National Academy of Sciences of Ukraine
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Lecture #1: Introduction in Nuclear Reactor Physics

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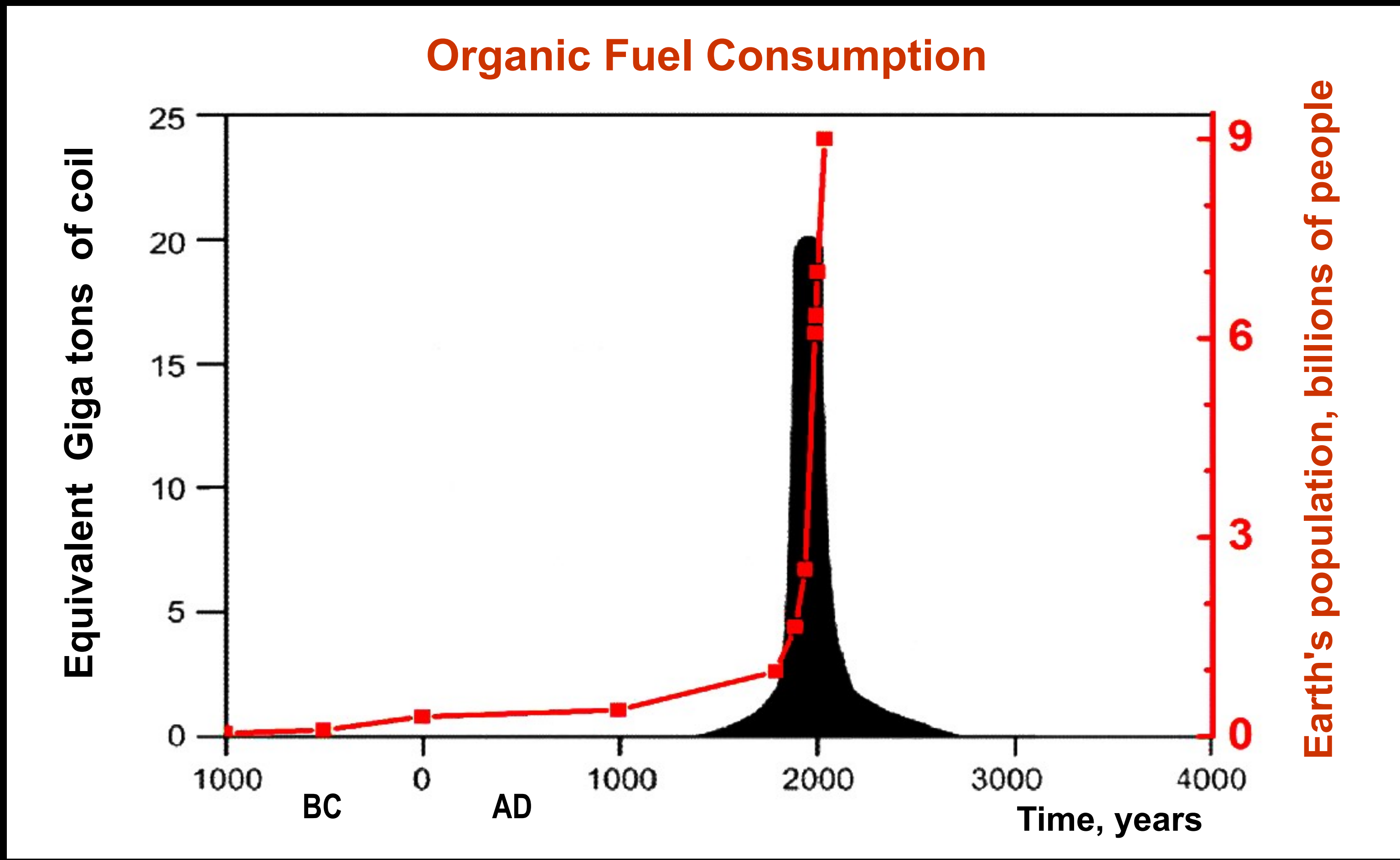
Outlook:

- Human Civilization & Power Consumption
- Fundamental differences between different types of "Energy sources"
- Basic principles of operation of a nuclear reactor
- Nuclear power in the world
- Main problems of nuclear power
- And ways to solve these problems
- Opened and closed nuclear fuel circles

Civilization & Power Consumption

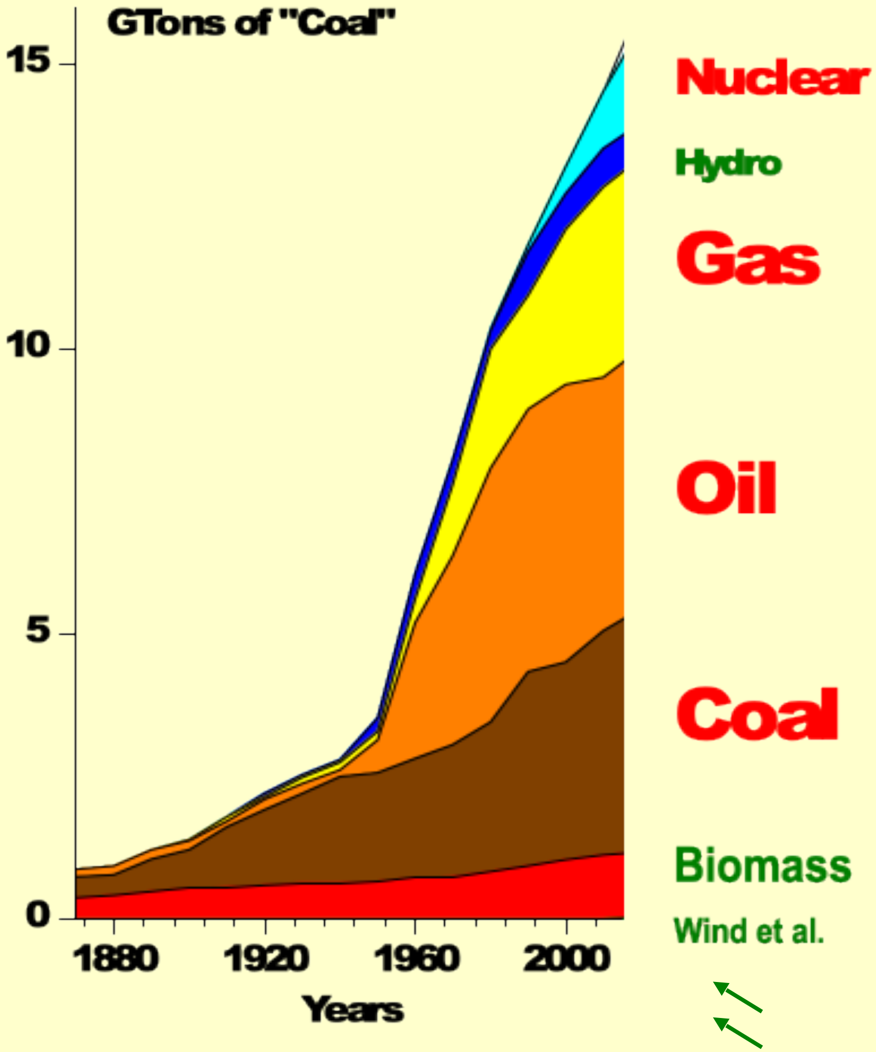
First cave-fire ~ 500 000 years ago : "Chinese Prometheus"

Metallurgy: Copper (5 ky BC) → Bronze (3 ky BC) → Iron (1 ky BC)



From the book: Ian Hore Lacy,"Nuclear Energy in the 21st Century", Elsevier Publ., 2006.

Dynamics of the global consumption of energy resources



CURRENT USE		2012	2016 (IEA)
Source	EJ/y	%	%
Oil	170	33.20	31,9
Coal	139	27.15	27.1
Gas	109	21.30	22.1
Biomass	51	9.96	9.8
Uranium	30	5.86	5.0
Hydro	12	2.34	2.5
Wind	0.72	0.14	0.83
Other renew	0.23	0.045	0.48
Solar	0.04	0.007	0.29
Total:	512	100%	100%
Fossil	448	87.5	86.1
Renewable	64	12.5	13.9

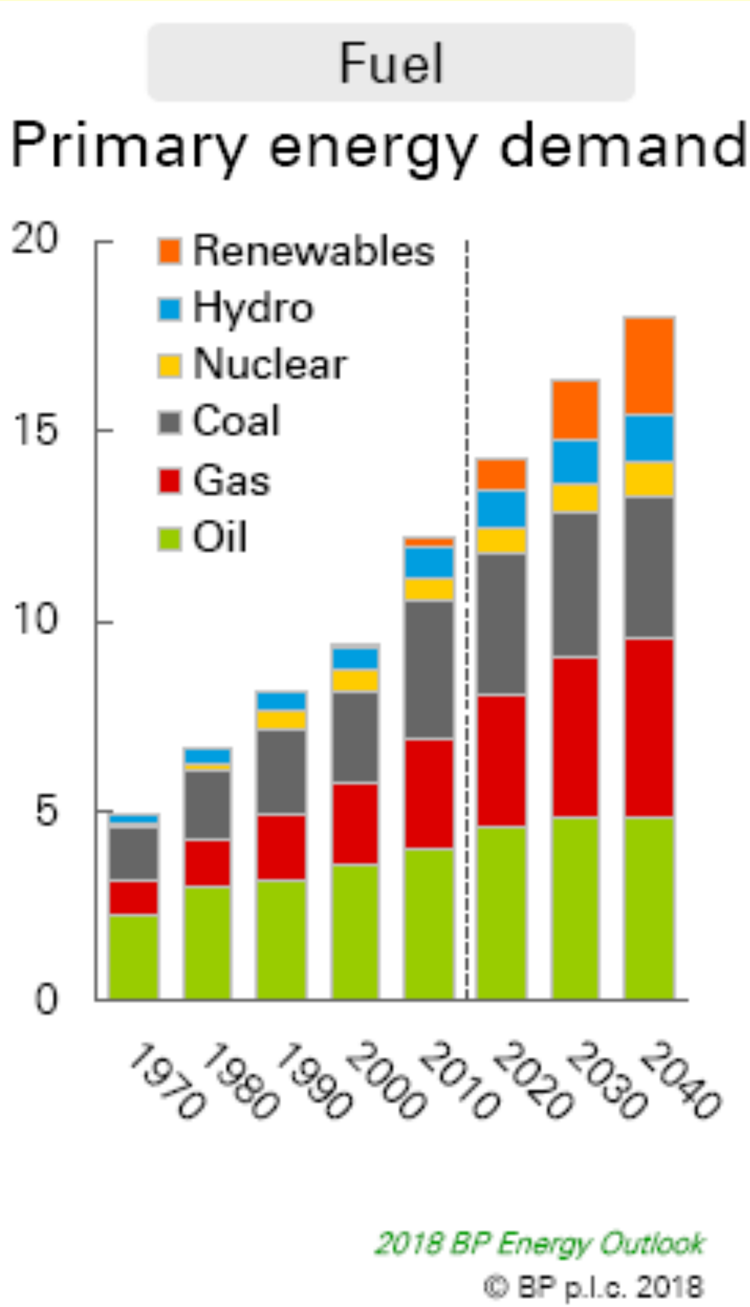
x 6 !!

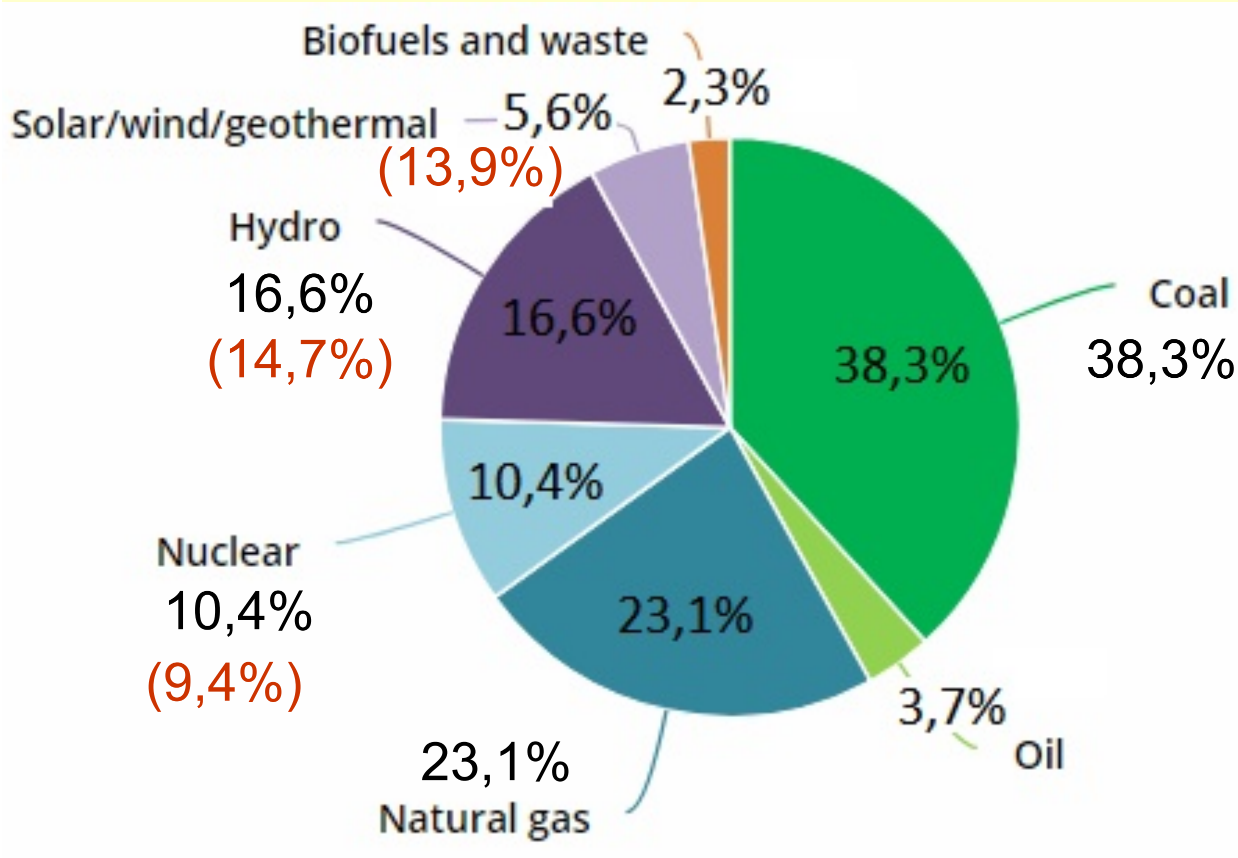
x 40 !!

1EJ (ExaJ) = 10^{18}J = $2.78 \cdot 10^{11}$ kW·h

J. Mercure, "Energy", 46 (2012) 322.

Global electricity production by types fuel **2016** (2023)





Different kinds of "Energy sources"

1) " Mechanical power " is the work by Gravitational field of the Earth

$$F = \gamma \frac{m \cdot M}{r^2}$$

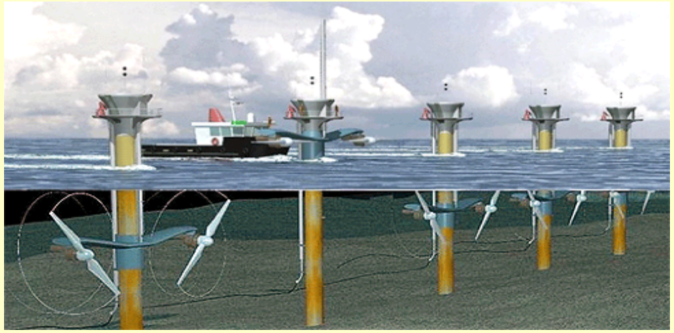
$$E = g \cdot m \cdot h$$

$$g = \gamma M_3 / R_3^2$$

To boil 1 liter of water

~ 0.1 kWh

~ 42 700 kg·m - mechanical energy (assuming 100% transform. efficiency!)



Different kinds of "Energy sources"

2) " Chemical power " (carbon oxidation) has Electromagnetic nature

$$C + O_2 = CO_2$$

$$F = k\frac{q \times Q}{r^2}$$

$E \sim 1$ eV/atom $= 1.6 \cdot 10^{-19}$ J/atom

To boil 1 liter of water ~ 0.1 kWh

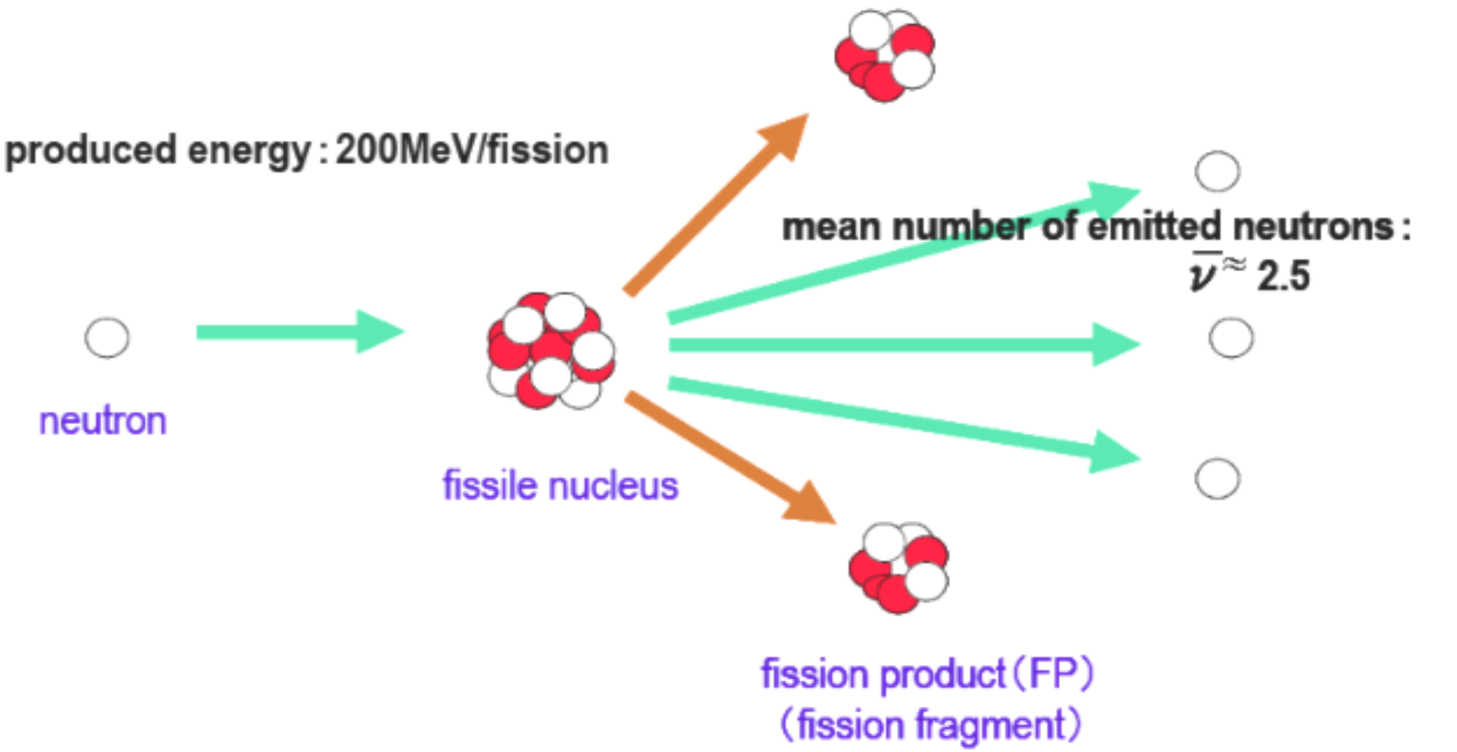
~ 10 g of gasoline ~ 40 t·m mech. energy - 10^8 times !!!

Different kinds of "Energy sources"

3) " Nuclear energy " is the binding energy of the nucleons in the nucleus - "Strong interaction"

$$E_N \approx \frac{Ze^2}{R_N}$$

Fission of 1 atomic nuclear of Uranium releases ~ 200 MeV, i.e. 10⁸ times more !!! than at oxidation of 1 carbon atom

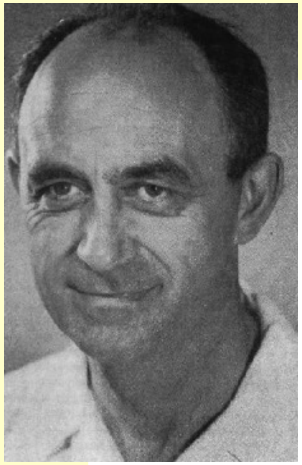


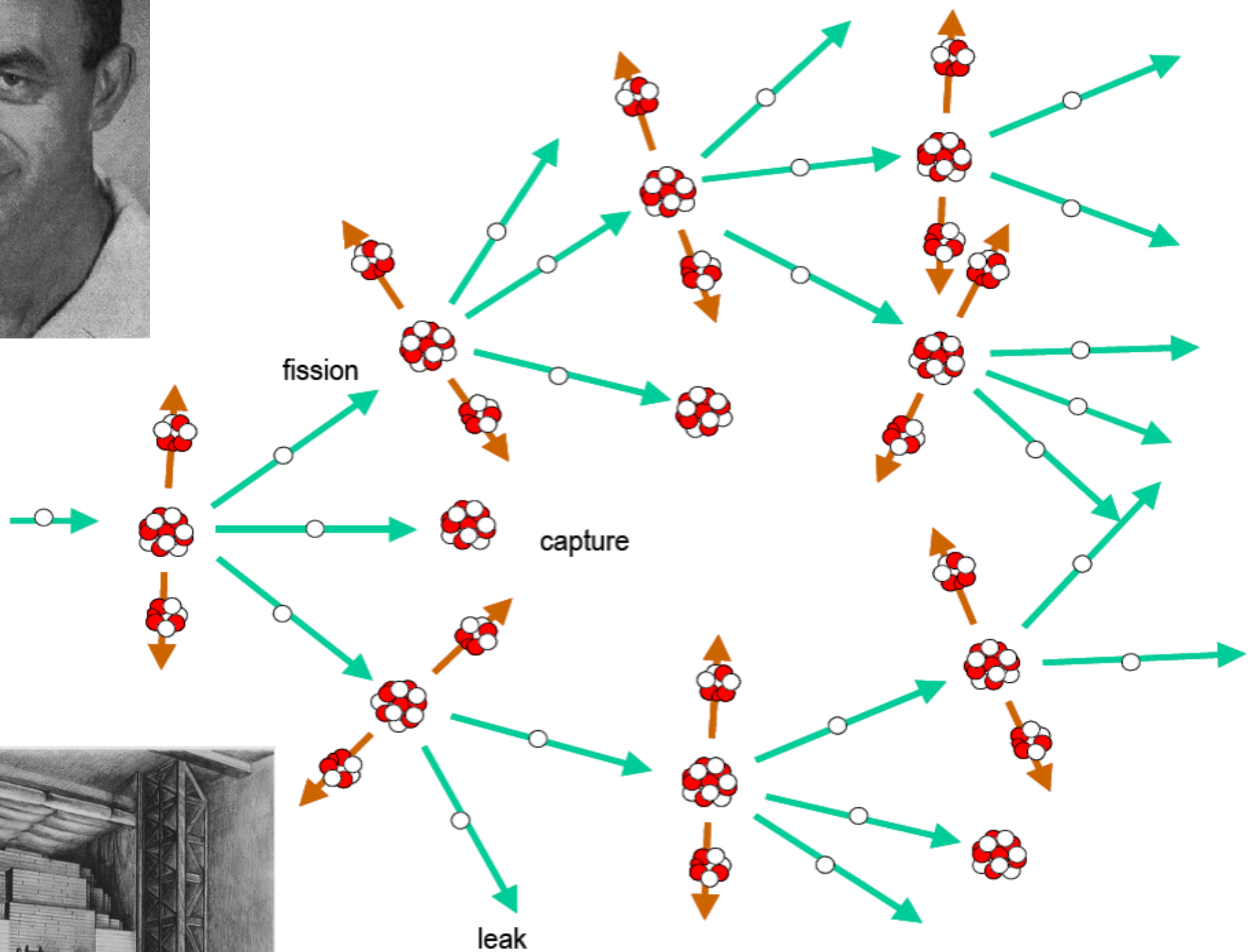
To boil 1 liter of water ~ 0.1 kWh

is equivalent of fission ~ 10^{16} nuclei of ^{235}U ($1 cm^3 \sim 10^{22}$ atoms !)

~ 10 g of gasoline ~ 40 t·m mechanical energy

Nuclear chain reaction (Leo Szilárd and Enrico Fermi - 1939)





Neutron lifetime

~ 10^{-7}s – fast n

~ 10^{-4} s – thermal n

Delayed neutrons

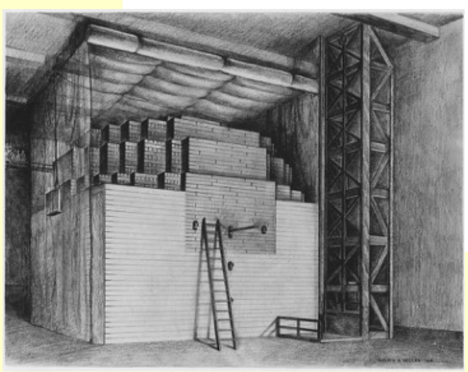
$N_d < 1\%$, $\Delta t \sim 10$ s

Neutron multiplication coefficient

$k_{eff} = 1$!!!

Reactivity

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \approx 10^{-5} \quad !!!$$

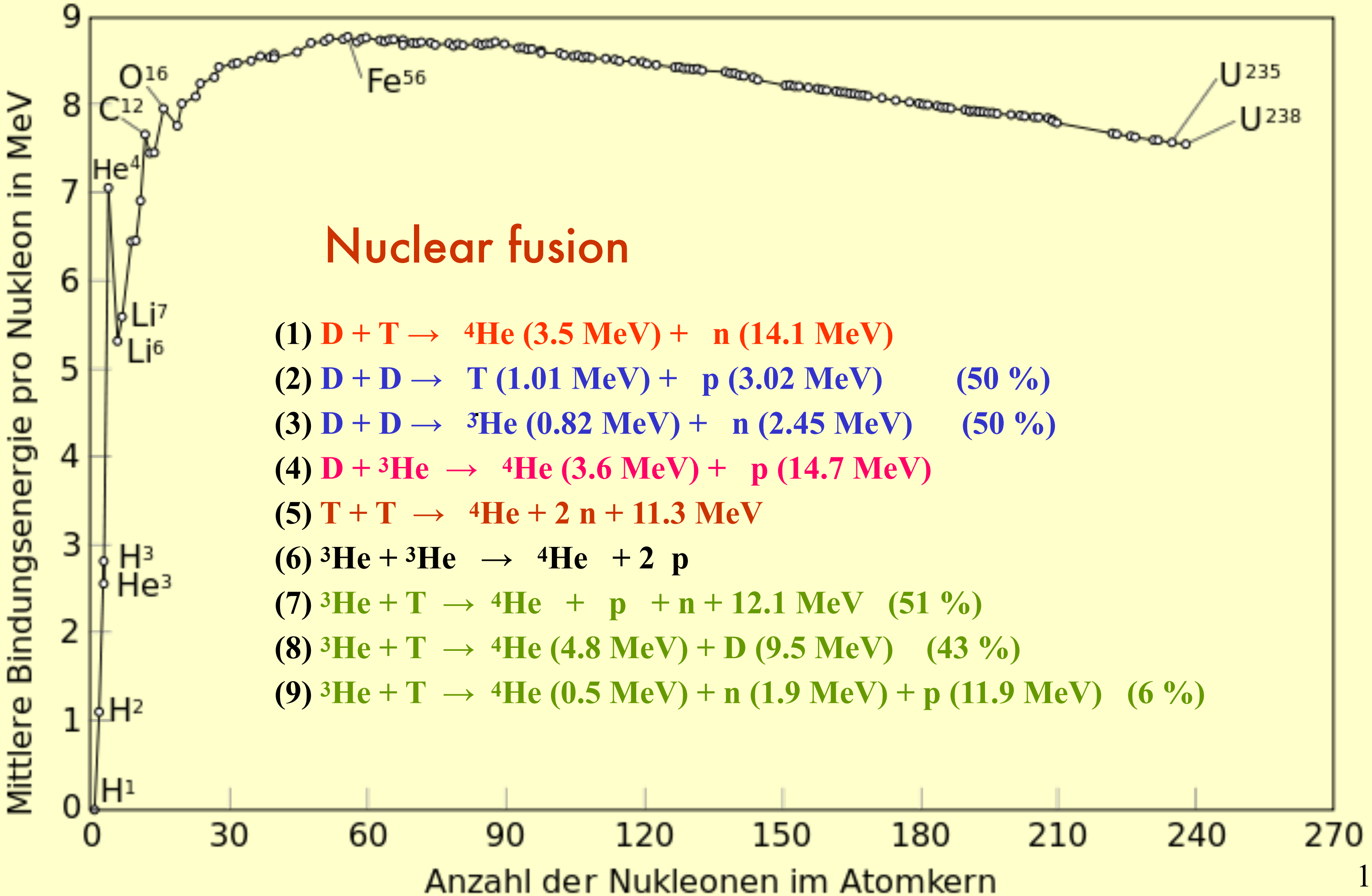


Chicago Pile-1 (1942) - 200 W or 2 liters of boiled water !

Source of nuclear energy is the mass defect

$$\Delta m = (Z \cdot m(p) + N \cdot m(n)) - M_n(Z, A) \qquad \Delta E = \Delta(m \cdot c^2) = c^2 \cdot \Delta m$$

Specific binding energy in the nucleus $\varepsilon = \Delta E / A$ (MeV/nucleon)



Nuclear fusion

(1) D + T → ^{4}He (3.5 MeV) + n (14.1 MeV)

(2) D + D → T (1.01 MeV) + p (3.02 MeV) (50 %)

(3) D + D → ^{3}He (0.82 MeV) + n (2.45 MeV) (50 %)

(4) D + ^{3}He → ^{4}He (3.6 MeV) + p (14.7 MeV)

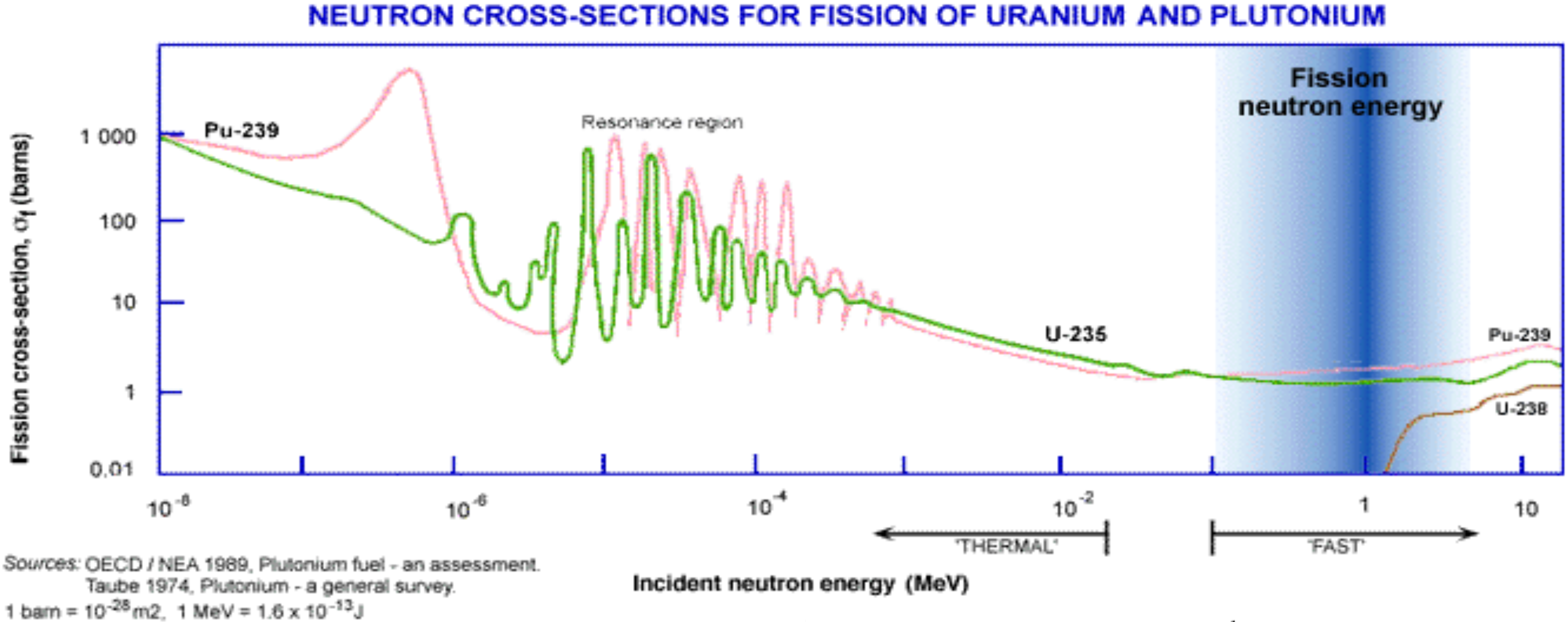
(5) T + T → ^{4}He + 2 n + 11.3 MeV

(6) ^{3}He + ^{3}He → ^{4}He + 2 p

(7) ^{3}He + T → ^{4}He + p + n + 12.1 MeV (51 %)

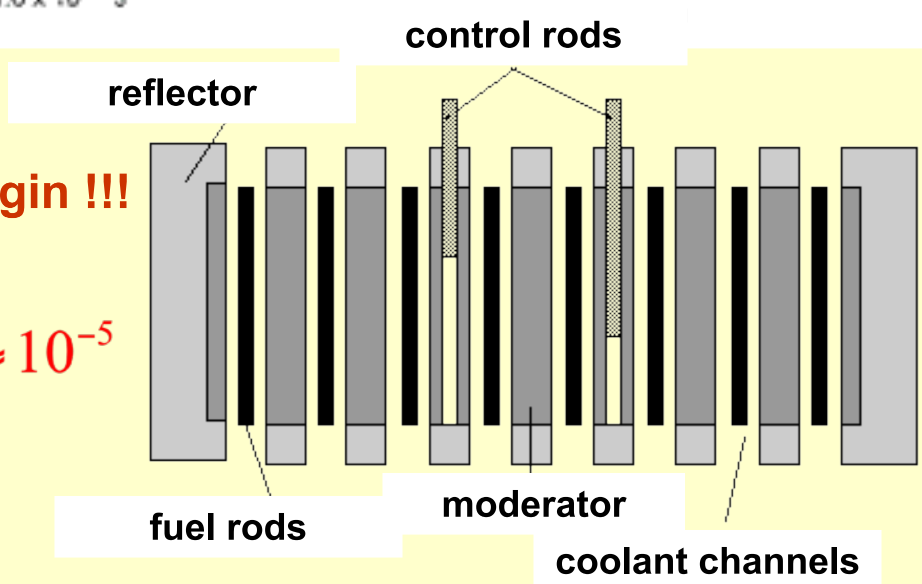
(8) ^{3}He + T → ^{4}He (4.8 MeV) + D (9.5 MeV) (43 %)

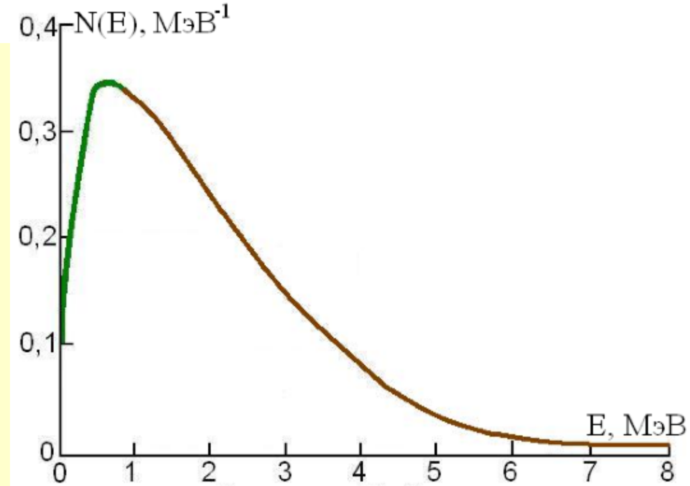
(9) ^{3}He + T → ^{4}He (0.5 MeV) + n (1.9 MeV) + p (11.9 MeV) (6 %)



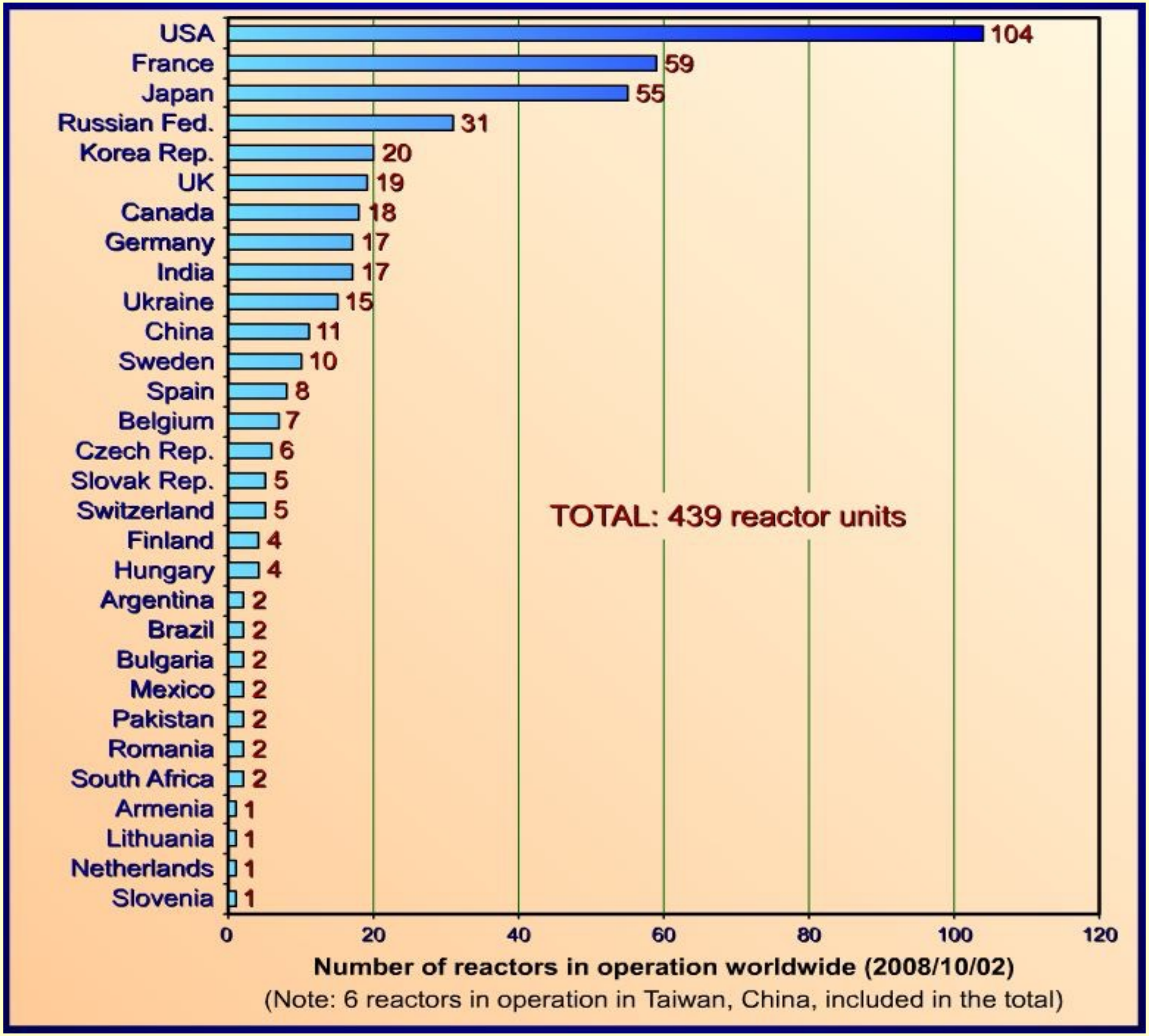
Reactivity margin !!!

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \approx 10^{-5}$$

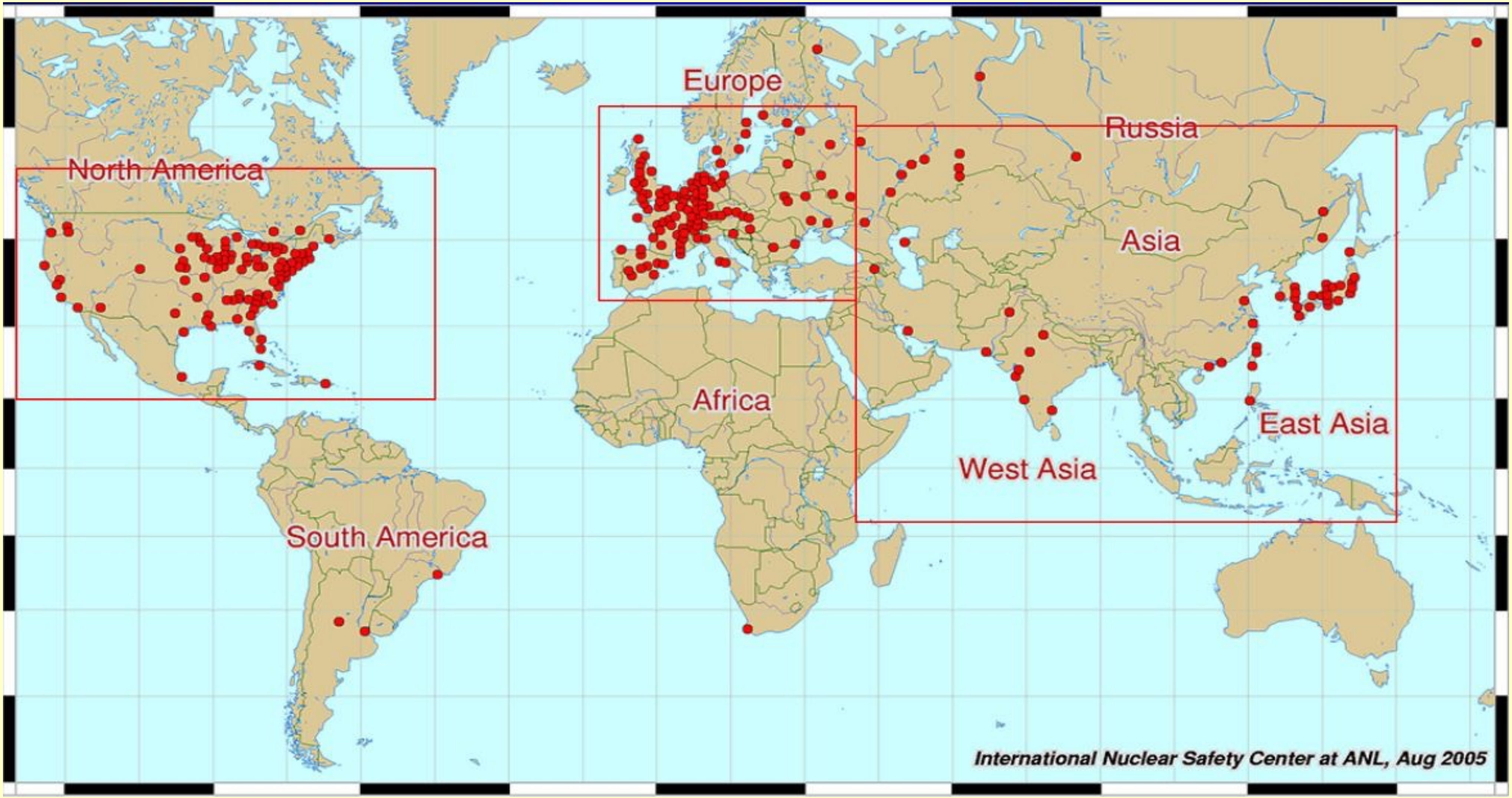


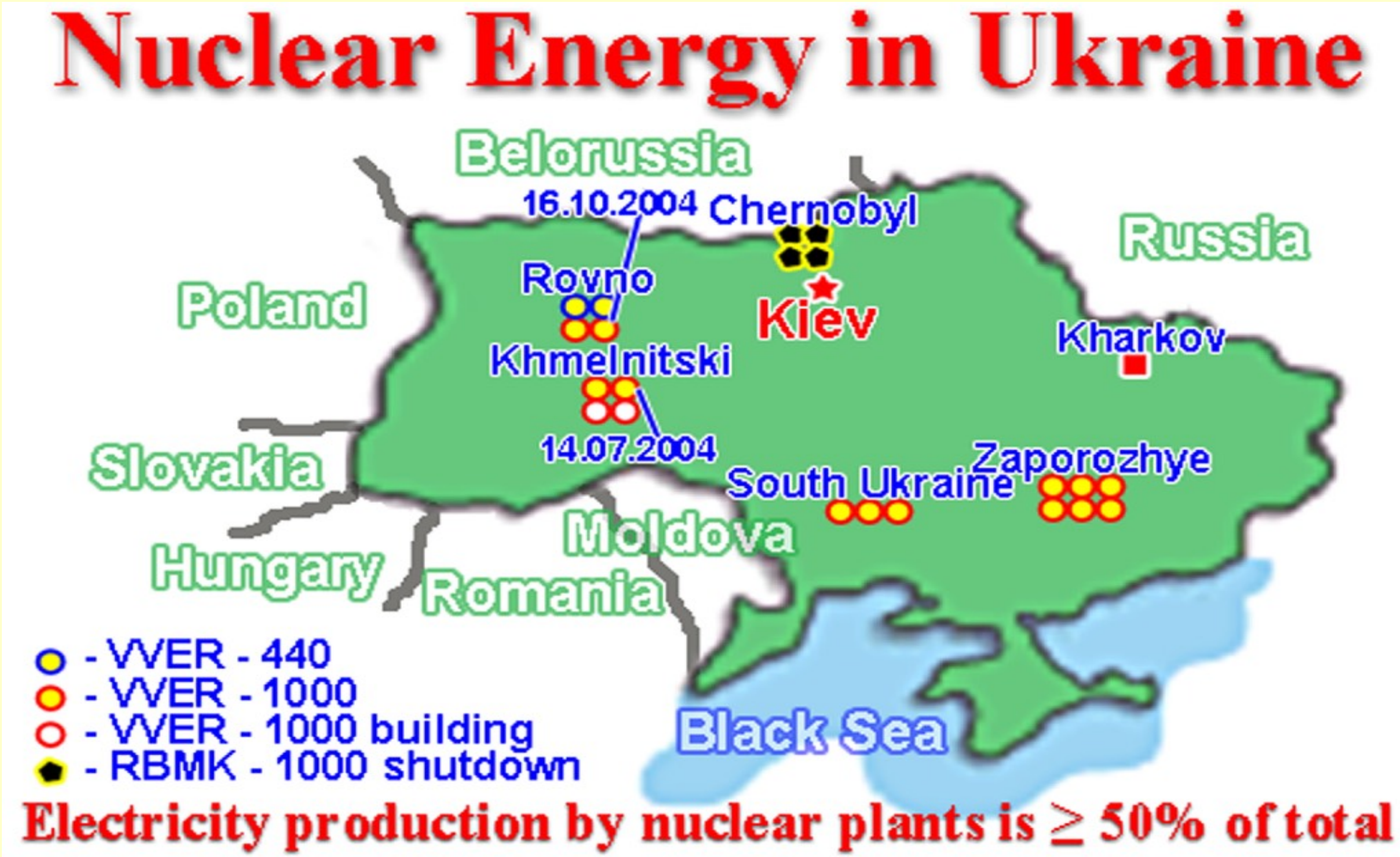


Nuclear Power (2019: Total = 450 reactor units)



Nuclear Power Today

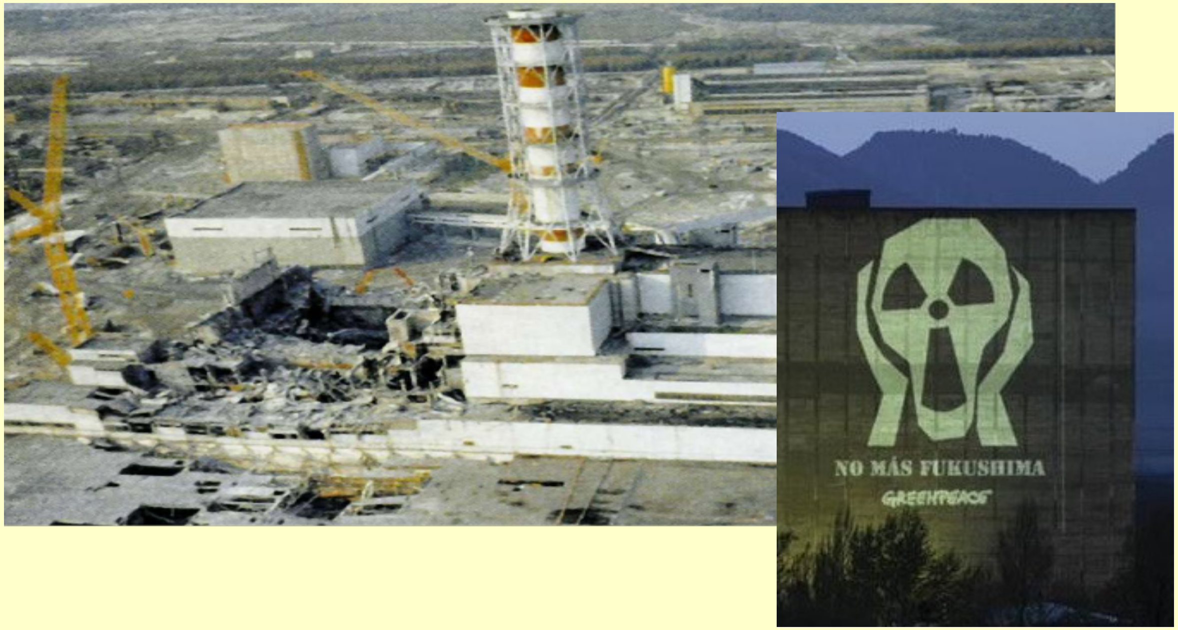


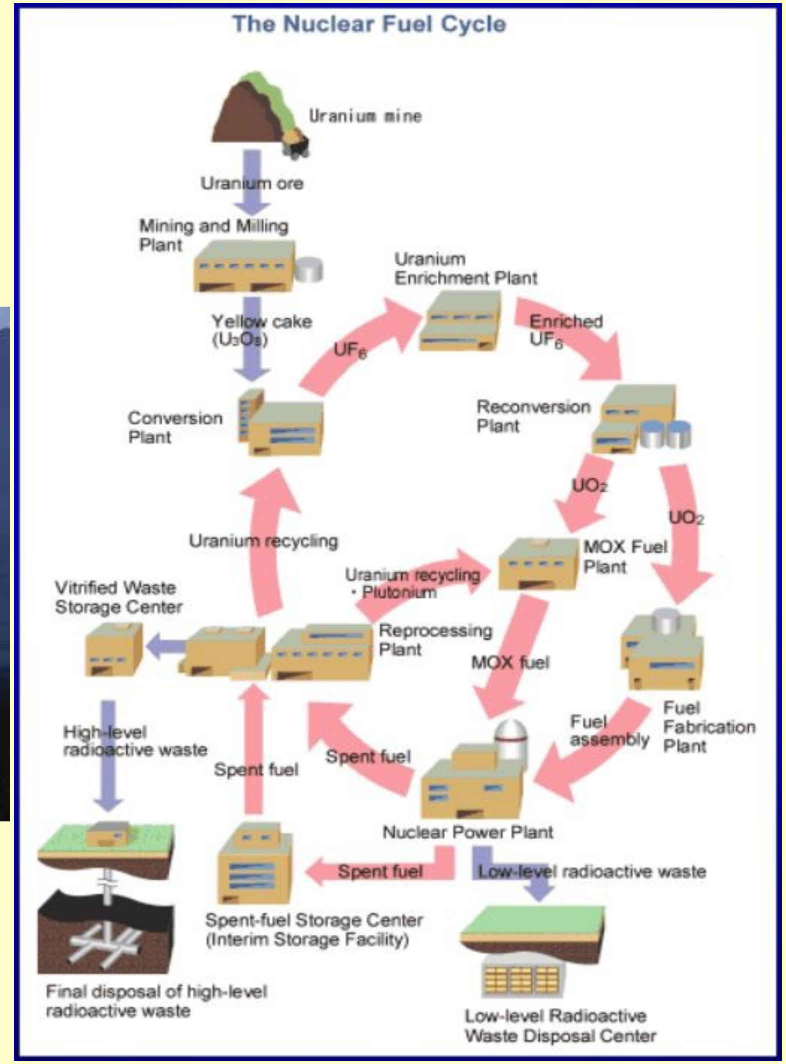


4 Nuclear Power Plants (13 WWER-1000 and 2 WWER-440)

Total Electric Power – 13,835 MWe.

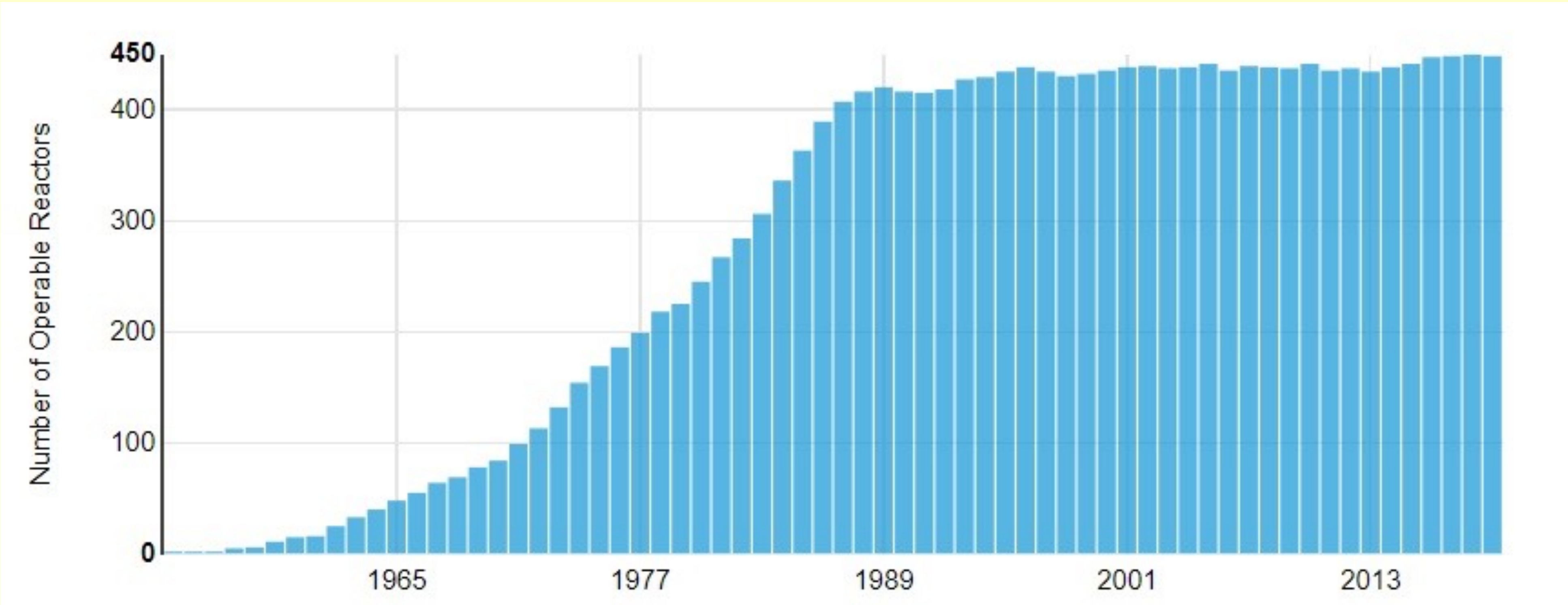
Nuclear Power Problems



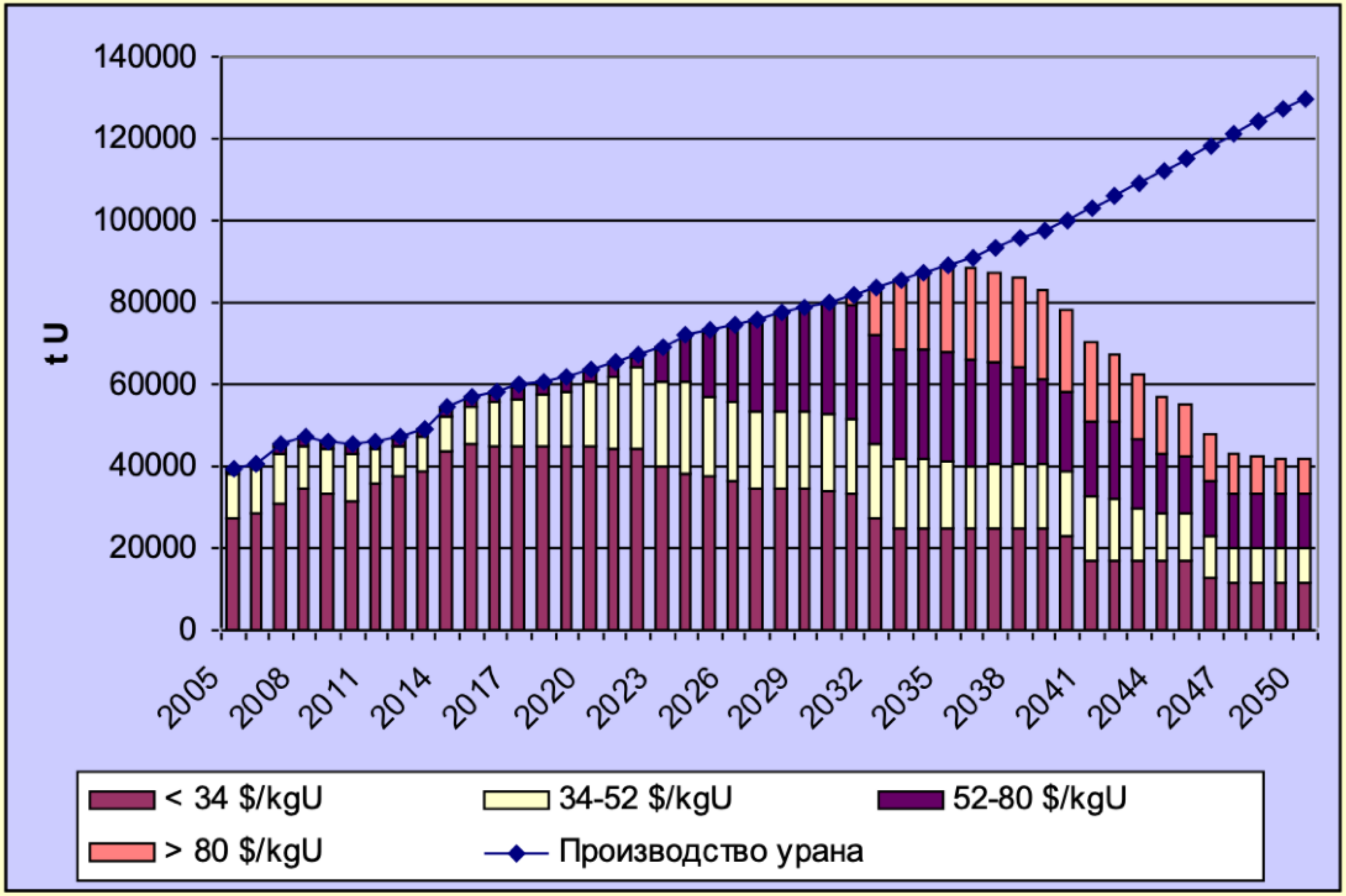


- **Safety !!!** (after Chernobyl accident)
- **Closed fuel cycle** (fuel reproduction)
- **Ecological problems** (nuclear waste utilization)
- **Nonproliferation of fissile materials** (nuclear terrorism)

Nuclear Power 2019

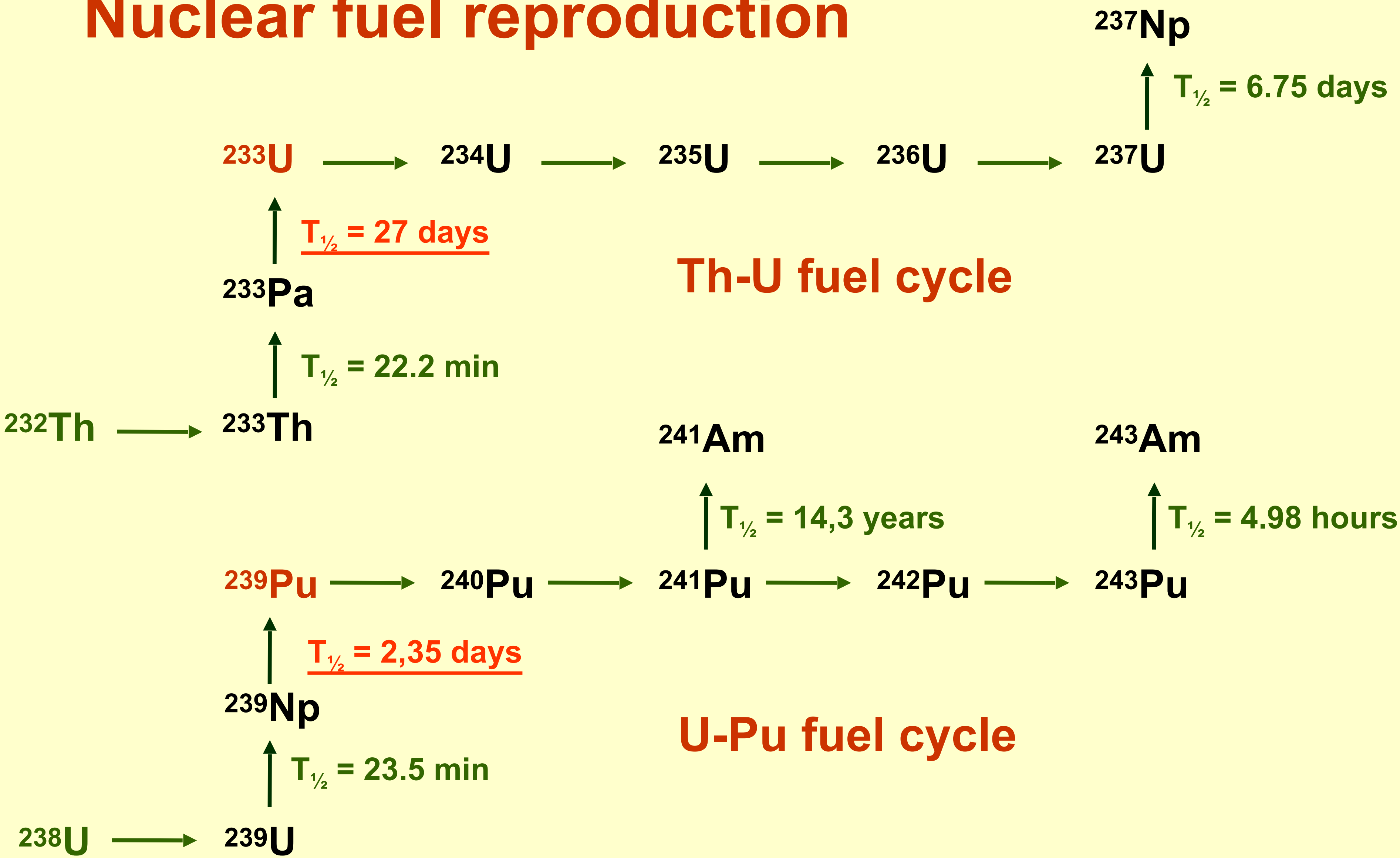


Explored Earth reserves of Uranium

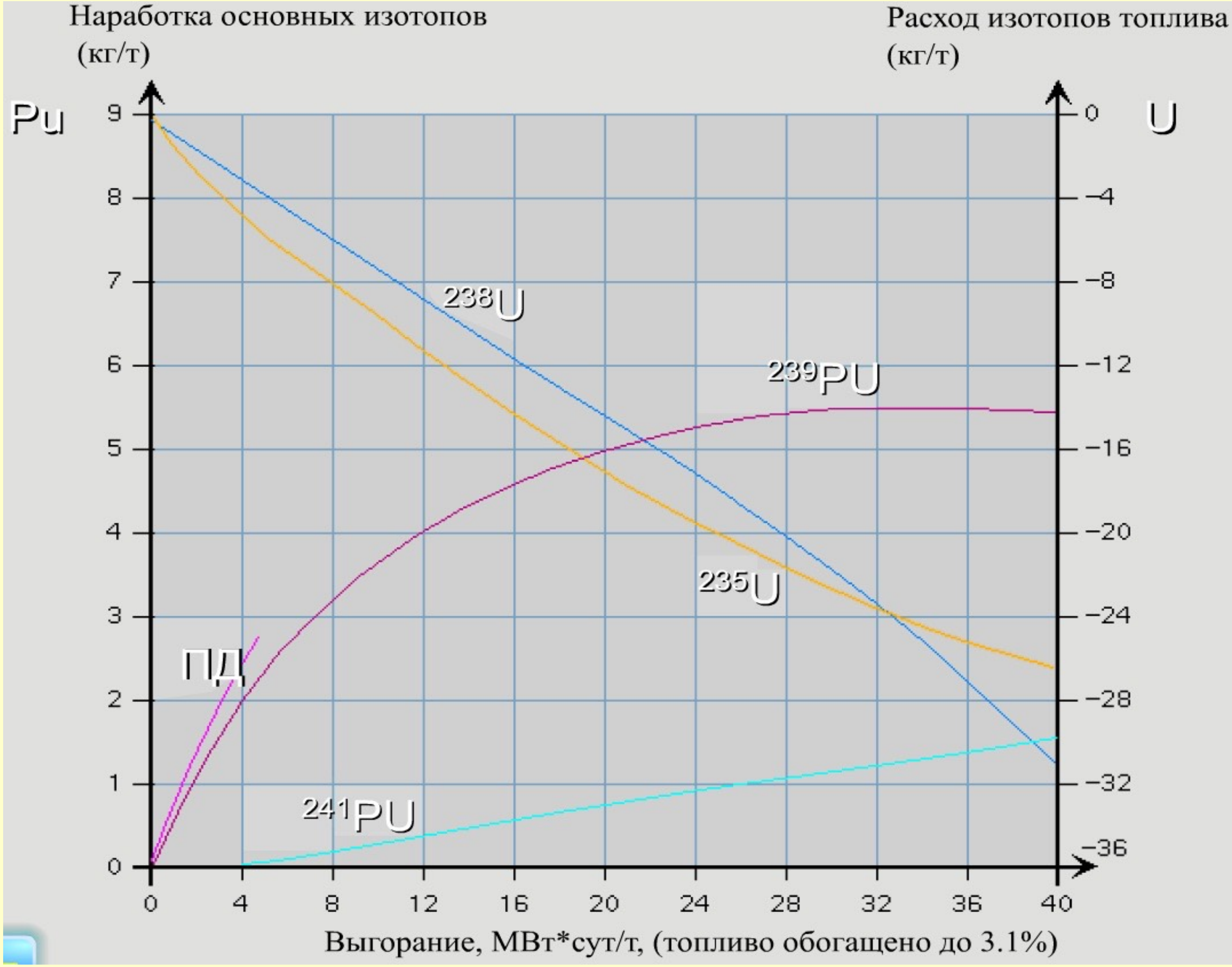


Nuclear plants are provided with Uranium-235 only until 2035!

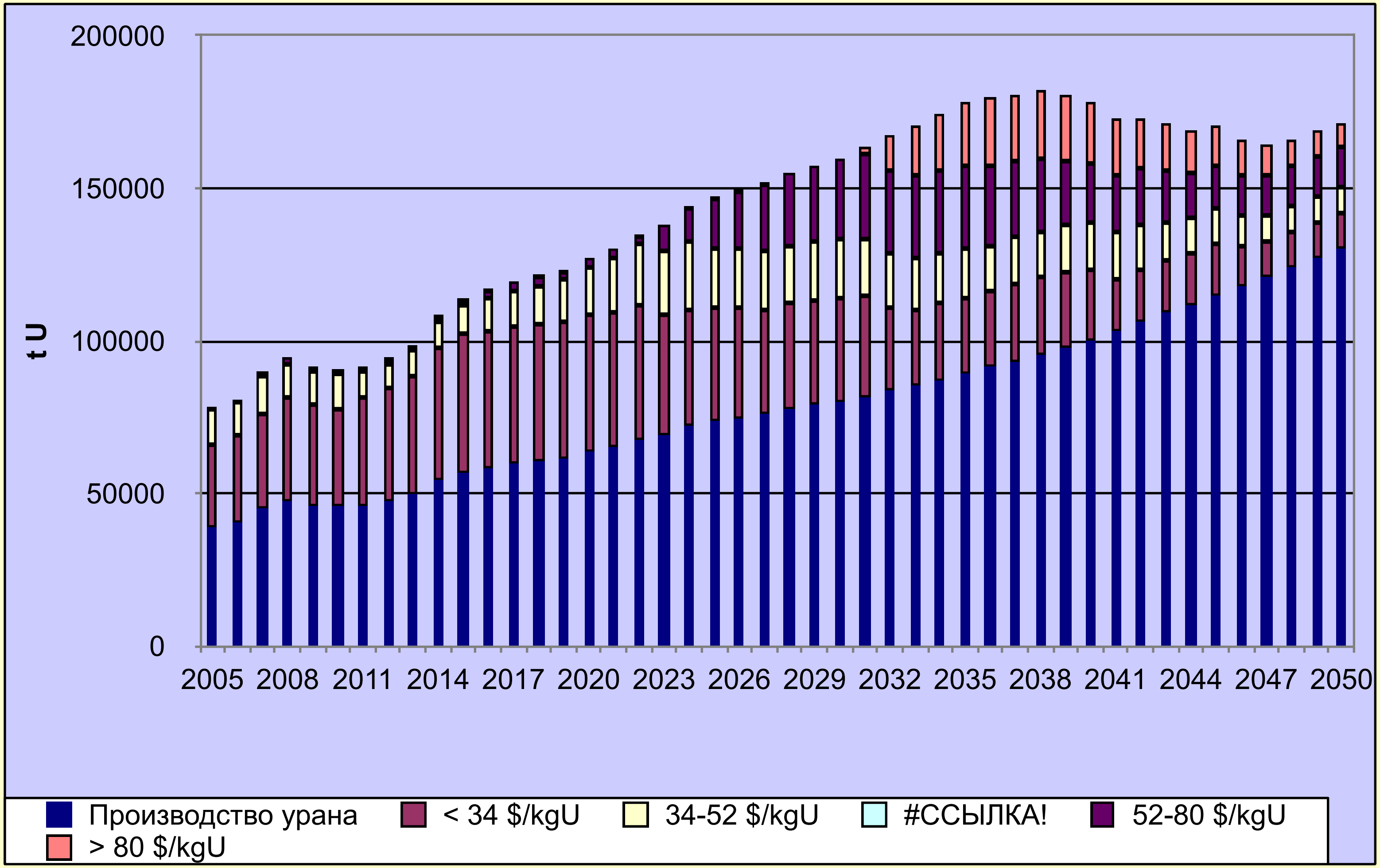
Nuclear fuel reproduction



Burnup and Reproduction of Nuclear Fuel

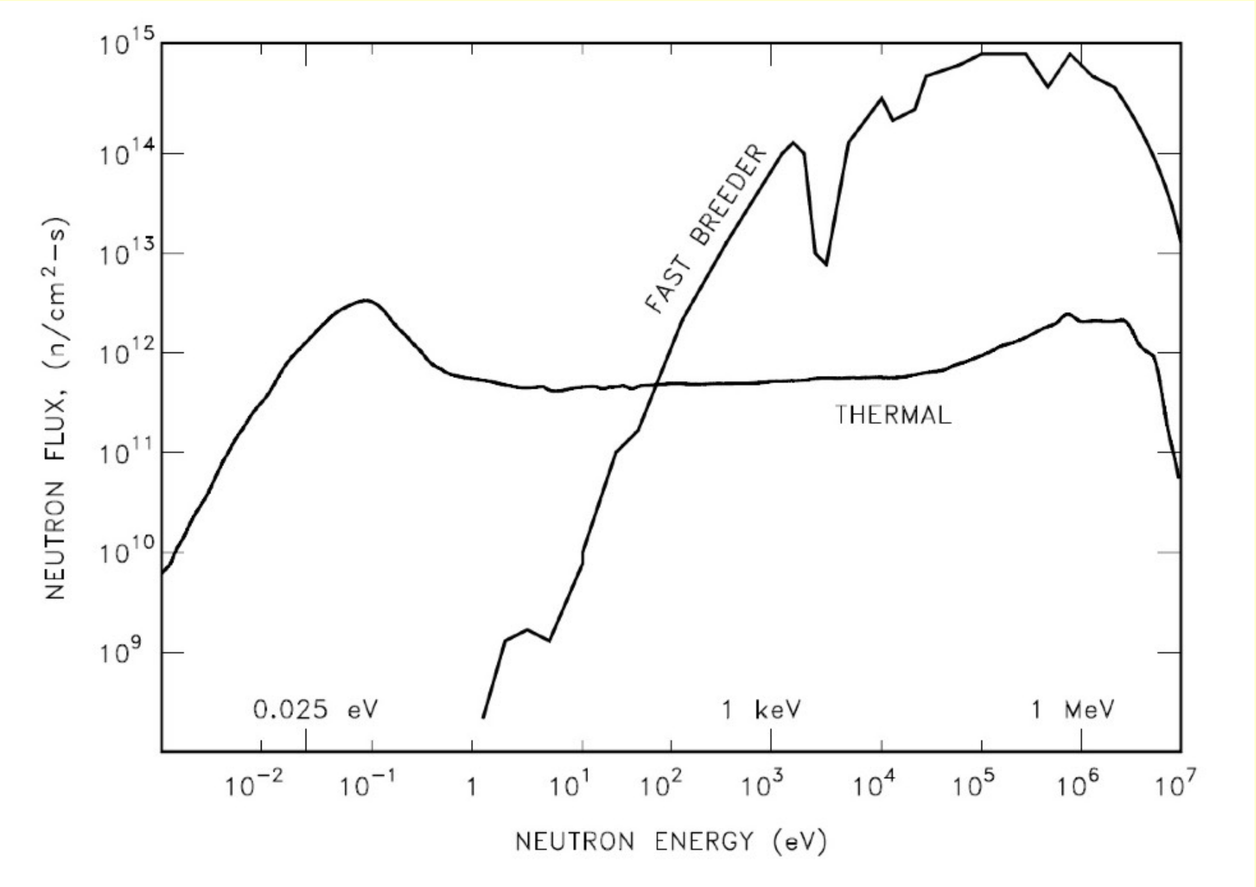


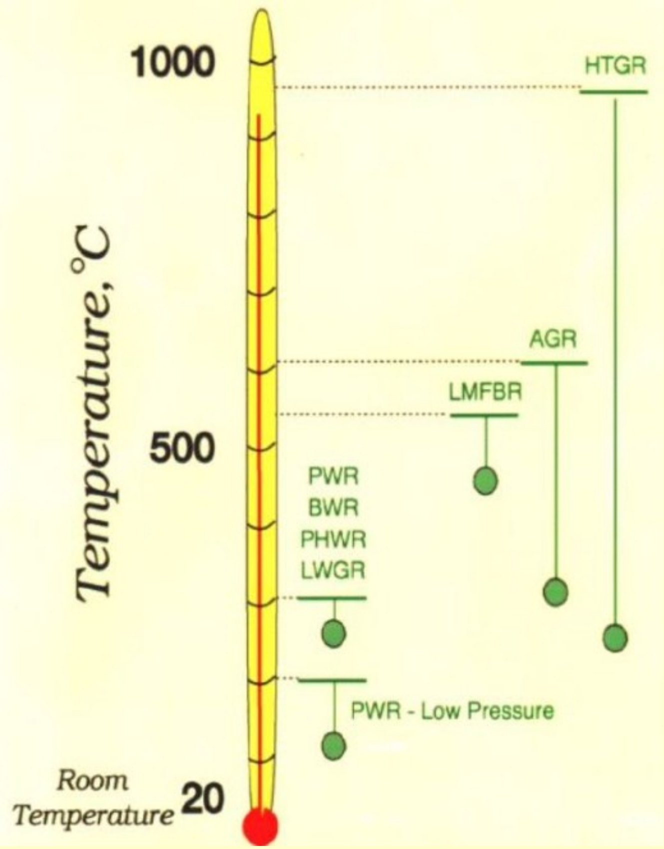
Forecast of ensuring uranium production until 2050 with explored reserves



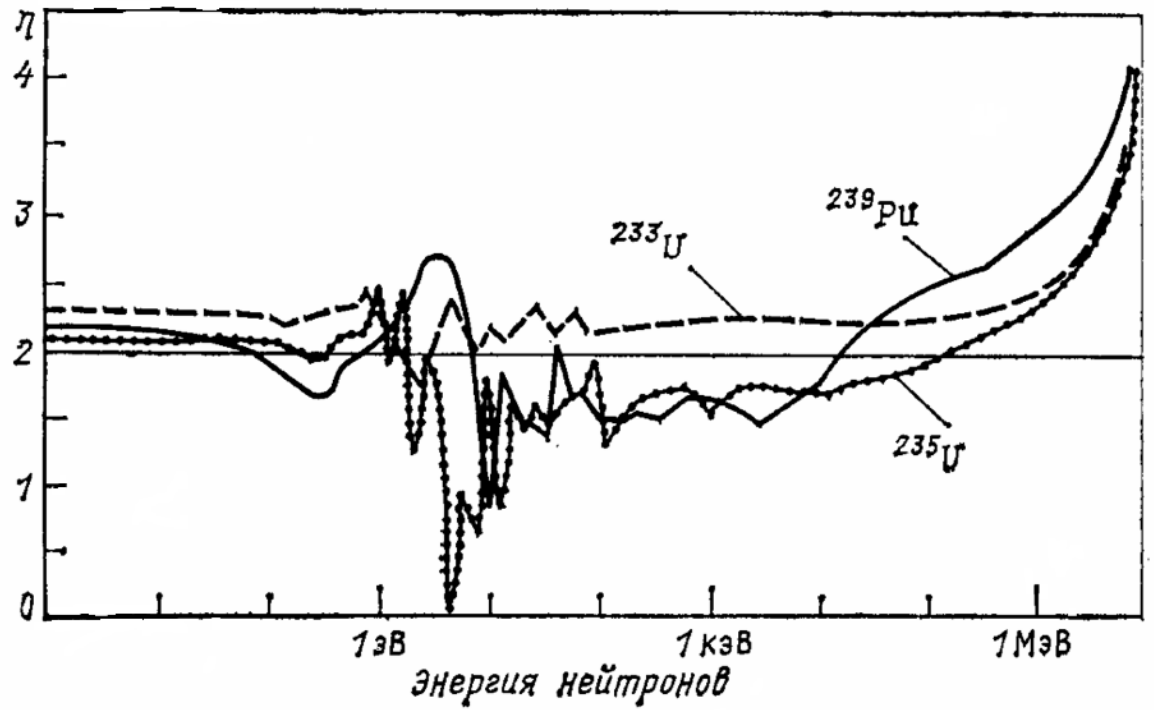
Production was provided with uranium reserves until 2035 (!)

Fast Reactors





Fast Reactors



Зависимость числа мгновенных нейтронов η на один акт поглощения от энергии падающих нейтронов

Значения η при усреднении по спектрам тепловых и быстрых нейтронов

Реактор *ν* ≈	^{239}Pu **2,9**	^{235}U **2,5**	^{233}U **2,5**
ЛВР	2,04	2,06	2,26
БН	2,45	2,10	2,31

Neutron balance

$\nu_{f5} = 2{,}42$ – average number of fast fission neutrons

$$\eta = \frac{\nu_{f5}\Sigma_{f5}}{\Sigma_{f5} + \Sigma_8} = \frac{\nu_{f5}}{1+\alpha}$$

$$\alpha = \Sigma_8 / \Sigma_{f5}$$

$$\eta - (1+L) \geq 1$$

$\eta \geq 2 + L \quad => \quad \boldsymbol{\eta \geq 2}$

BR = η – (1+*L*)
- breeding ratio

Fast Reactors

The main advantages of fast neutron reactors:

1) the possibility of reproduction of nuclear fuel (breeding reactors) $K_R = 1.4$

2) deep fuel burnout (economy)

3) high temperatures of the coolant - higher efficiency

4) small size (transportability)

Disadvantages of fast neutron reactors:

1) higher enrichment of nuclear fuel (4÷5 times)

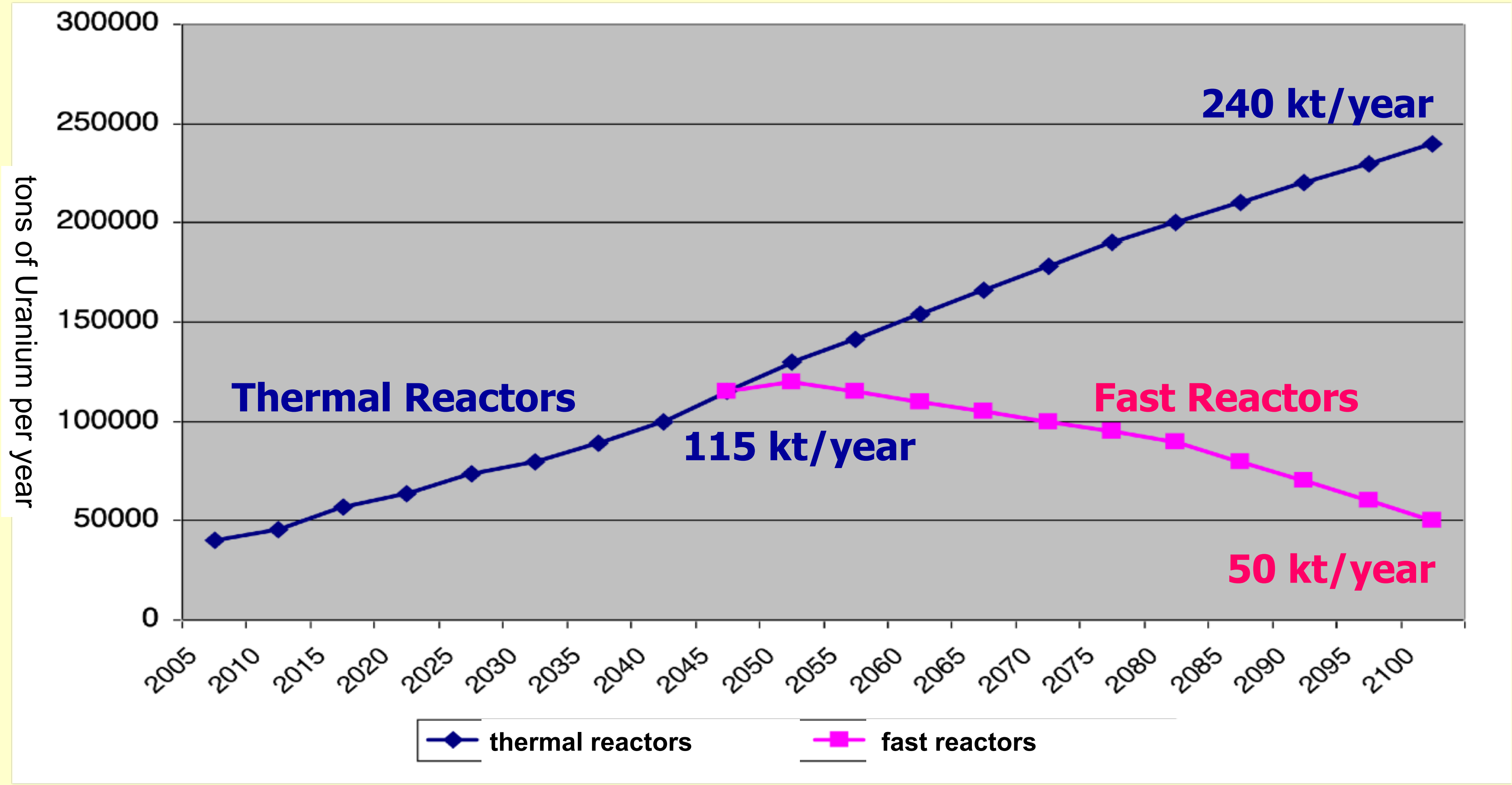
2) higher energy tension (4÷5 times)

3) coolant problem (liquid metal: Na, NaK, Hg, Pb, Bi; gas: He)

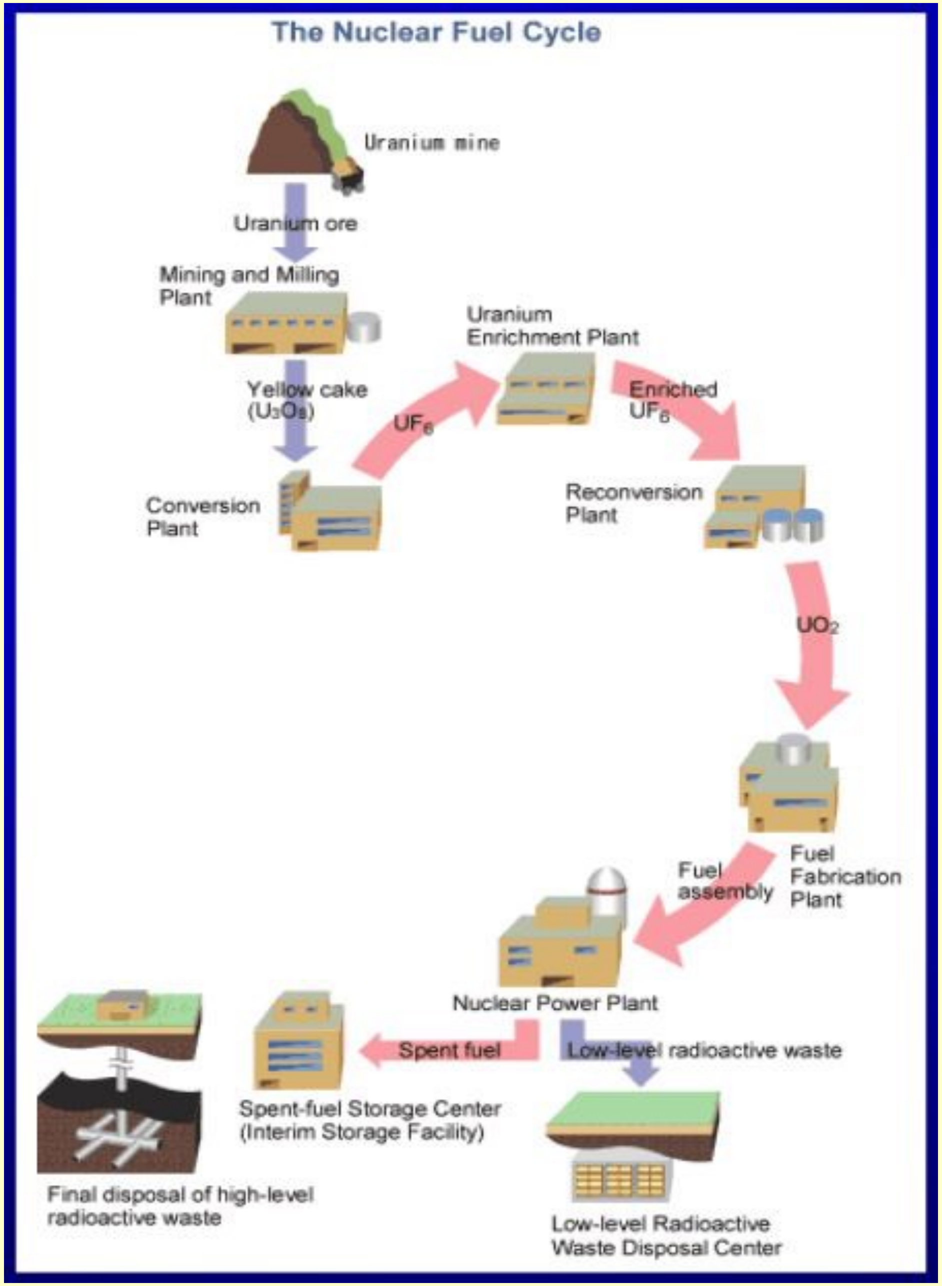
(TM = 98C, 20C)

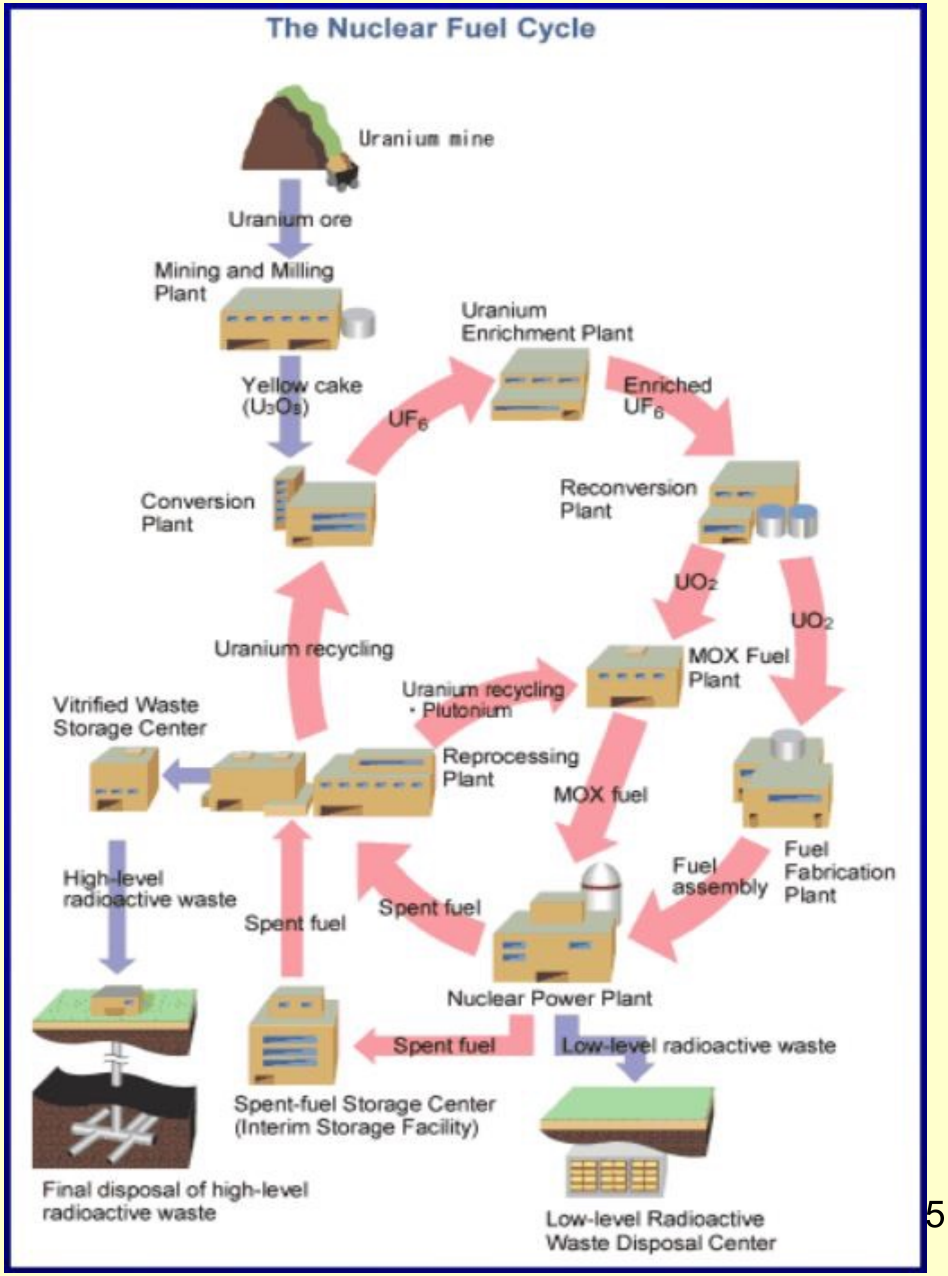
4) construction materials

Forecast world demand for Uranium up to 2100

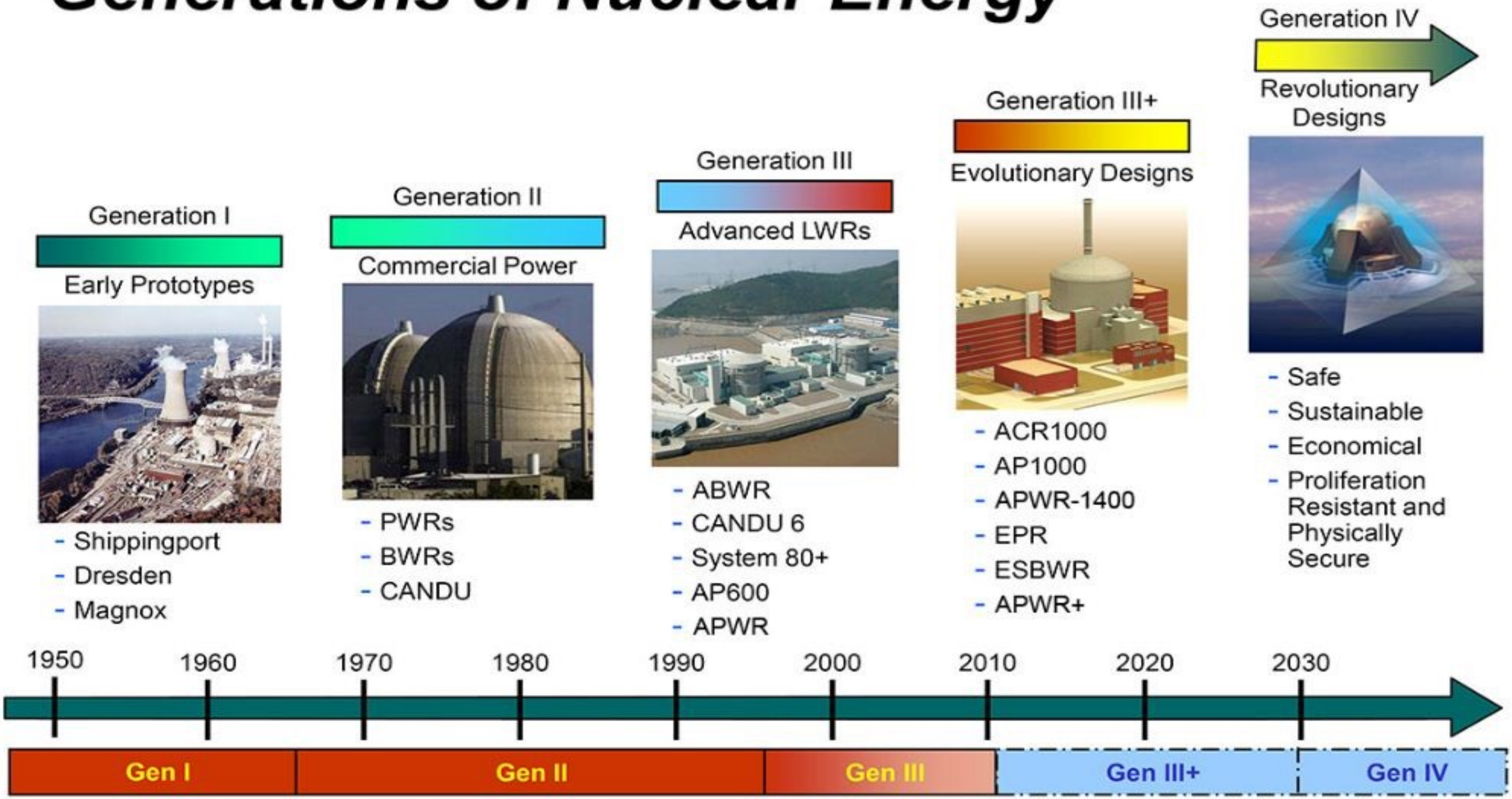


Opened and closed nuclear fuel circles





Generations of Nuclear Energy



Thank you for attention !

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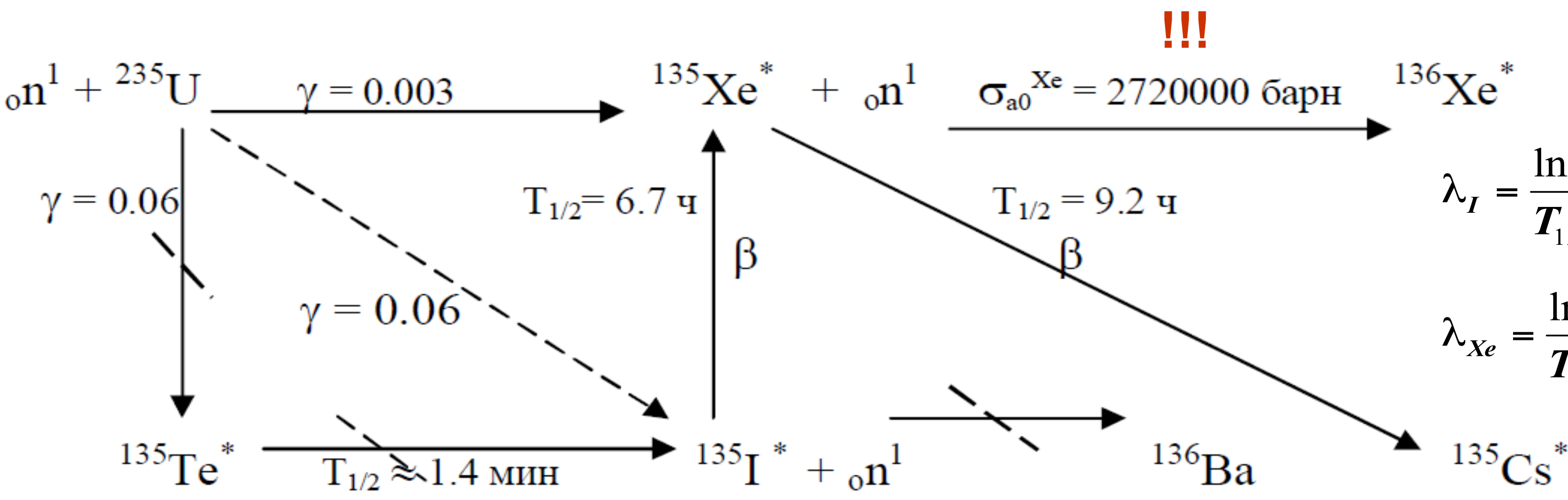
Time for questions!

Poisoning of the reactor with fission products



$$\lambda_I = \frac{\ln 2}{T_{1/2}} = 2.86 \cdot 10^{-5},\ c^{-1}$$

$$\lambda_{Xe} = \frac{\ln 2}{T_{1/2}} = 2.07 \cdot 10^{-5},\ c^{-1}$$

Рис.19.2. Схема образования и убыли йода и ксенона и её упрощение.

$$\frac{dN_I}{dt} = \gamma_I \sigma_{f5} \Phi N_5 - \lambda_I N_I. \qquad \frac{dN_{Xe}}{dt} = \lambda_I N_I + \gamma_{Xe} \sigma_{f5} N_5 \Phi - \sigma_{Xe} N_{Xe} \Phi - \lambda_{Xe} N_{Xe}$$

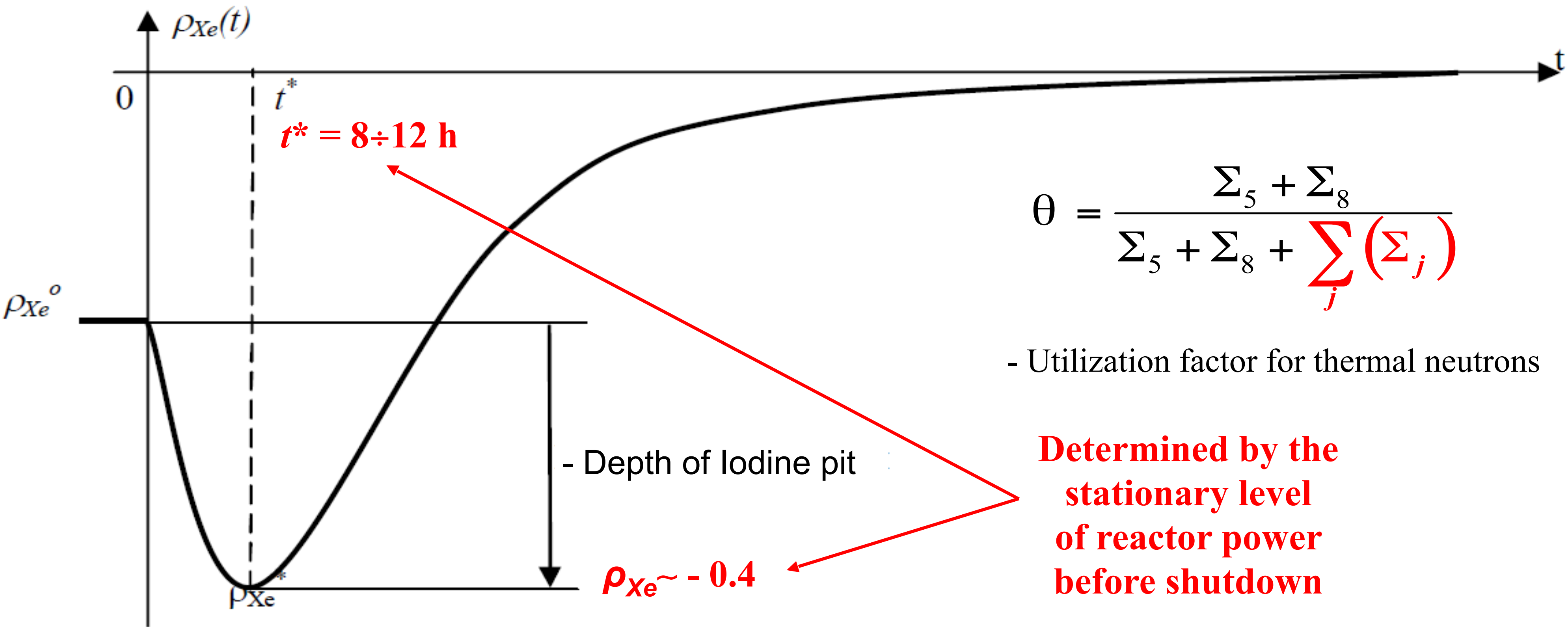
$$\Phi = \Phi_0 = const \ : \qquad \lambda_I N_I = \gamma_I \sigma_{f5} \Phi_0 N_5 = const \qquad N_{Xe} = \frac{(\gamma_I + \gamma_{Xe}) \sigma_{f5} N_5 \Phi_0}{\lambda_{Xe} + \sigma_{Xe} \Phi_0}$$

Reactor poisoning - $P = \dfrac{N_{Xe}\, \sigma_{c\,Xe}}{N_5\, \sigma_{a5}}$ $\qquad \tau_{eff} = \dfrac{1}{\lambda_{Xe} + \sigma_{Xe} \Phi_0}$ - effective living time of $^{135}_{54}Xe$

For powerful reactors : **$\Phi \sim 10^{14}$ см$^{-2}$с$^{-1}$:** $\quad$ **$P \approx 5 \cdot 10^{-2}$** $\rightarrow$ **$\rho = -0.05$**

Overpoisoning after reactor shutdown: "Iodine pit"

Iodine pit is a non-stationary Xe poisoning of the reactor at the time of shutdown, due to the excess of the rate of iodine decay accumulated before the moment of shutdown, over the rate of xenon decay



$$\theta = \frac{\Sigma_5 + \Sigma_8}{\Sigma_5 + \Sigma_8 + \sum_j (\Sigma_j)}$$

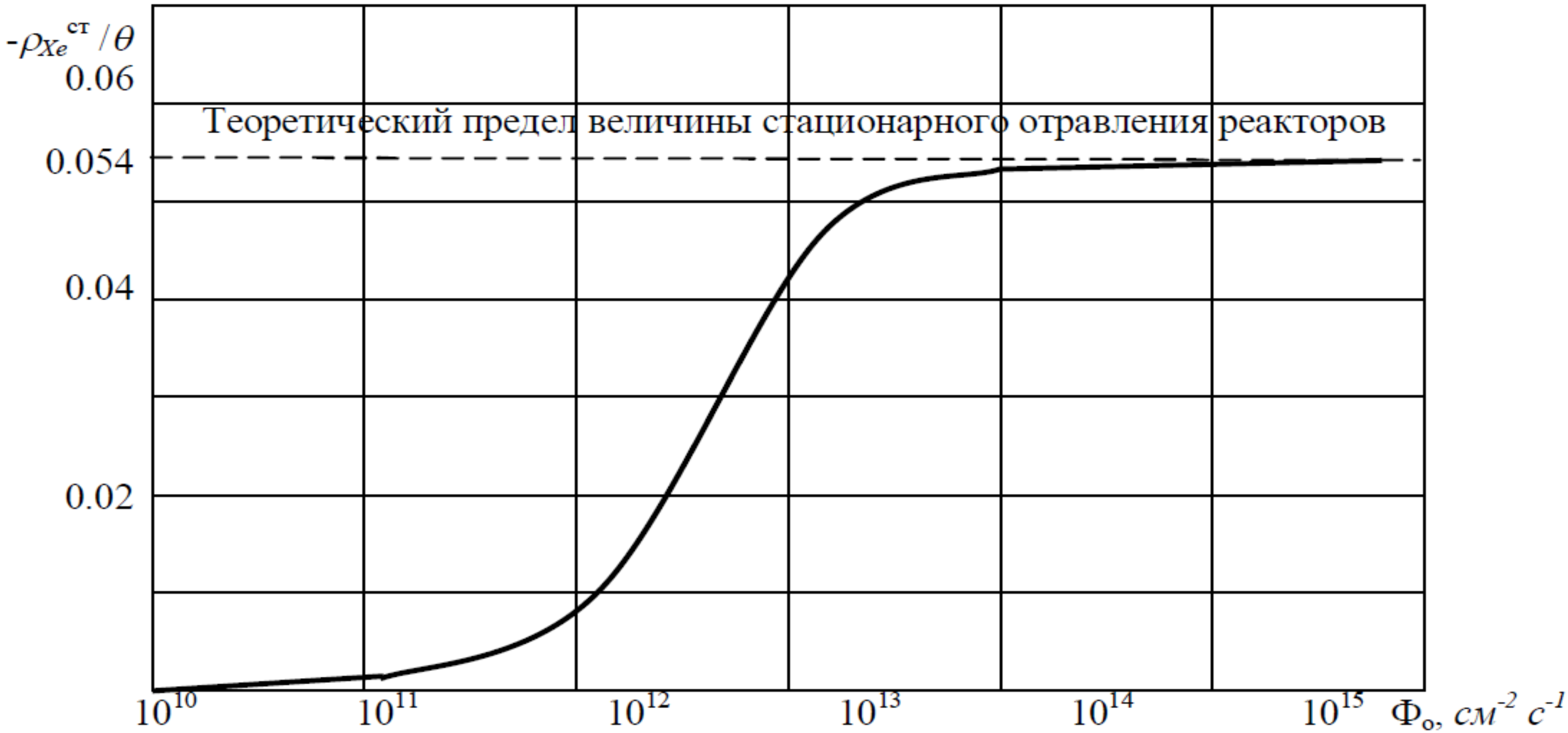
- Utilization factor for thermal neutrons

Determined by the stationary level of reactor power before shutdown

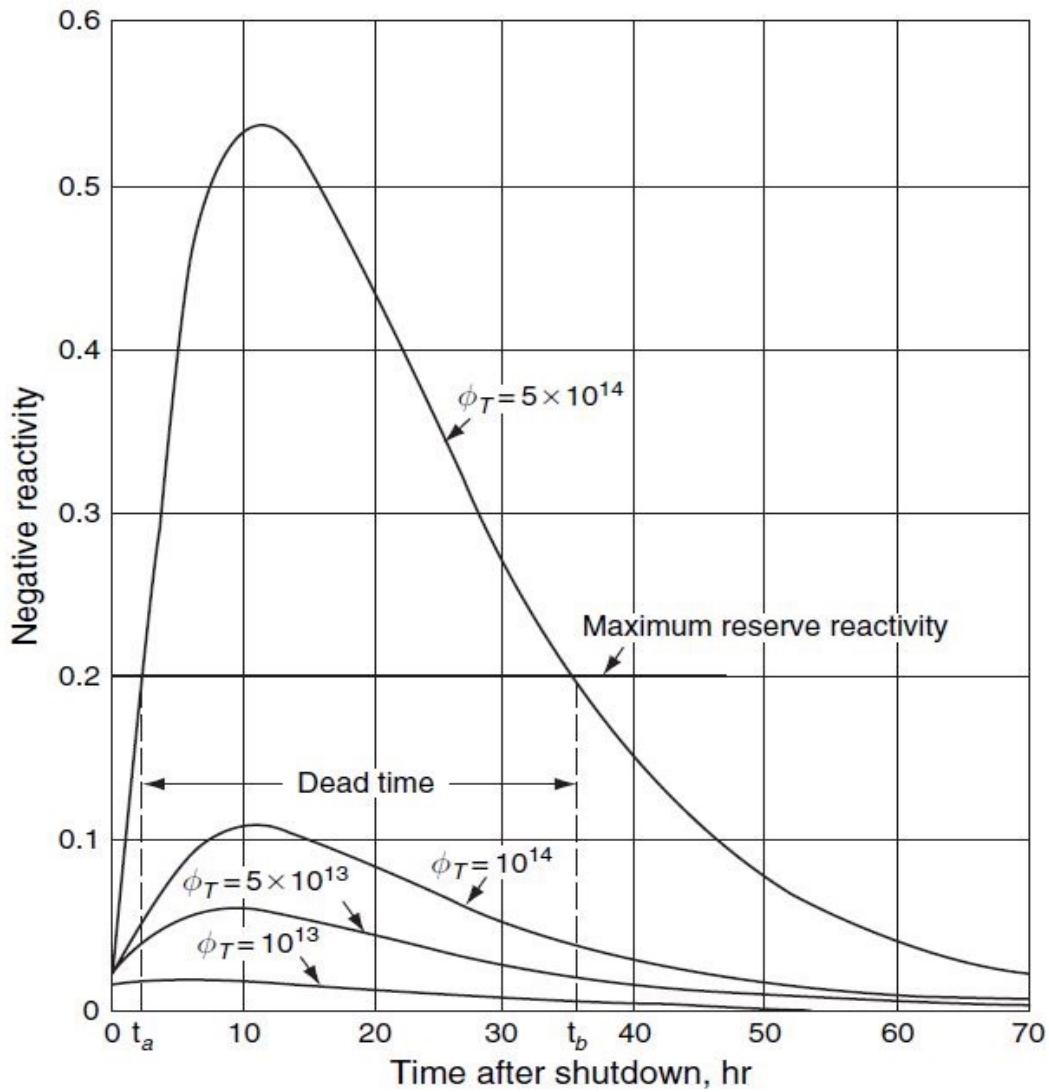
Regardless of the power level for which the reactor worked before the shutdown, complete recovery of the reactor after the Xe poisoning occurs in 3 days after the reactor shutdown

Poisoning of the reactor with fission products

Dependence of the value of stationary Xe poisoning of the reactor on the average flux density of thermal neutrons in the active zone

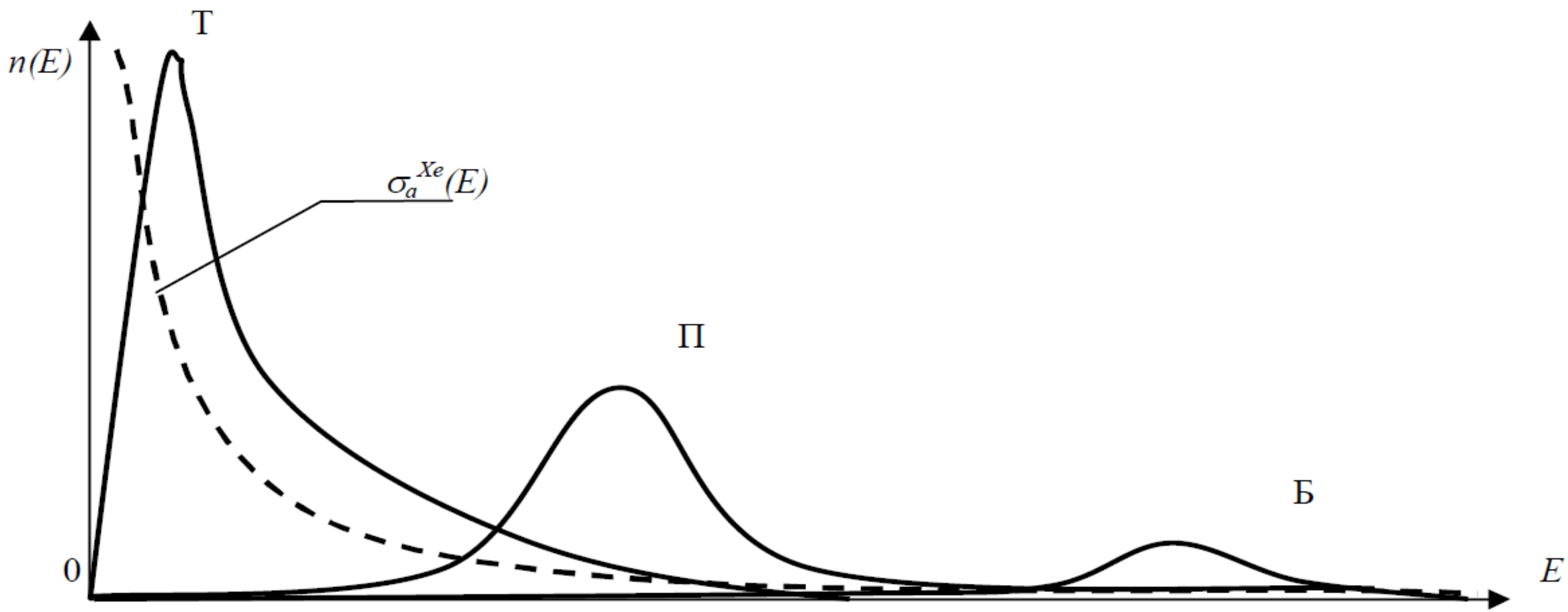


Dependence of the iodine pit depth from the reactor power



Poisoning of the reactor with fission products

Xenon poisoning is essential for thermal reactors,
Insigible - for intermediate and
Not essential - for fast reactors!



Nuclear safety regulations require that after the thermal reactor is shutdown an excessive concentration of boric acid was created in the water of the first circuit, guaranteeing the impossibility of self-restarting of the reactor due to its recovery after Xe poisoning