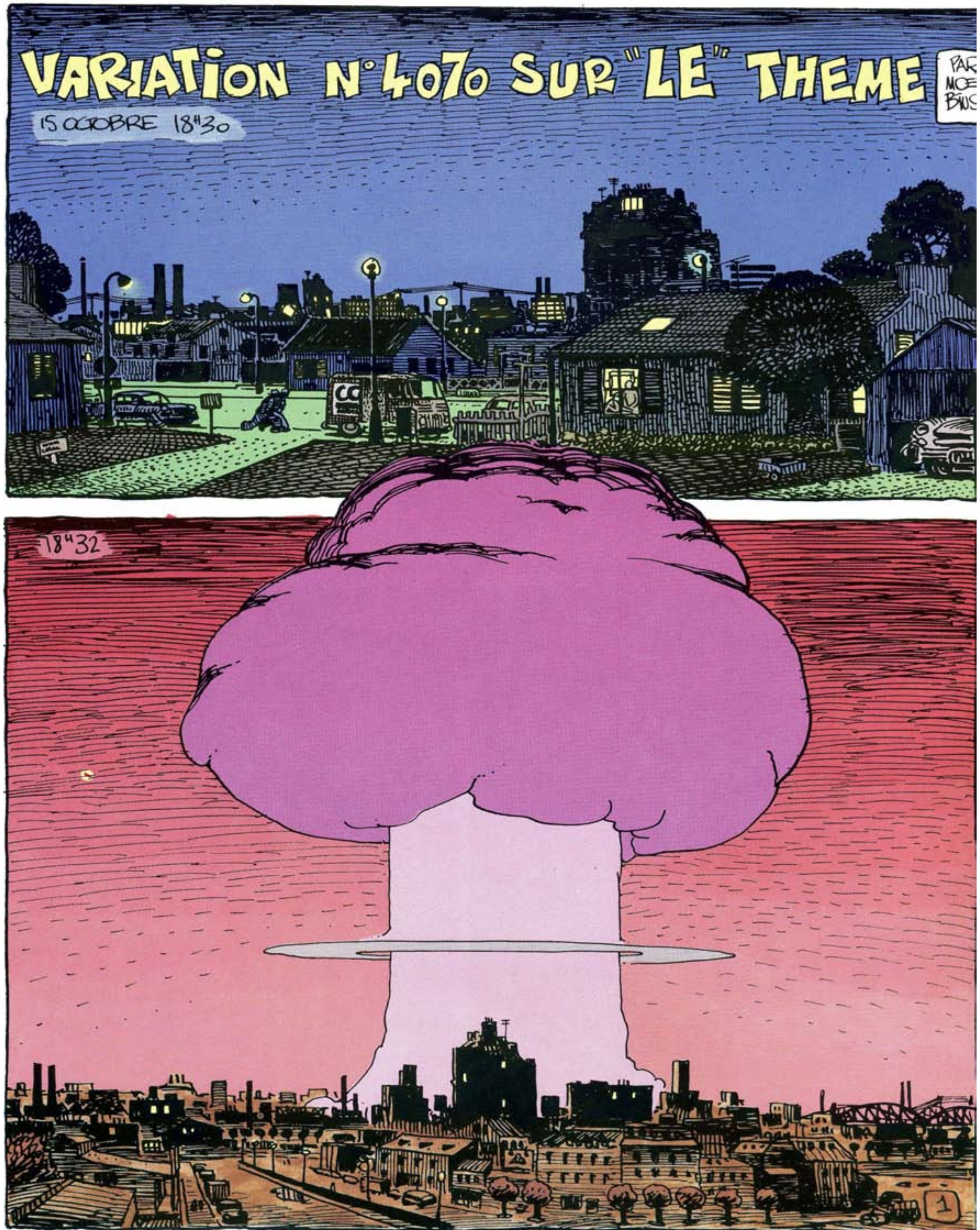


841 Reactors Found

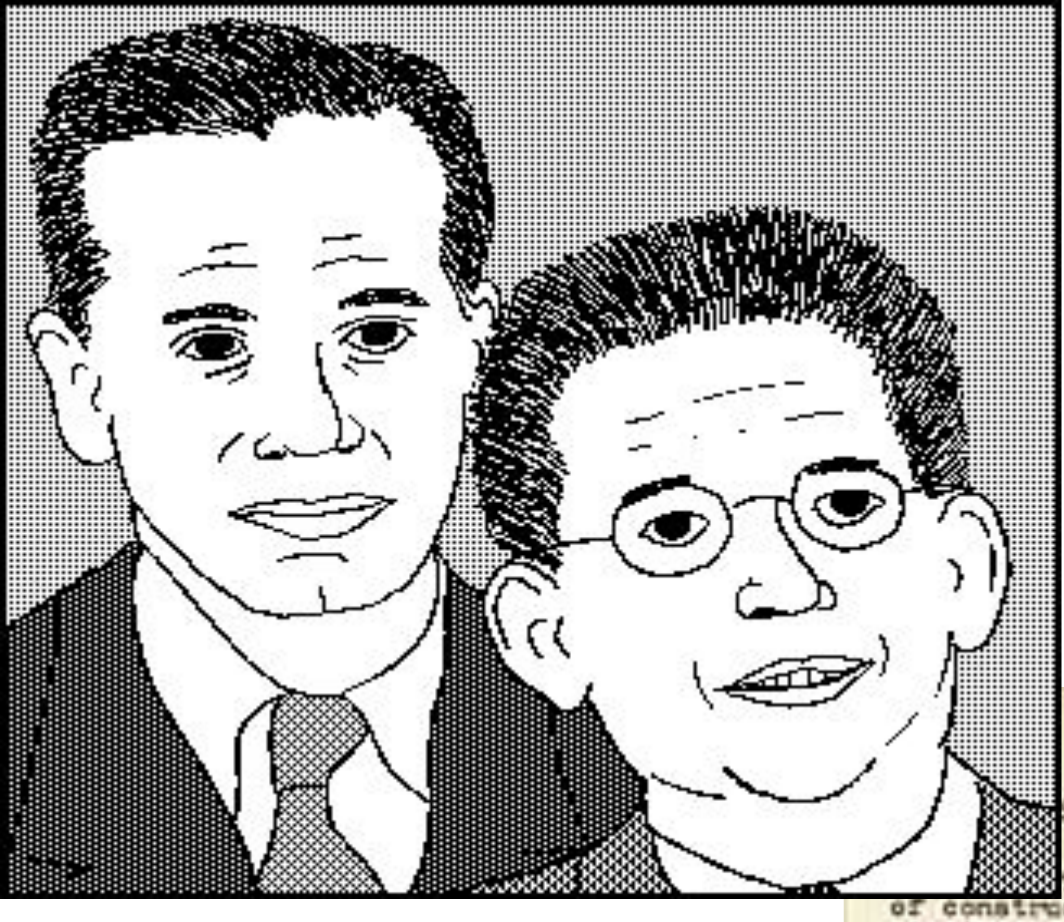
Status	Developed Countries	Developing Countries	All Countries
PLANNED	2	12	14
UNDER CONSTRUCTION	4	5	9
OPERATIONAL	140	87	227
TEMPORARY SHUTDOWN	8	4	12
EXTENDED SHUTDOWN	5	8	13
PERMANENT SHUTDOWN	42	14	56
UNDER DECOMMISSIONING	63	4	67
DECOMMISSIONED	413	30	443

Legend: ✳ ! ▢ ▢ | Glossary | RRDB Feedback | Archive | © 2009-19 IAEA. All rights reserved

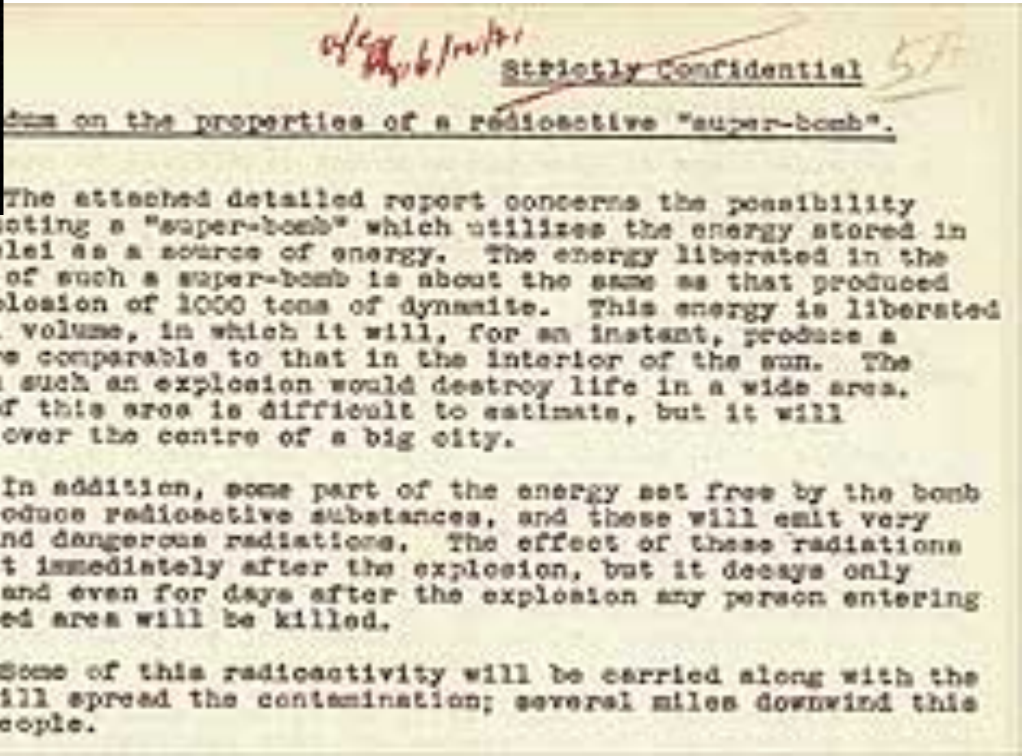
the way to the bomb



Memorandum on the Properties of a Radioactive “Super-bomb”, March 1940



Otto Frisch and Rudolf Peierls



Strictly Confidential

dum on the properties of a radioactive "super-bomb".

The attached detailed report concerns the possibility of constructing a "super-bomb" which utilizes the energy stored in atomic nuclei as a source of energy. The energy liberated in the explosion of such a super-bomb is about the same as that produced by the explosion of 1000 tons of dynamite. This energy is liberated in a small volume, in which it will, for an instant, produce a temperature comparable to that in the interior of the sun. The blast from such an explosion would destroy life in a wide area. The size of this area is difficult to estimate, but it will probably cover the centre of a big city.

In addition, some part of the energy set free by the bomb goes to produce radioactive substances, and these will emit very powerful and dangerous radiations. The effect of these radiations is greatest immediately after the explosion, but it decays only gradually and even for days after the explosion any person entering the affected area will be killed.

Some of this radioactivity will be carried along with the wind and will spread the contamination; several miles downwind this may kill people.

timing

- neutron interaction time 0.01 μs
- after 40 generations (0.4 μs) the released energy is enormous, the temperature rises up to ≈ 40×10^6 °C; the material becomes a plasma and moves with a velocity of ≈ 10^6 m/s
- a few centimeters expansion of the material is enough to decrease the density below the critical value and to stop the chain reaction

➡ the time at disposal for the full chain is ≈ 0,5 μs
it is impossible to slow down the neutrons to the best velocity

production of the fissile material

- material extremely enriched in U-235 (over 90%) or in Pu-239 is necessary in quantities larger than the critical mass
- U-235 has to be extraced from natural Uranium, where it is present only in 7 parts per thousand
  - ▹ no chemical process is at disposal
  - ▹ the physical difference between U-238 and U-235 is only of 3 parts over 238

➡ you have to separate U-235 atom by atom

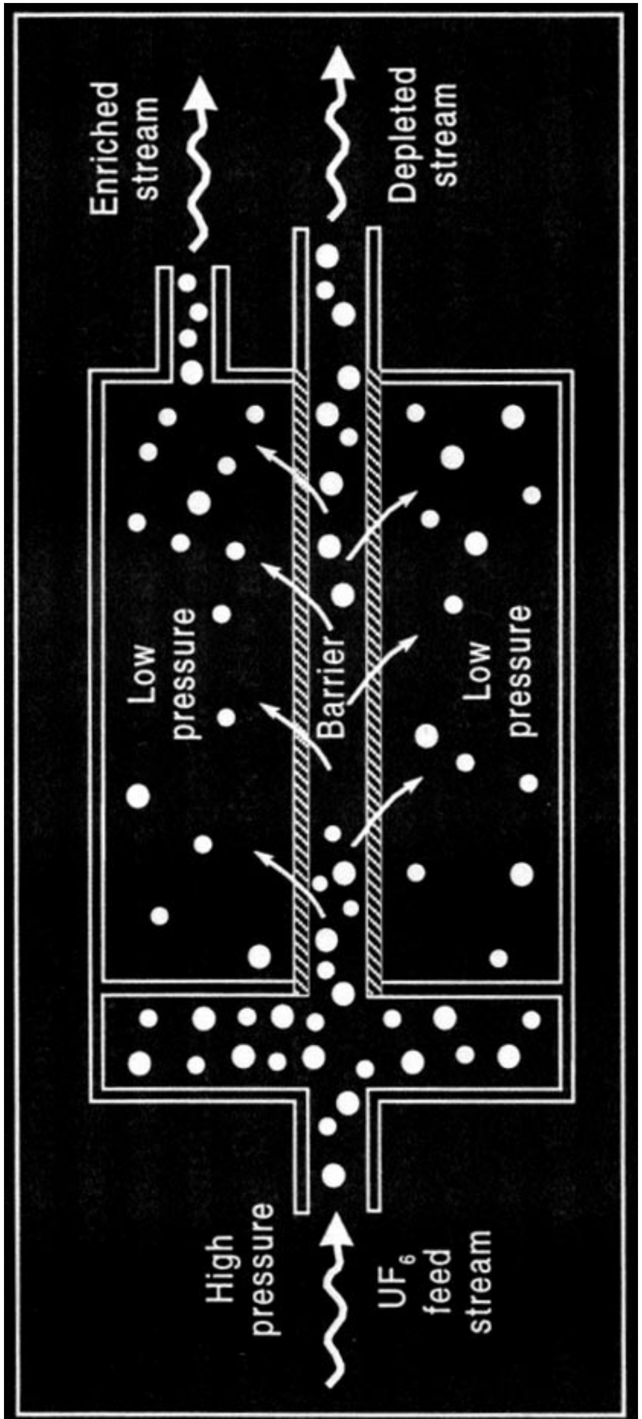
yellowcake (natural Uranium oxide)

a part of the core of a nuclear weapon of U-235 pure over 93%

Uranium enrichment

- several techniques have been pursued, all pretty inefficient and energy consuming
  - ▻ the main ones are gas diffusion and centrifuges
- natural Uranium is converted in a gaseous compound (UF_6)
  - ▻ the gas is forced to diffuse at high pressure throw a special membrane

  or
  - ▻ the gas is made spinning at hyper-velocity in special centrifuges
- the process is repeated thousand of times



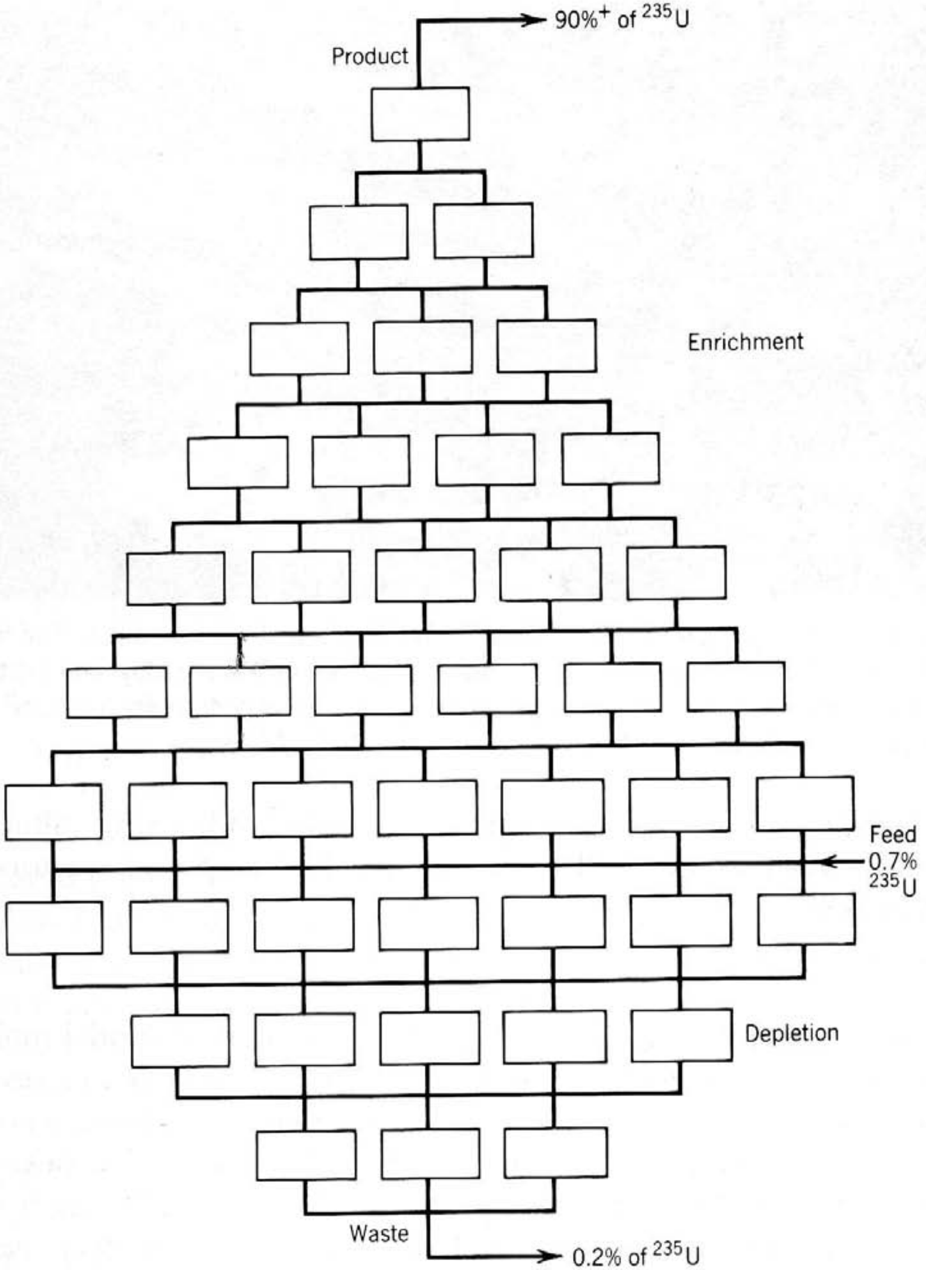
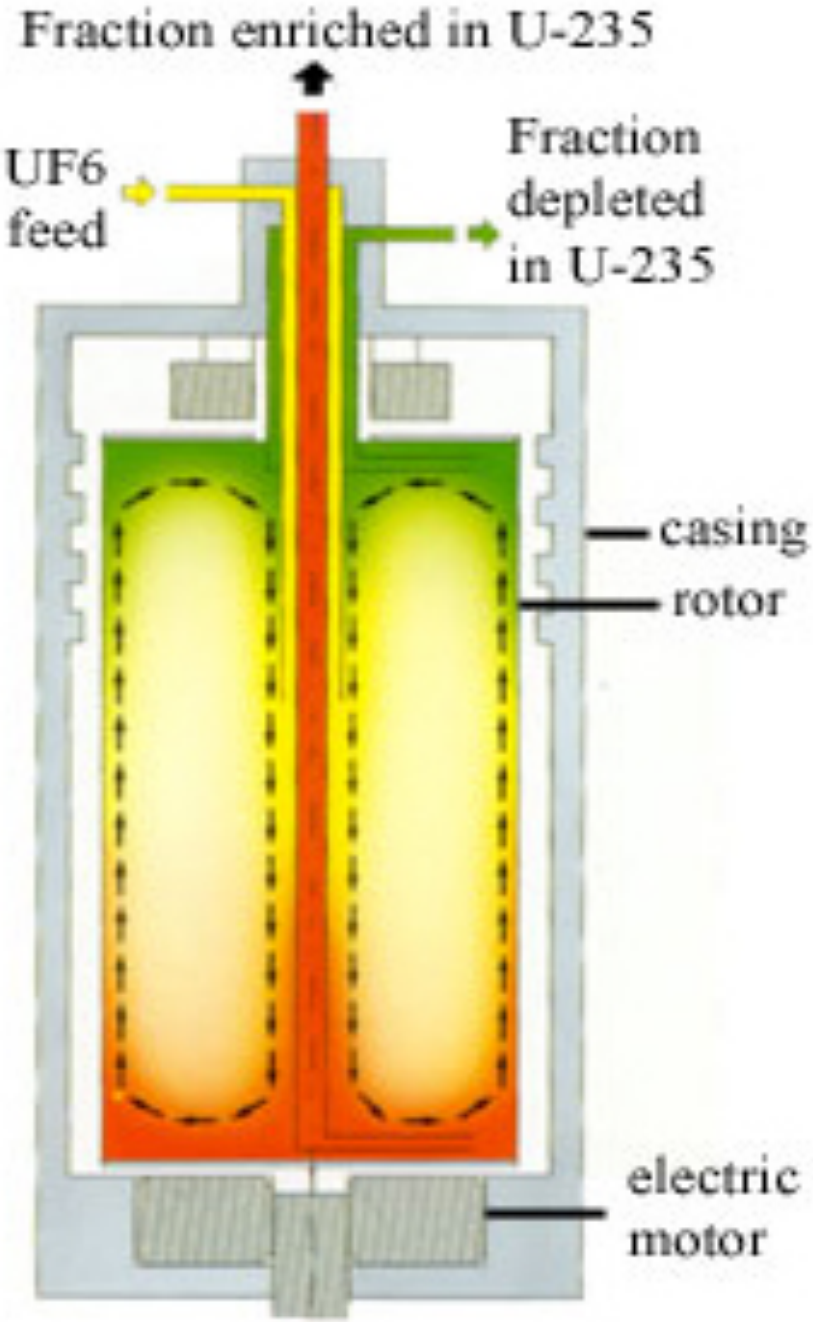
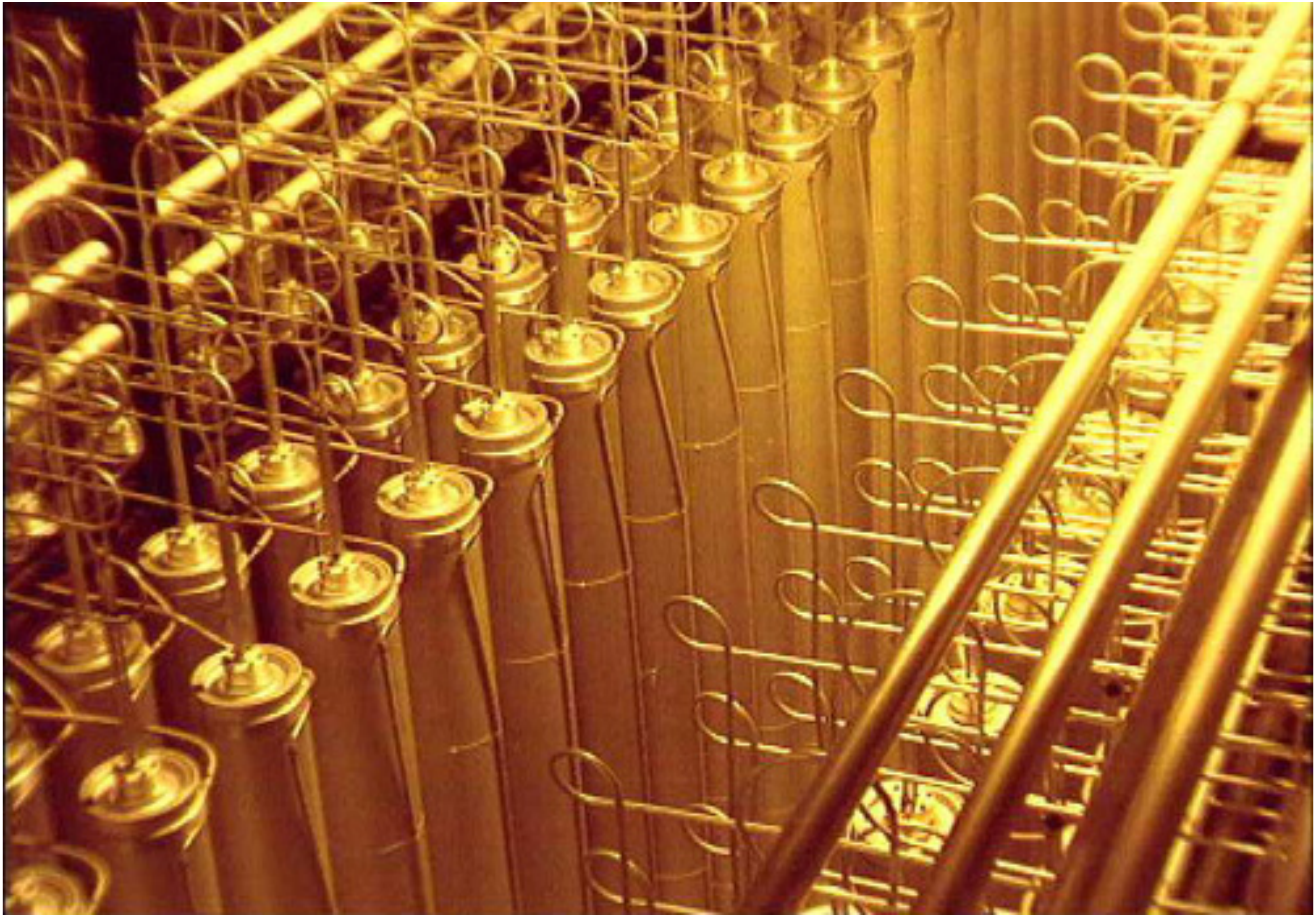


Figure 2.6 4000 diffusion stages can turn natural uranium with 0.7% ^{235}U into weapons-grade uranium enriched to 90% in ^{235}U while rejecting tailings containing uranium depleted to 0.2% in ^{235}U.

centrifuge enrichement

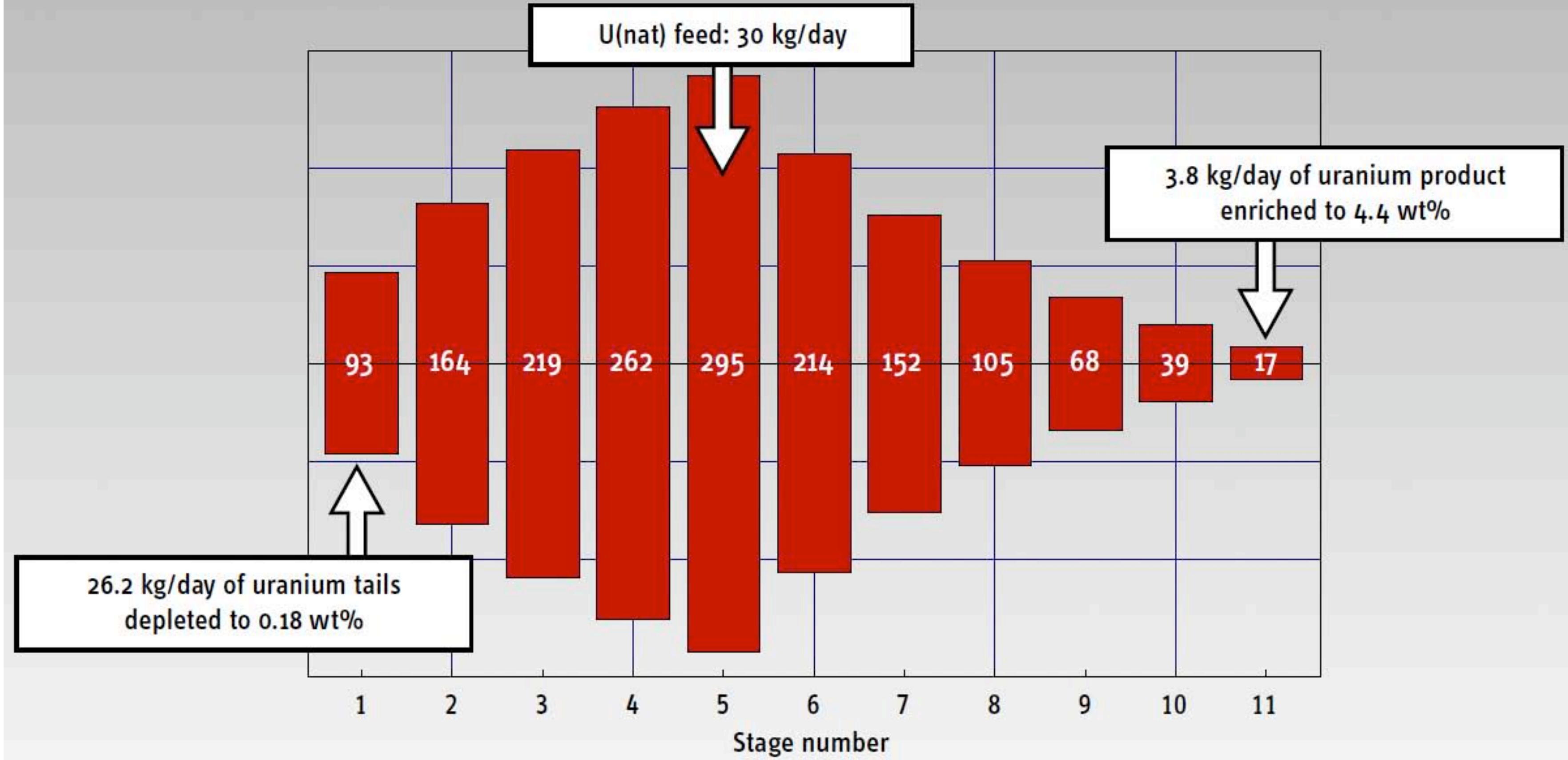
scheme of functioning





Operation of Centrifuge Cascade

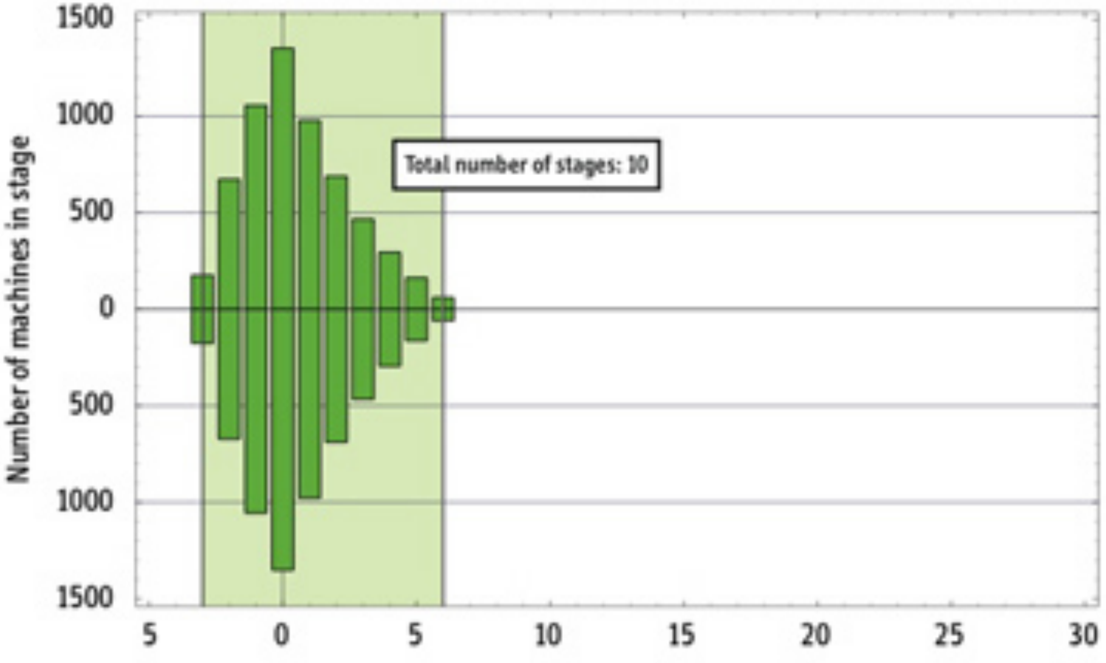
(Preliminary data)

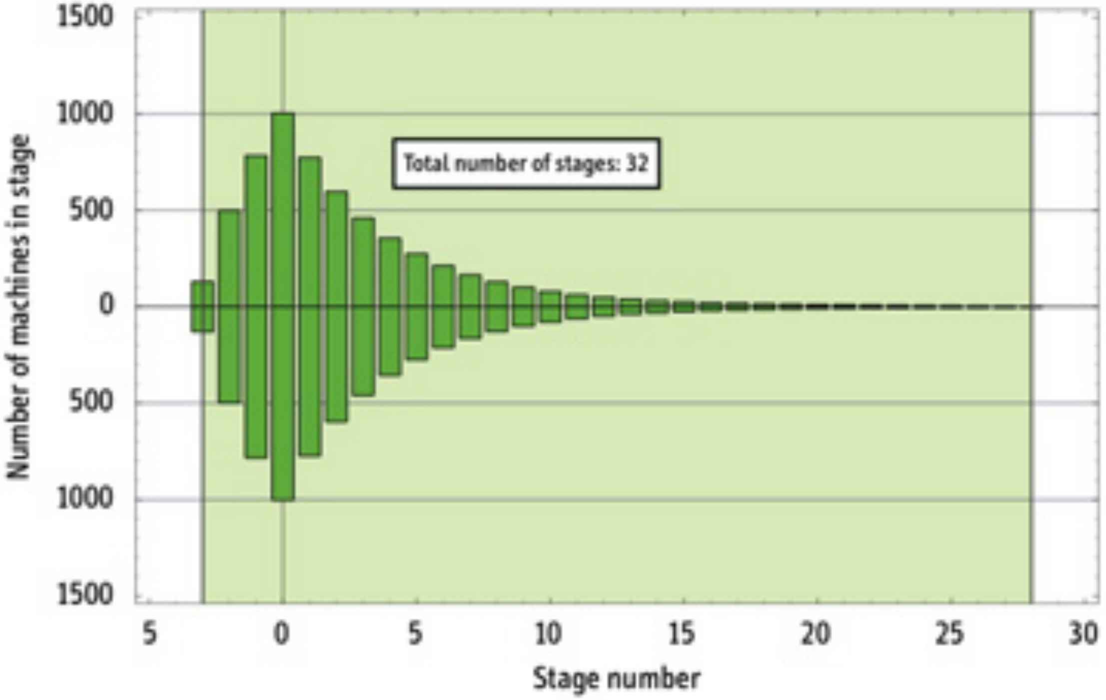


1628 machines, feed rate: 5.8 mg/sec, hold-up: 12.93 seconds
Assumed uranium inventory: 75 mg per machine, 122 grams in cascade
Capacity of cascade ca. 11 tSWU/yr

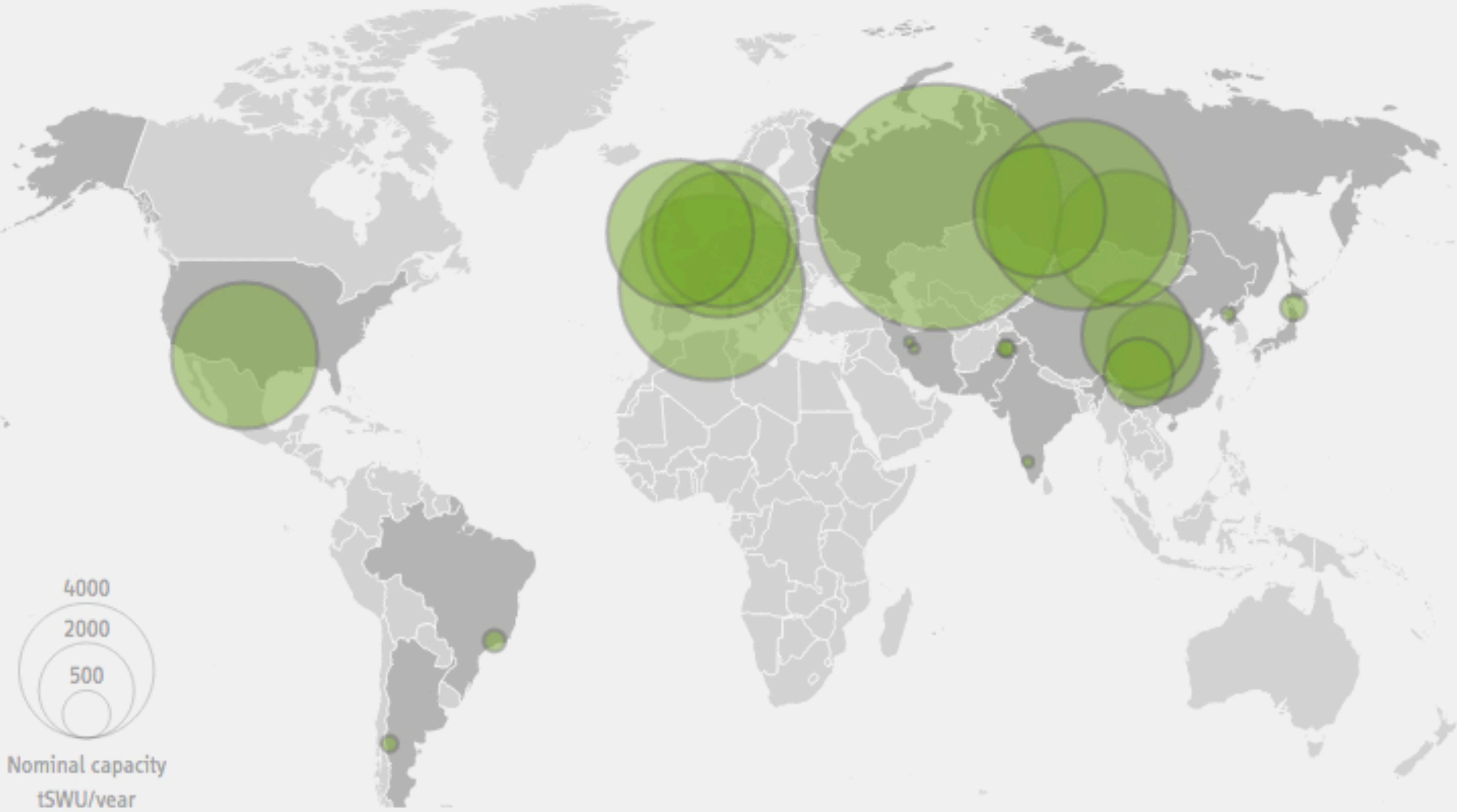
proliferation problem

the same plant of enrichment can produce fuel for nuclear power plants (LEU) or WGU, just rearranging the centrifuge cascade

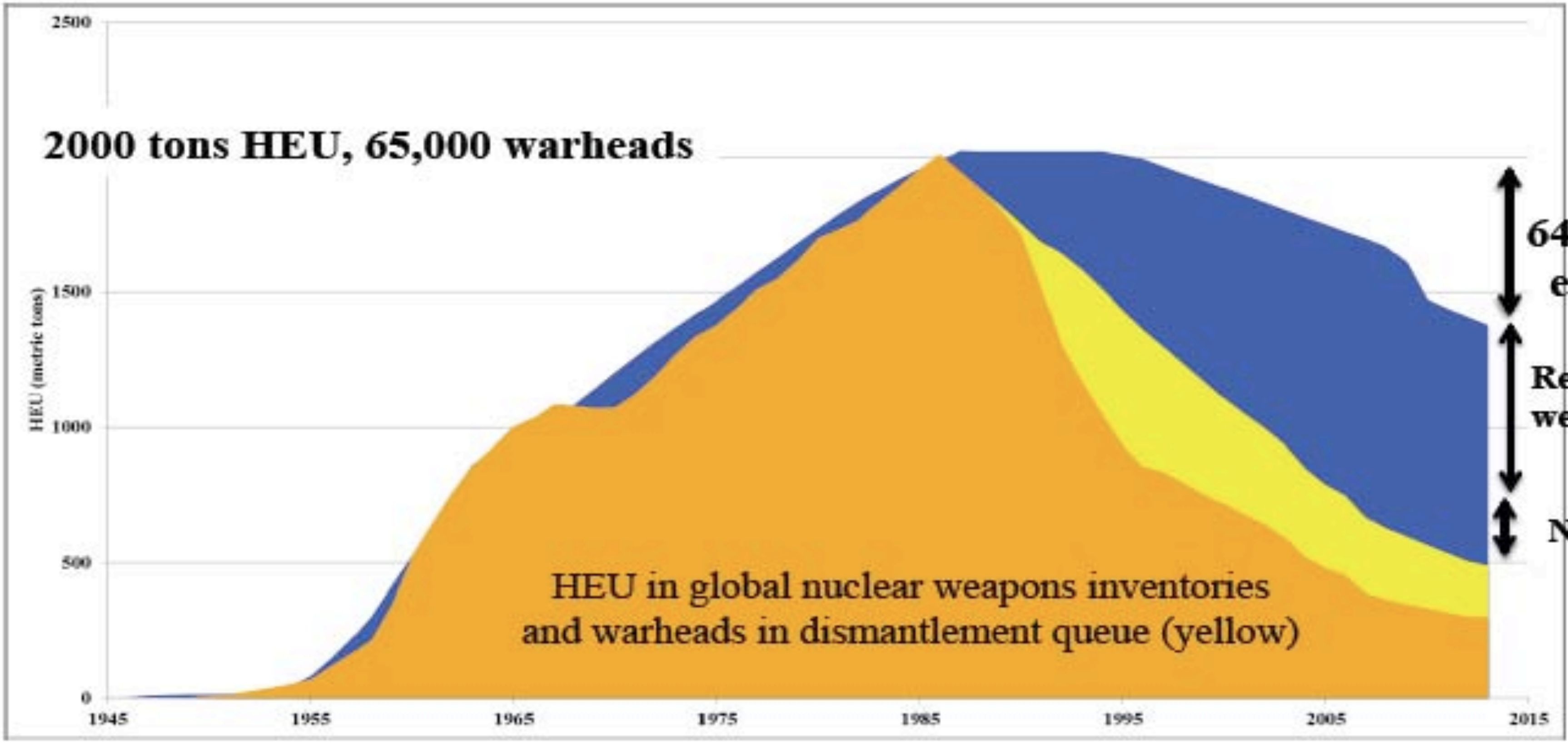




Facilities: Enrichment plants



The map shows all known uranium enrichment facilities worldwide as of the end of 2016. More detailed information about the facilities is in the table below.



2000 tons HEU, 65,000 warheads

640 tons eliminated

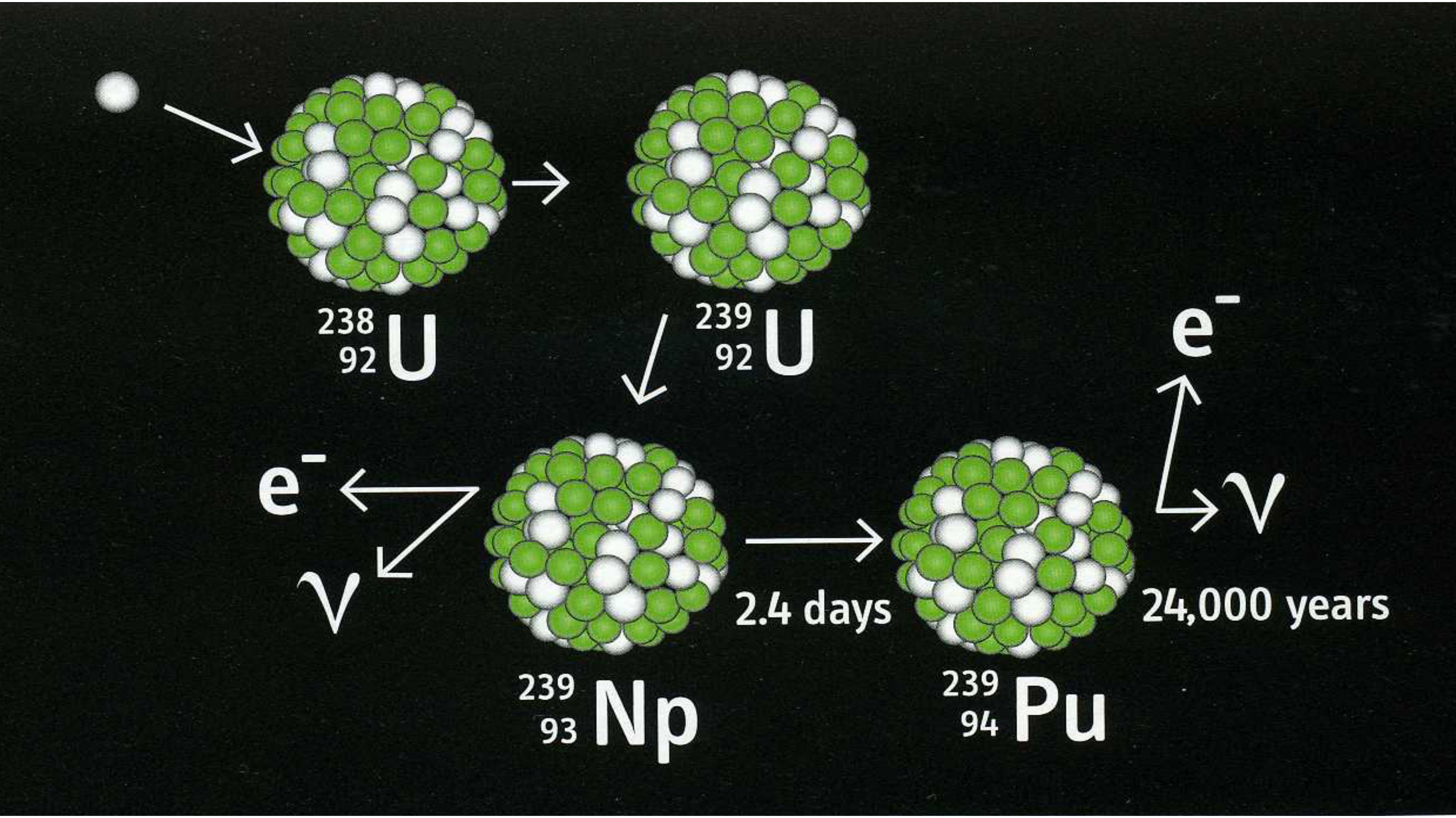
Reserved for weapons

Naval fuel

HEU in global nuclear weapons inventories and warheads in dismantlement queue (yellow)

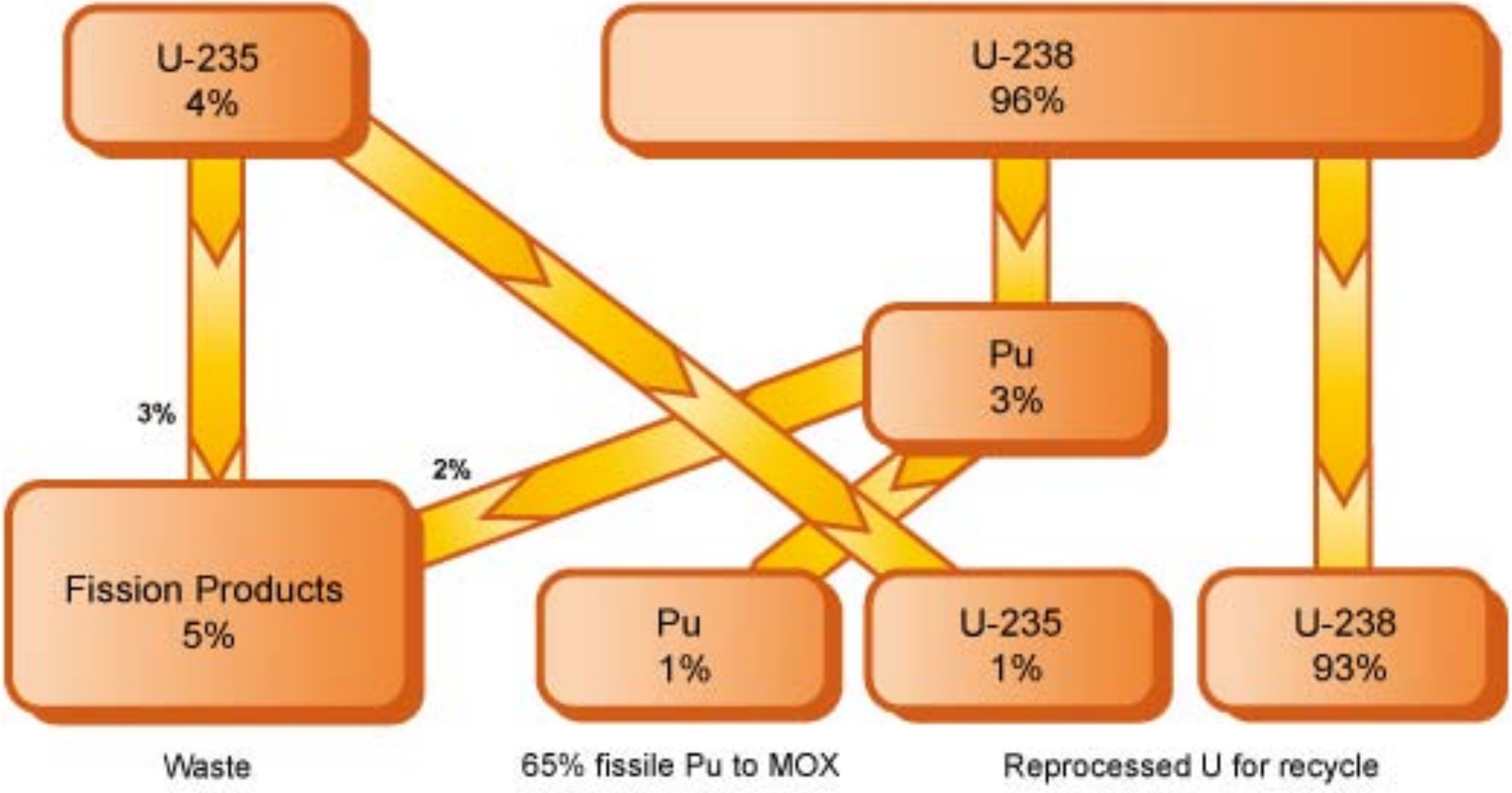
alternative approach to Uranium enrichment: production of Plutonium

- Pu is more fissile than HEU
  - ▻ its critical mass is significantly smaller
- Pu is produced in nuclear reactors from U-238 after absorption of a neutron
- Pu can be separaded from the reactor spent fuel with chemical procedures
- Pu has a long half-life (54,000 years) and can be worked metalurgically



reactions leading to the production of Plutonium

Reaction in Standard UO_2 Fuel



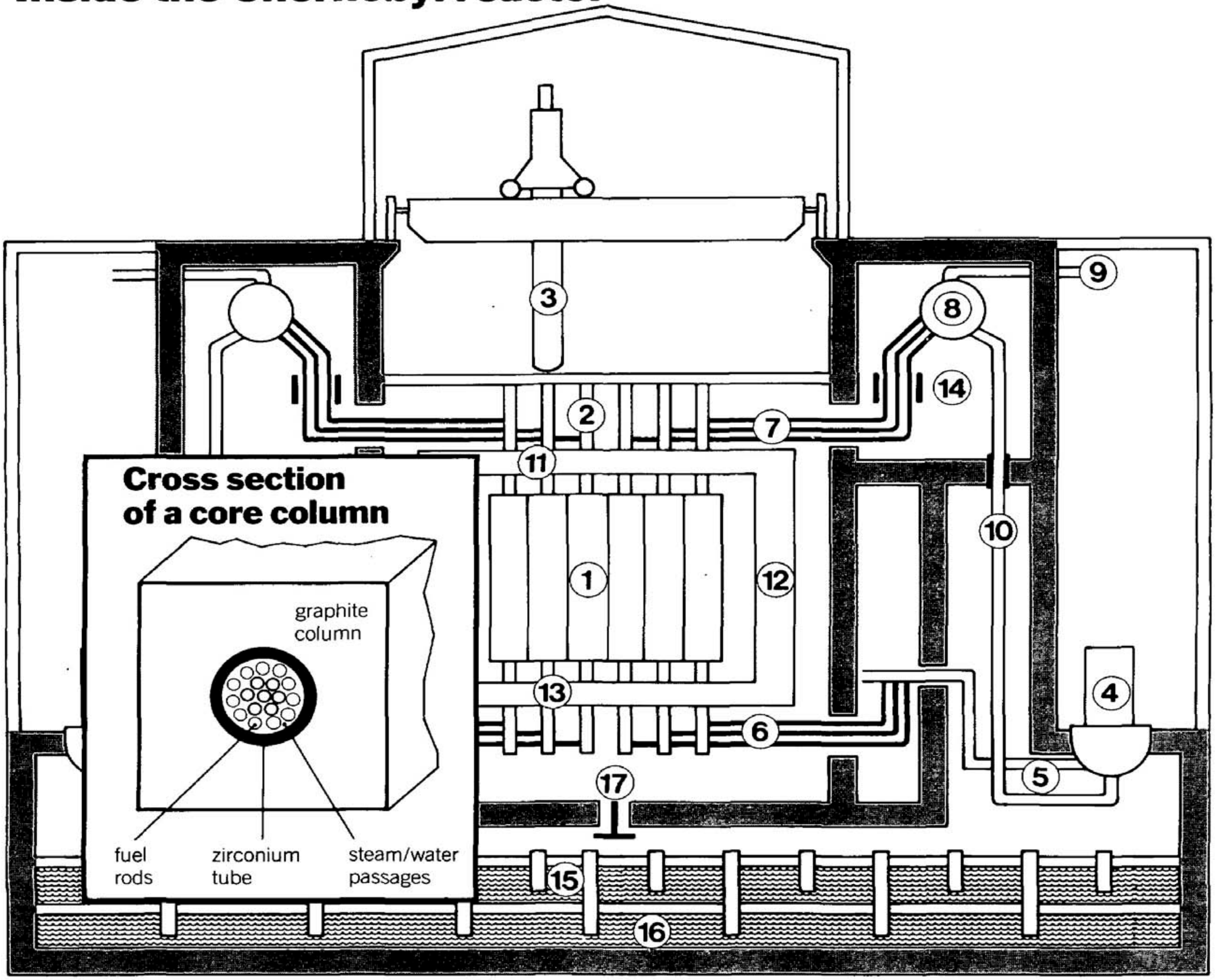
Basis: 45,000 MWd/t burn-up, ignores minor actinides

reactions in a water moderated reactor

heavy water or graphite moderated reactors for Plutonium production

- use natural or low-enriched Uranium
- produce more Plutonium than other reactors
- operate at atmospheric pressure
- fuel elements are in independent tubes and can be extracted without shutting down the reactor
- extraction before Pu-239 is contaminated by Pu-240 and higher isotopes

Inside the Chernobyl reactor



PUREX Plutonium separation

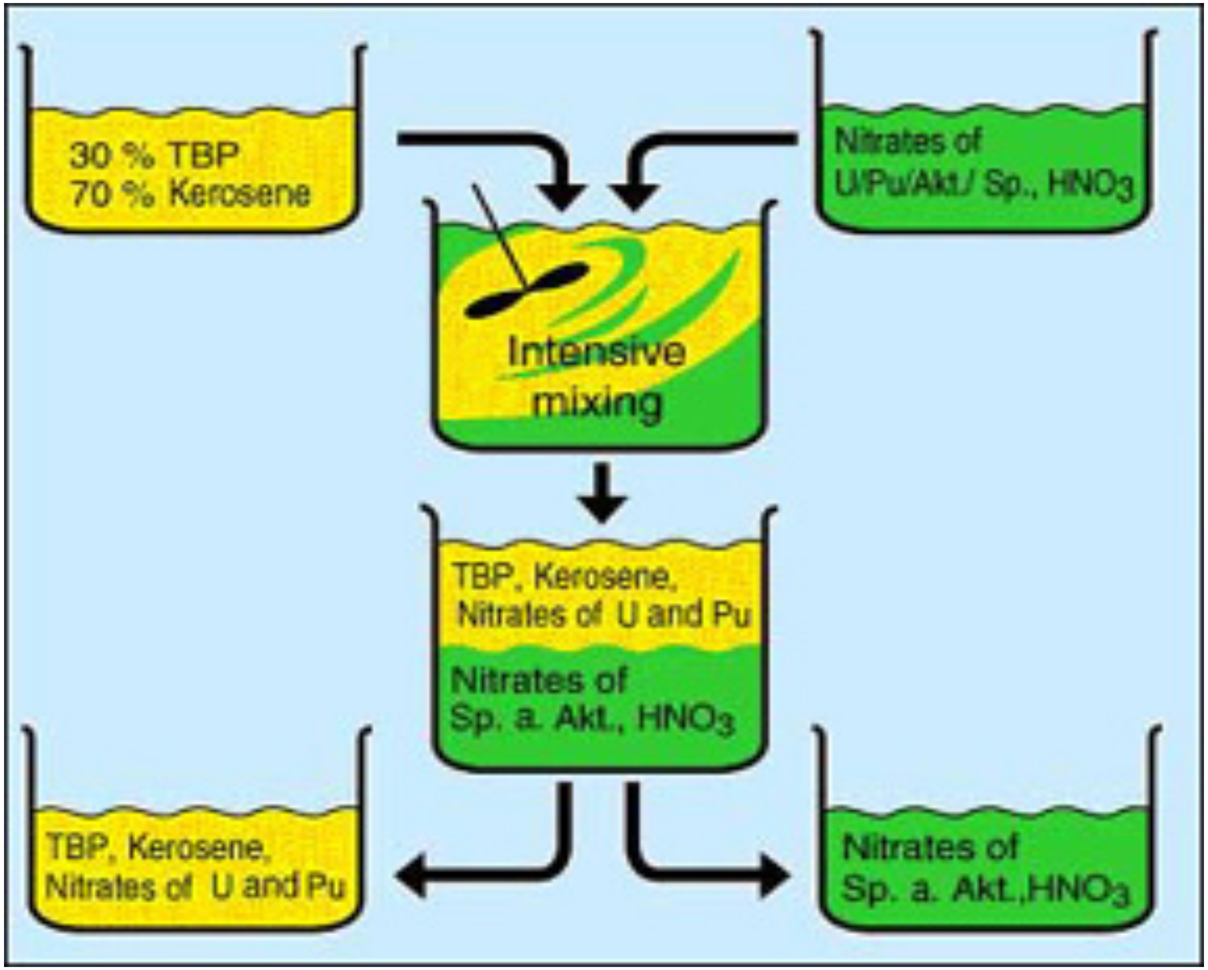
The fuel is first dissolved in nitric acid. Solids are removed by filtration. The organic solvent consists of 30% tributyl phosphate in kerosene.

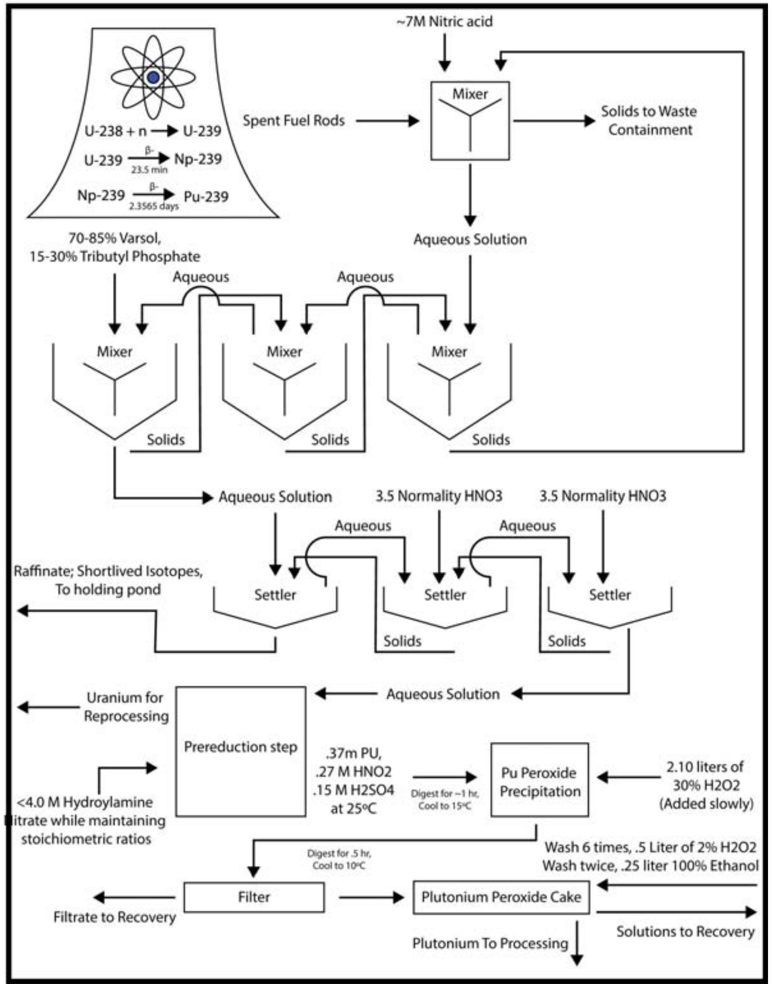
Uranium ions are extracted as Uranyl nitrate complexes, and Plutonium as similar complexes. Other fission products remain in the aqueous phase, including Americium and Curium.

Plutonium is separated from Uranium by treating the kerosene solution with reducing agents to convert the plutonium to the +3 oxidation state. The plutonium 3+ passes into the aqueous phase.

The uranium is stripped from the kerosene solution by back-extraction into nitric acid.

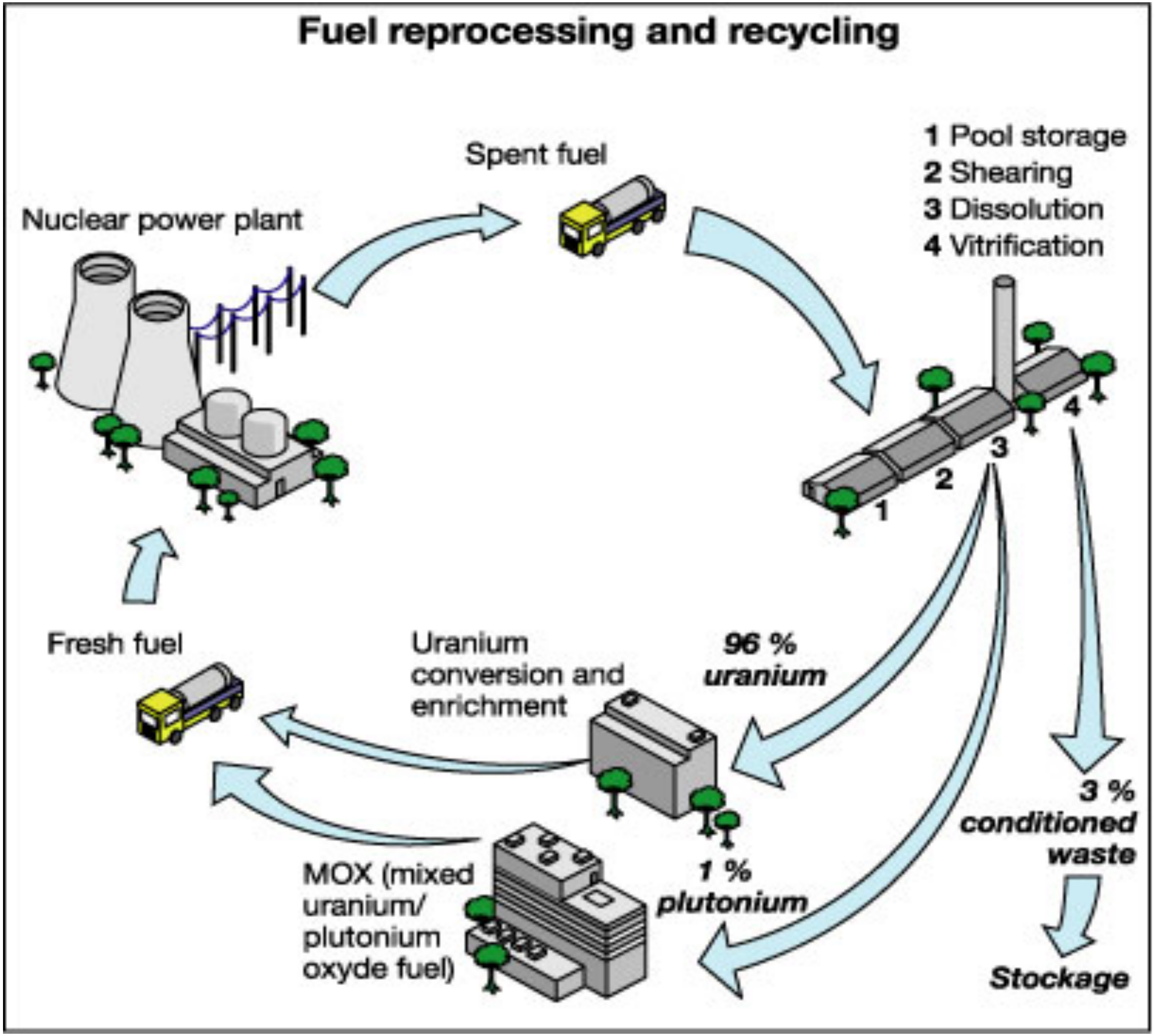
PUREX reprocessing





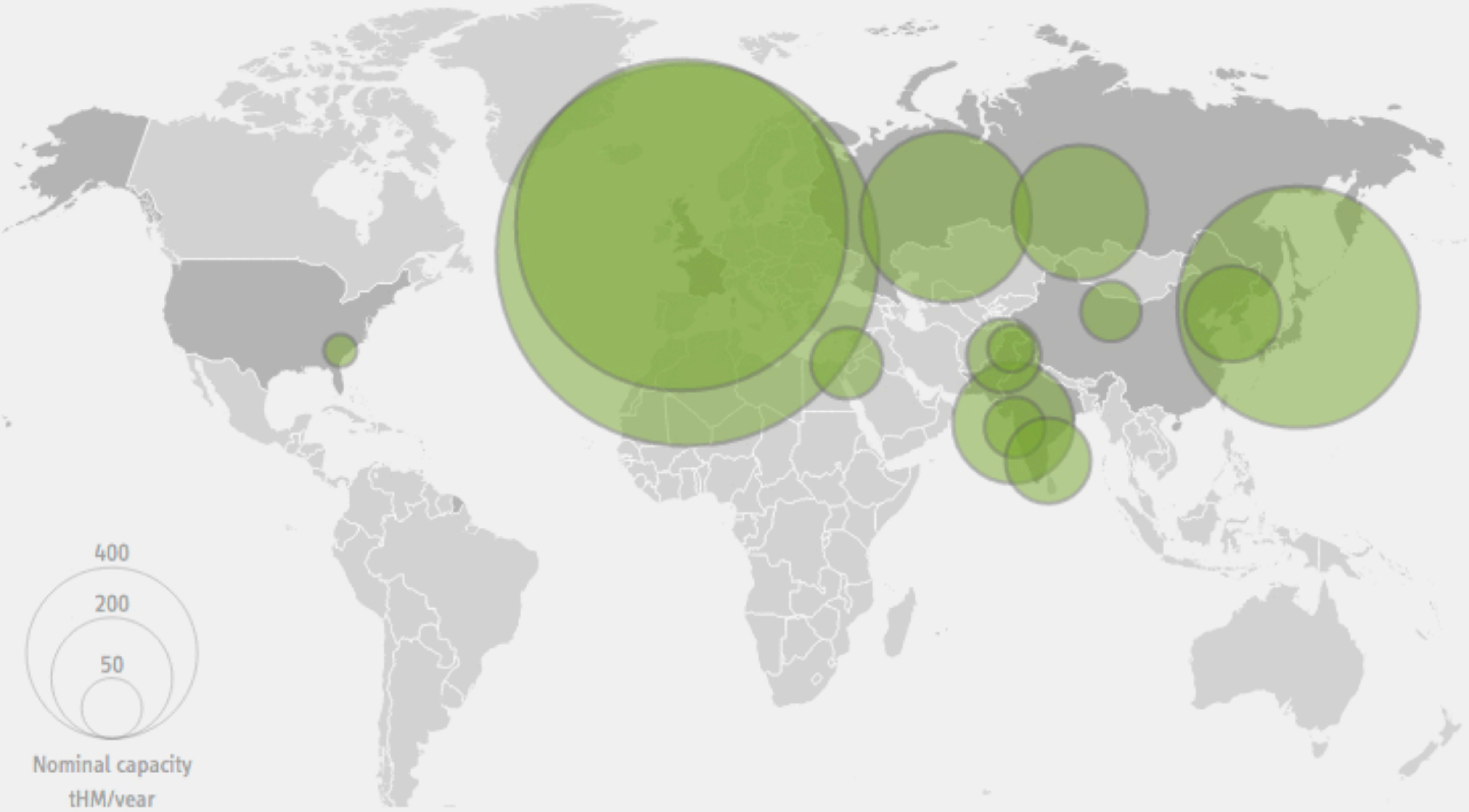
Plutonium and other Trans-Uranics.

Windscale at Sellafield



Fuel reprocessing and recycling

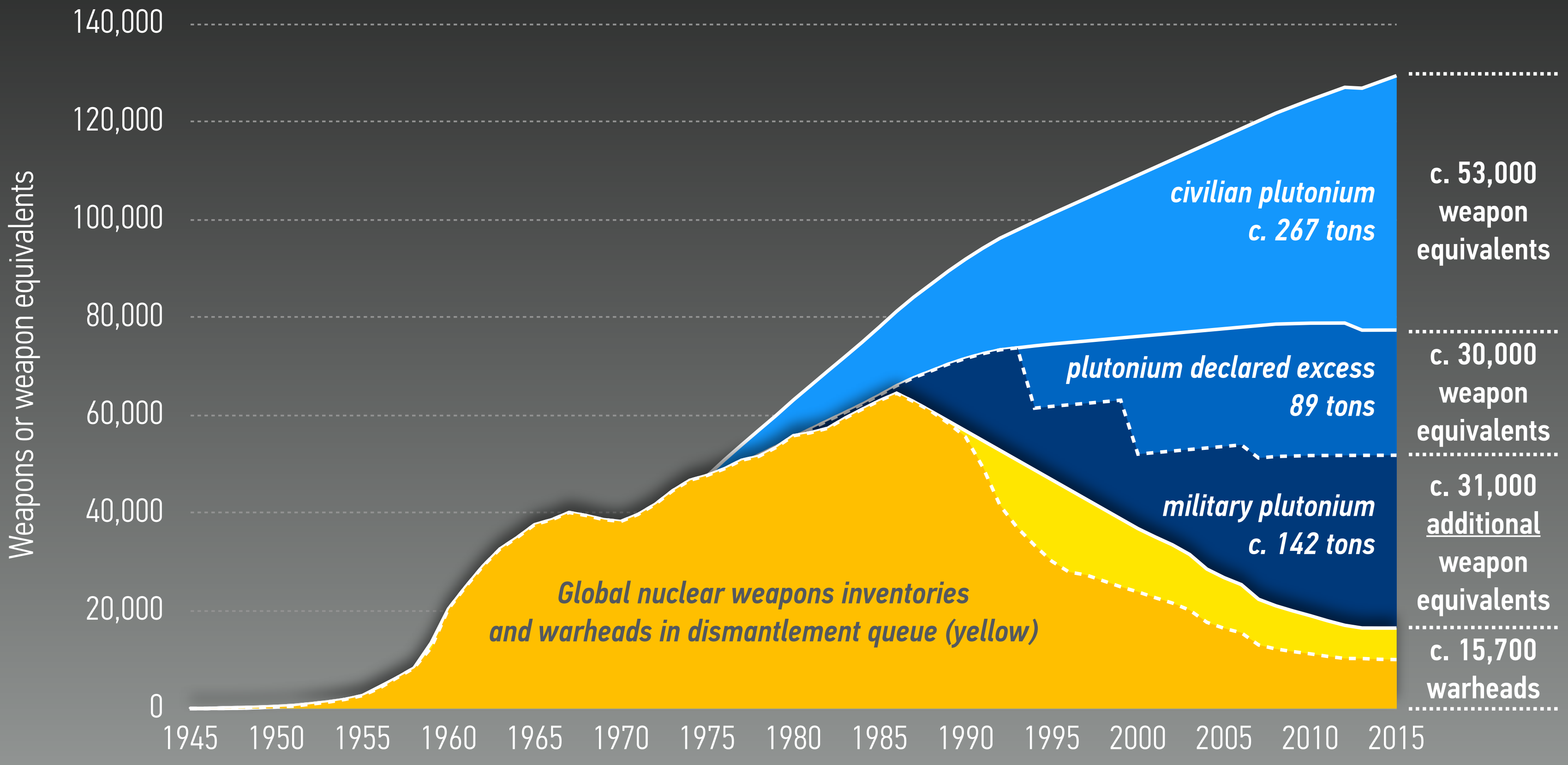
This page shows known reprocessing plants worldwide as of 2018. It includes reprocessing plants that are at advanced stages of construction, preparing for operations, or temporarily shut down.



NUCLEAR WEAPONS AND FISSILE MATERIALS

GLOBAL INVENTORIES, 1945–2015

THE CASE OF SEPARATED PLUTONIUM



"Status of World Nuclear Forces," *Federation of American Scientists*, fas.org, April 2015

Fissile material estimates and weapon-equivalents are authors' estimates; assumes an average of 3 kg for weapon-grade and 5 kg for reactor-grade plutonium per weapon

the fissile material necessary for a fission weapon is matter of kilograms, while the existing inventories are hundreds of di tons

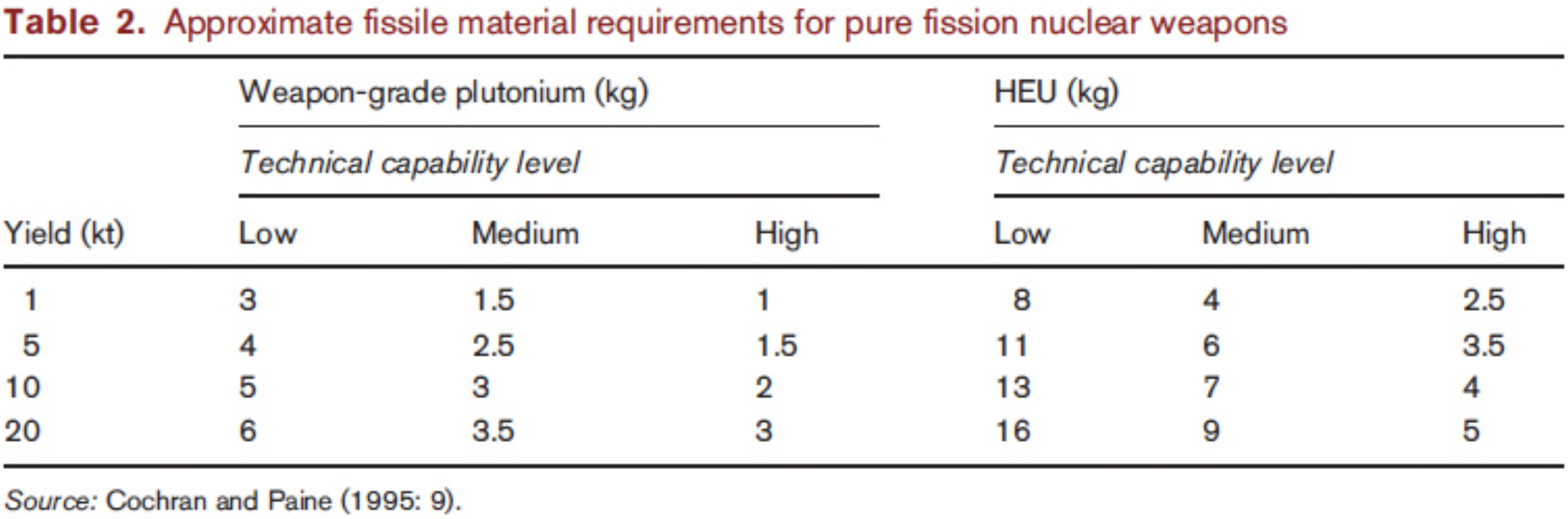


Table 2. Approximate fissile material requirements for pure fission nuclear weapons

	Weapon-grade plutonium (kg)			HEU (kg)		
	Technical capability level			*Technical capability level*		
Yield (kt)	Low	Medium	High	Low	Medium	High
1	3	1.5	1	8	4	2.5
5	4	2.5	1.5	11	6	3.5
10	5	3	2	13	7	4
20	6	3.5	3	16	9	5

Source: Cochran and Paine (1995: 9).

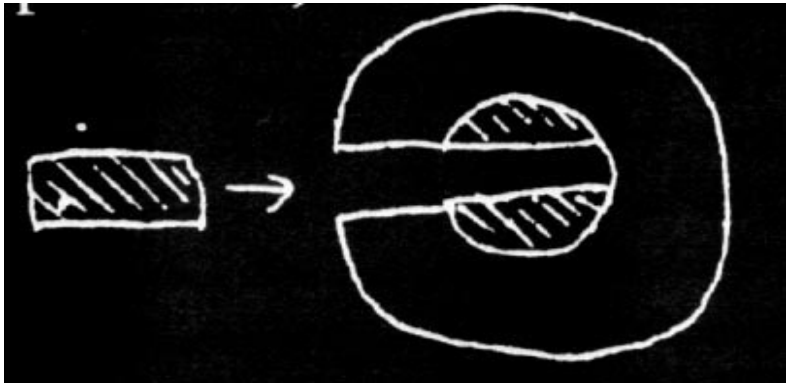
weapon design

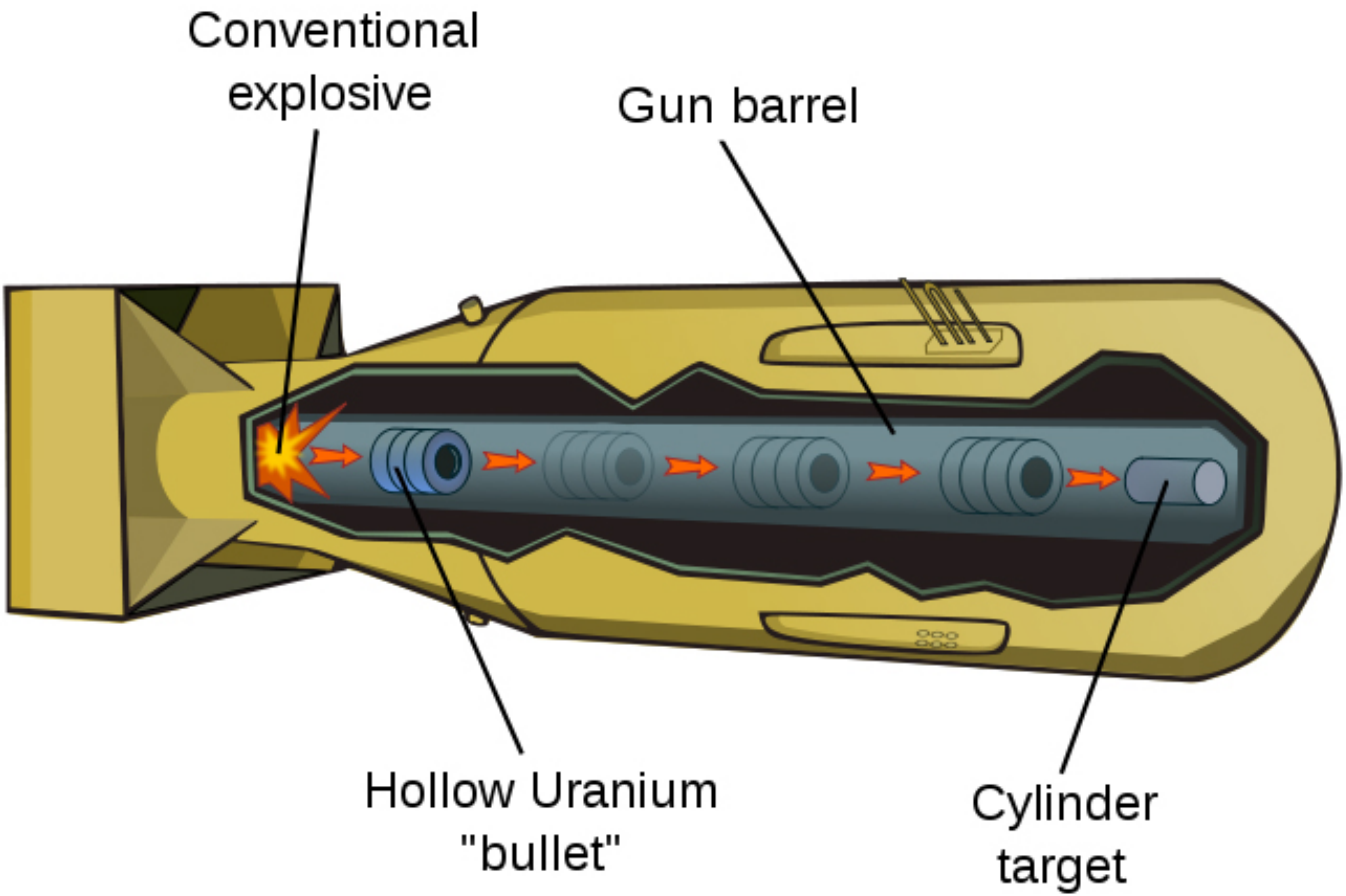
- the device must remain safe before firing (safety)
- detonation must rearrange the fissile material from sub-criticality to hyper-criticality in an extremely short time
- when hyper-criticality is achieved a flux of neutrons has to be produced
- pre-detonation has to be avoided (reliability)
- efficiency has to be maximized
- unauthorized detonation has to be prevented (security)
- the device must be militarly operational

detonation design: gun-type assembly

- the fissile material is split in two sub-critical masses for safety
- the two pieces are brought together with a relative velocity greater of 100 m/s, in order to avoid pre-detonation
- a neutron source is activated at impact

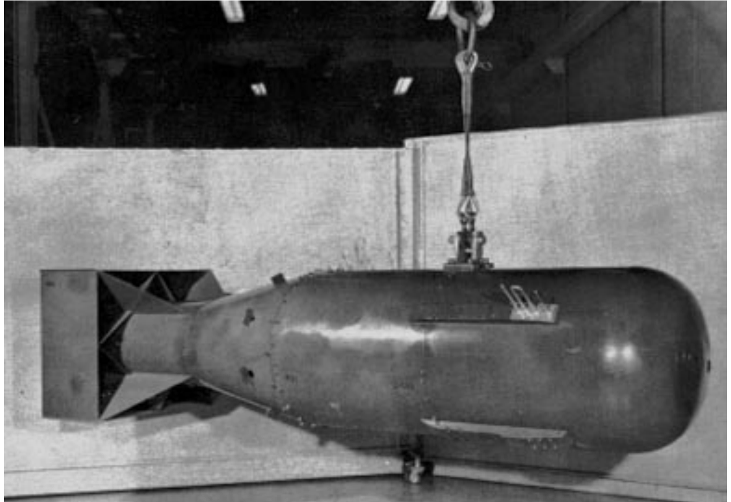
◆ too much slow for Plutonium weapons




Conventional explosive
Gun barrel
Hollow Uranium "bullet"
Cylinder target

Gun type: little boy

- enriched uranium up to 89% (average 80%)
- 2.4 critical masses 64.1 kg
- the projectile was a hollow cylinder with 60% of the total mass (38.5 kg)
- the target was a 4-inch-diameter solid spike, 7 inches long, with 40% of the total mass (25.6 kg)
- tamper and neutron reflector of tungsten carbide and steel, with a combined mass of 2,300 kg
- fired at 300 m/s in 1.80 m anti-aircraft gun
- supercriticality reached in 1.35 ms
- total length 3 m, diameter 70 cm
- total weight 4,000 kg
- energy 15 kton, efficiency 1.3%

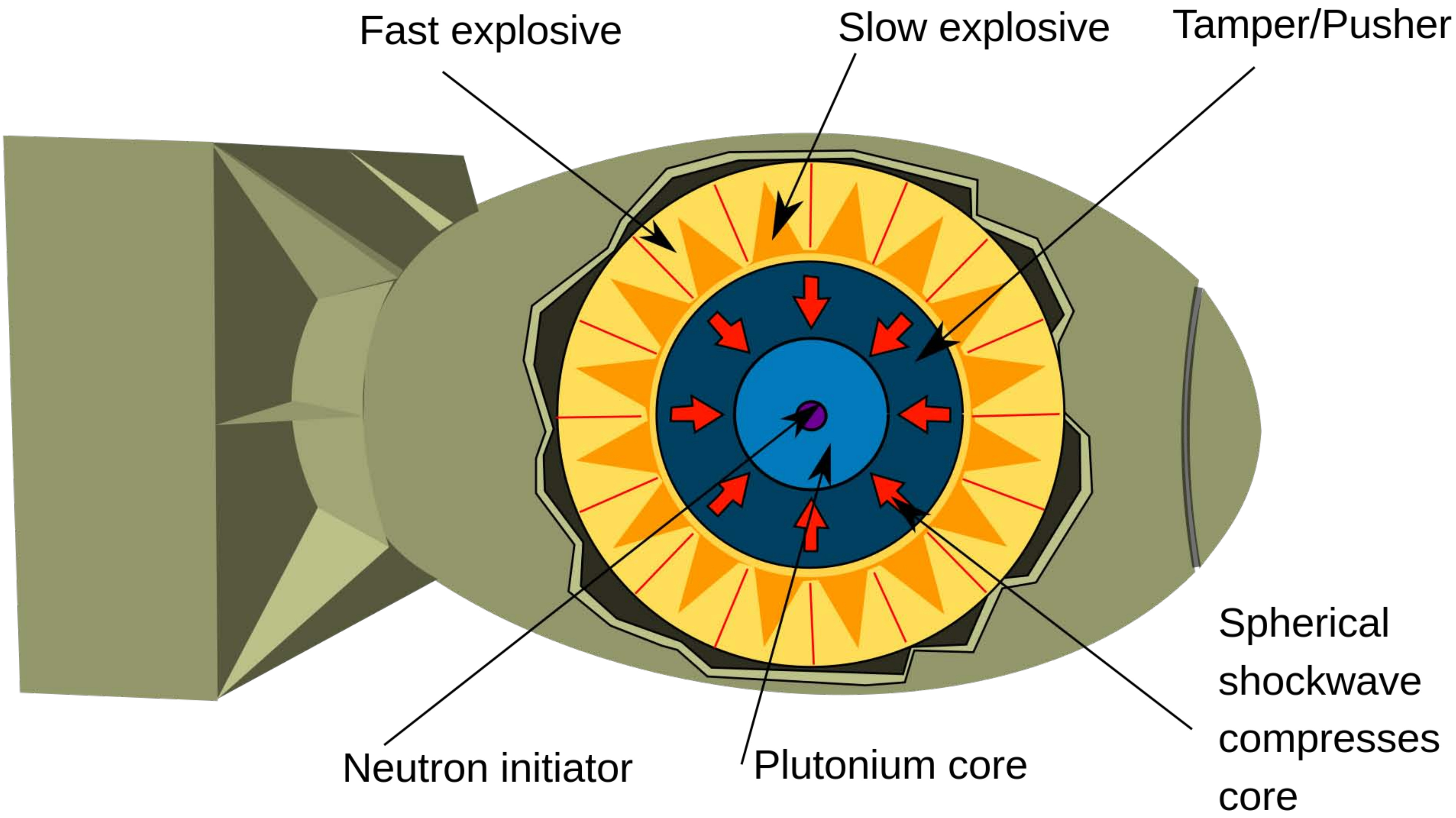


remnants of Hiroshima

detonation design: implosion assembly

- the higher the density, the shorter the mean free path of neutrons, and higher the frequency of fissions
- a factor two increase of the density makes a subcritical mass equivalent to four critical masses

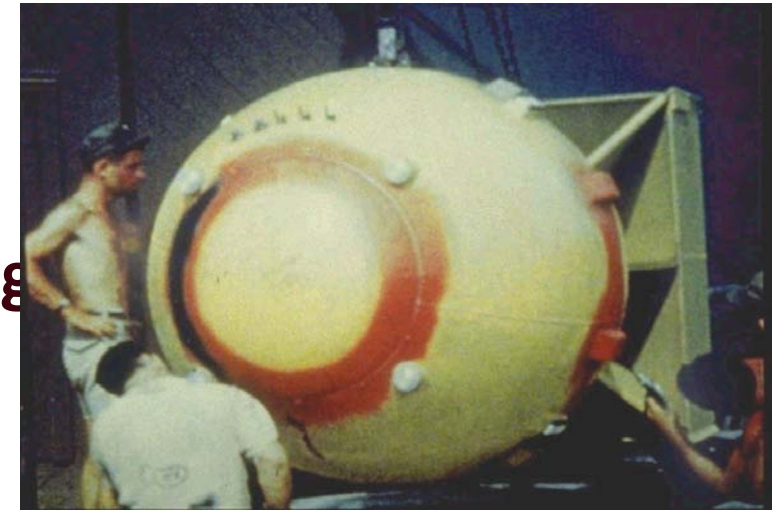
◆ a special arrangement of fast and slow conventional explosives properly fired in time produce a converging wave (implosion) to compress the fissile material initially in a sub-critical configuration



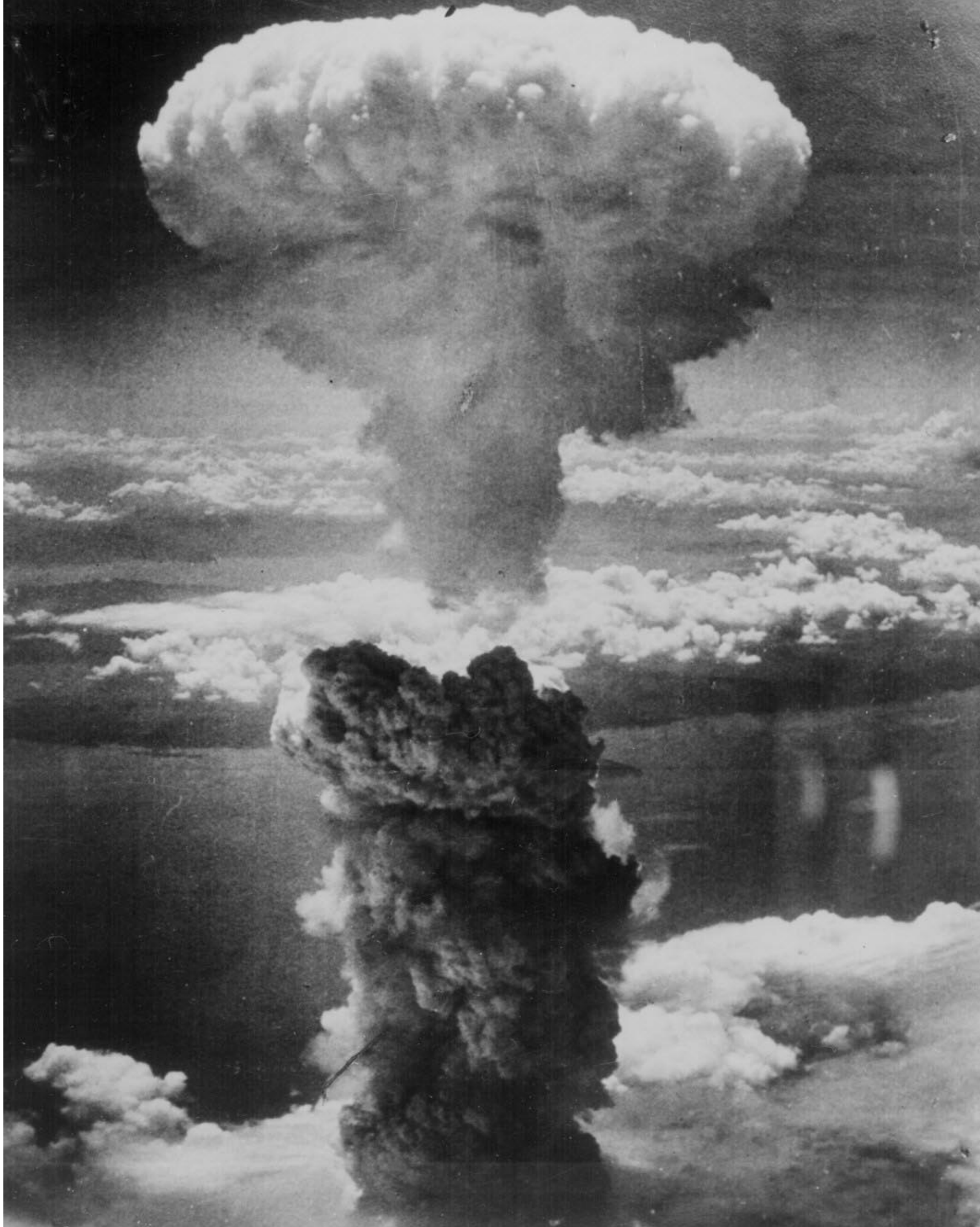
implosion is safer, more secure and reliable than gun assembly and ensures greater efficiency

Implosion weapon: fat man

- Plutoniun-239 (delta phase) with 3% Gallium
- fissile mass 6.2 kg
- structured in concentric spheres :
  - polonium-berillium neutron source
  - fissile material
  - natural uranium pusher/tamper (120 kg)
  - alluminium shell
  - 32 high explosive lenses mass 2500 kg
  - external egg-shell, diameter 150 cm
- implosion time ≈ 2 microseconds
- total length 365 cm, total weight 4900 kg
- energy 22 kton, efficiency ≈ 20%



the nuclear “mashrom” over Nagasaki



nuclear scientists have developed over the years a variety of weapon devices, optimized for military or strategic objectives, suited to a lot of delivery platforms.

Several contries started nuclear weapon programs; presently 10 have nuclear forces with a total of some 15000 operational devices

CIC-9: CN70-2103

Bibliography

- G. Charpak, R.L. Garwin, V. Journé, de Tchernobyl en Tchernobyls, Jacob, Parigi, 2005
- United Nations Scientific Committee on the Effects of Atomic Radiation, Biological mechanisms of radiation actions at low doses, United Nations, New York, 2012
- Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons, third edition, United States Department of Defense and the Energy Research and Development Administration, Washington, 1977
- R. Serber, The Los Alamos Primer, University of California press, Berkeley, 1992

Alessandro Pascolini

pascolini@pd.infn.it
userwww.pd.infn.it/~pascolin
@pascolin