National Academy of Sciences of Ukraine
National Science Center
“Kharkiv Institute of Physics and Technology”
V.N. Karazin Kharkiv National University

Nuclear Power: Problems & Prospective. Traveling Wave Reactor

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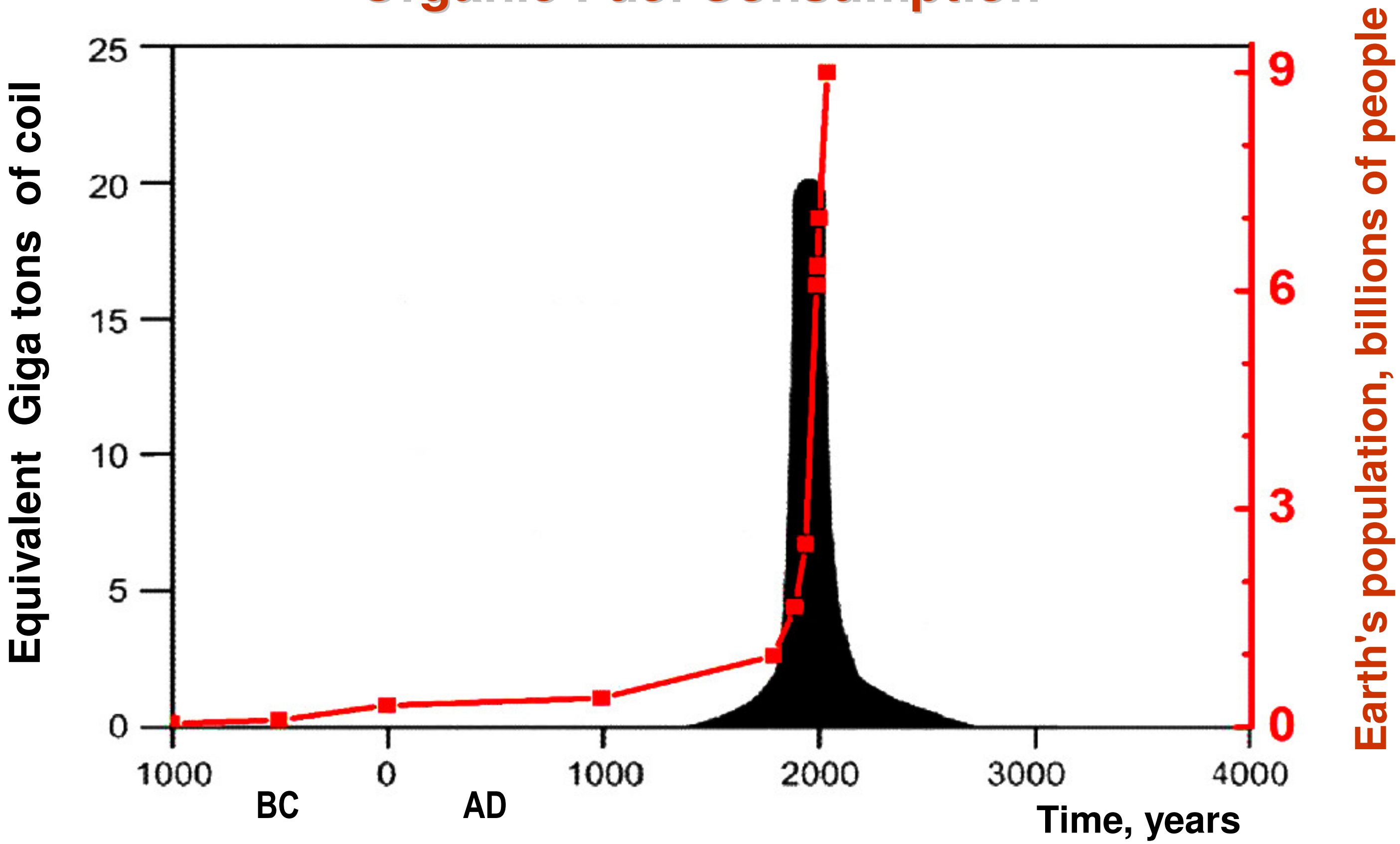
LIA Topical discussion 12 May 2021 Webinar

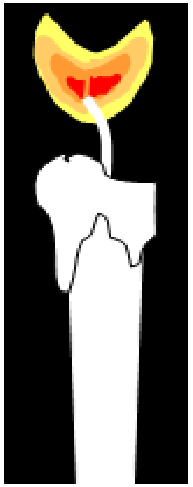
Civilization & Power Consumption

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

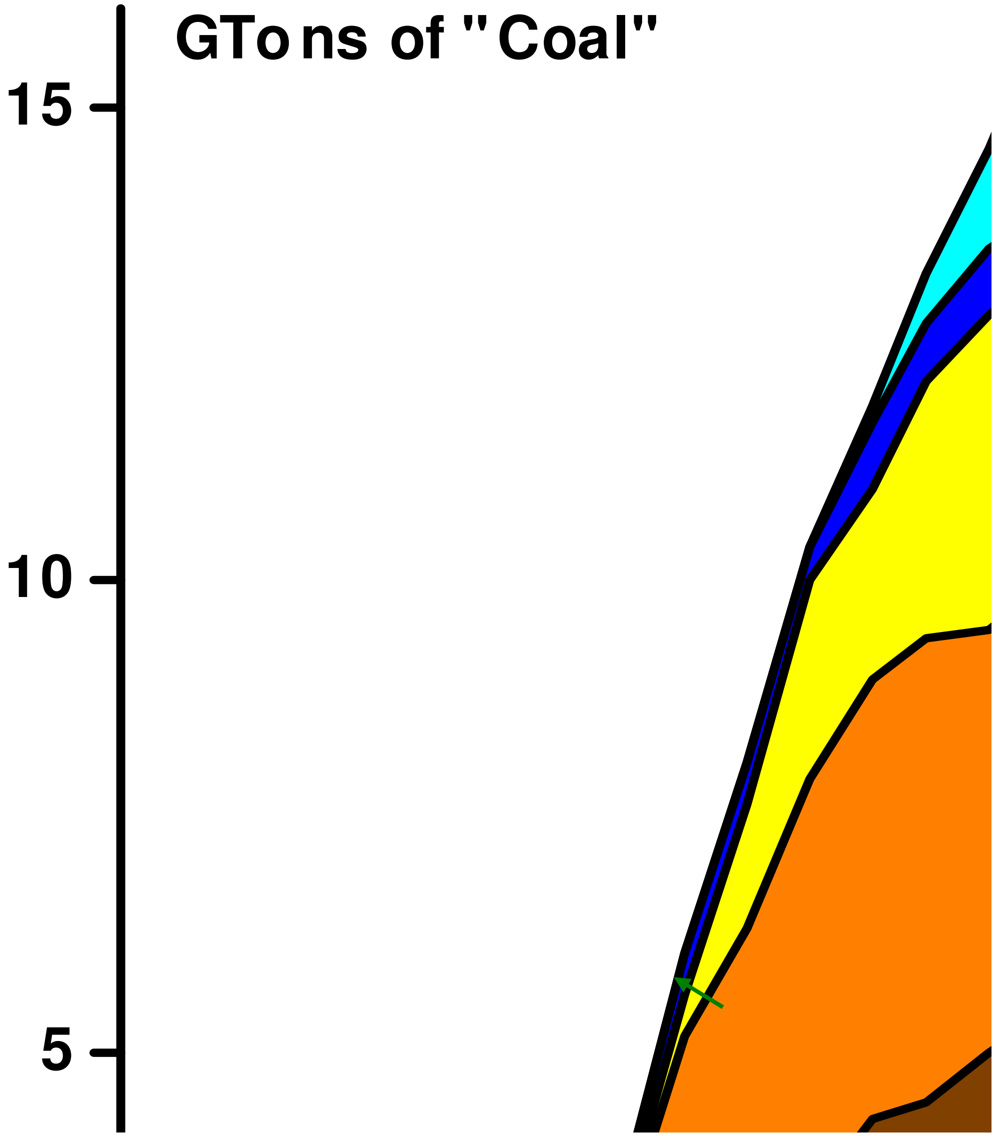
Metallurgy: Copper (5 ky BC) → Bronze (3 ky BC) → Iron (1 ky BC)

Organic Fuel Consumption





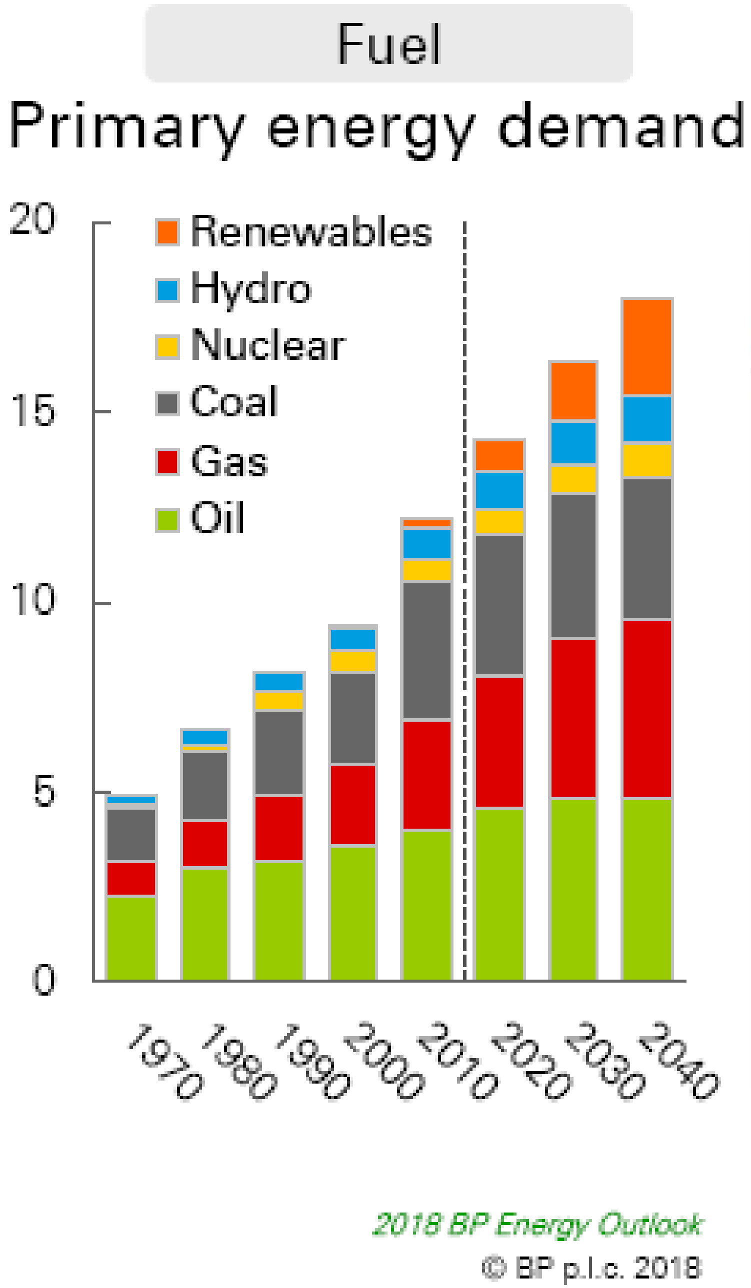
Dynamics of the global consumption of energy resources



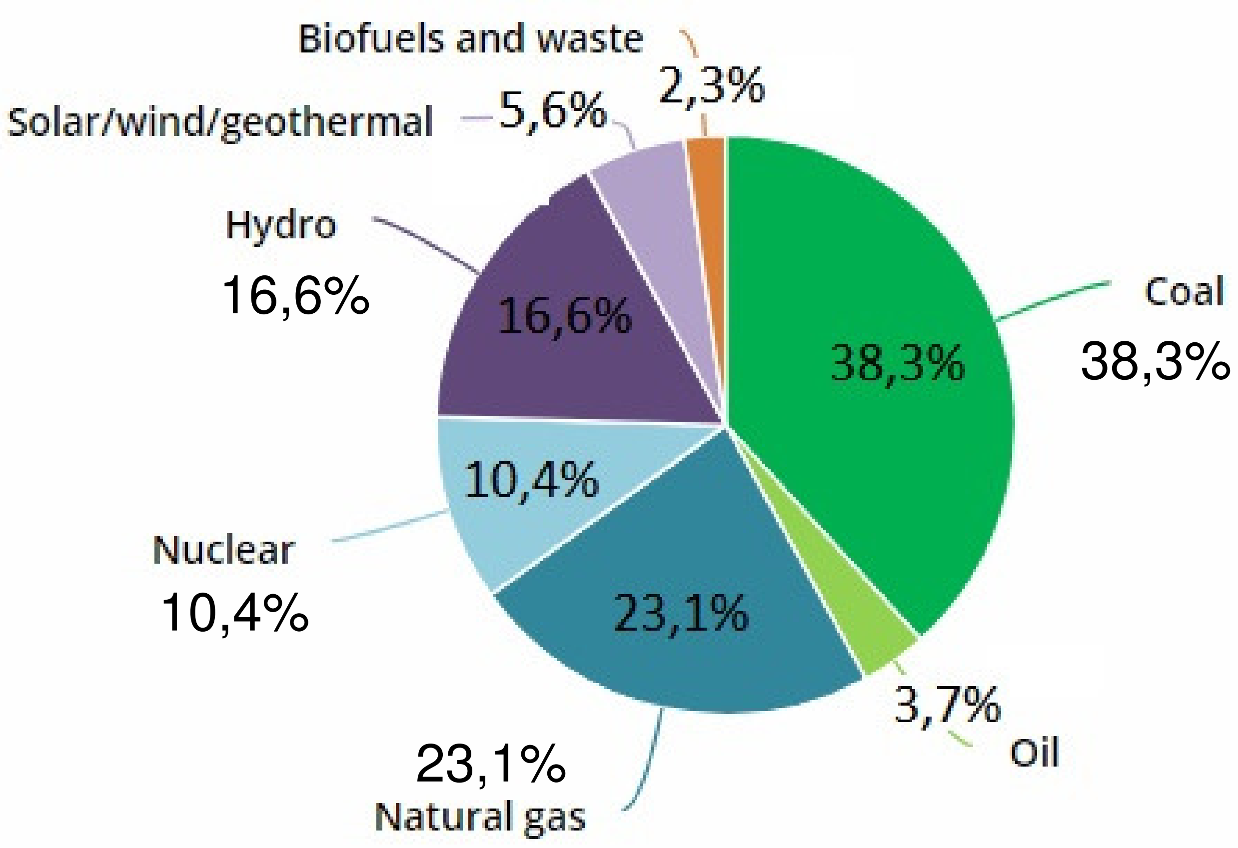
CURRENT USE		2012	2016 (IEA)	
Source	EJ/y	%	%	
Oil	170	33.20	31,9	
Coal	139	27.15	27.1	
Gas	109	21.30	22.1	
Biomass	51	9.96	9.8	
Uranium	30	5.86	5.0	
Hydro	12	2.34	2.5	
Wind	0.72	0.14	0.83	x 6 !!
Other renew	0.23	0.045	0.48	
Solar	0.04	0.007	0.29	x 40 !!
Total:	512	100%	100%	
Fossil	448	87.5	86.1	
Renewable	64	12.5	13.9	

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



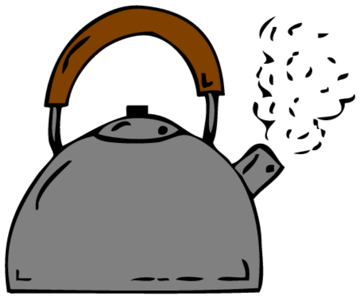
Different kinds of "Energy sources"

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

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

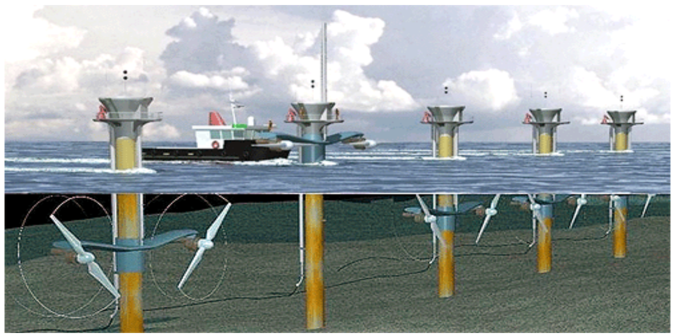
$$E = g \cdot m \cdot h$$

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



To boil 1 liter of water ~ 0.1 kWh

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



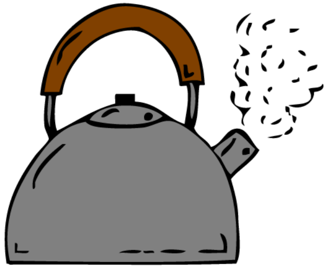
Different kinds of "Energy sources"

2) " Chemical energy " (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

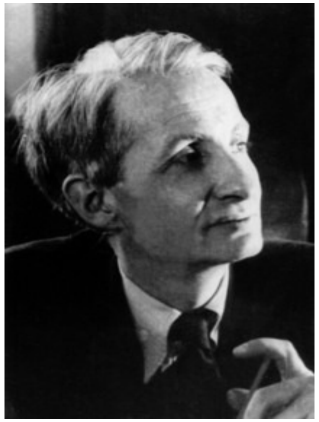
~ 10 g of gasoline ~ 40 t·m mech. energy - 10^8 times !!!

“High-Voltage Brigade” of UPhTI

“PRAVDA” October 22, 1932 : Nucleus of lithium atom is destroyed.

Great achivement of soviet scientists

A. Leypunskii



K. Sinel’nikov

A. Valter

G. Latyshev

Цена номера 5 коп.

Всесоюзная Коммунистическая Партия (больш.).

ПРАВДА

Орган Центр. Ком. и Моск. Ком. ВКП (б)

ОКТЯБРЬ 22 1932 г. СУББОТА № 293 (5458).

Разрушено ядро атома лития.

Крупнейшее достижение советских ученых.

МОСКВА, ТТ. СТАЛИНУ, МОЛОТОВУ, ОРДЖОНИКИДЗЕ, «ПРАВДЕ».

Украинский физико-технический институт в Харькове в результате ударной работы к XV годовщине Октября добился первых успехов в разрушении ядра атома.

10 октября высоковольтная бригада разрушила ядро лития; работы продолжаются.

Директор УФТИ *Обреимов*. Секретарь парткома *Шепелев*. Местком — *Федоритенко*.

John Cockcroft

George Gamow

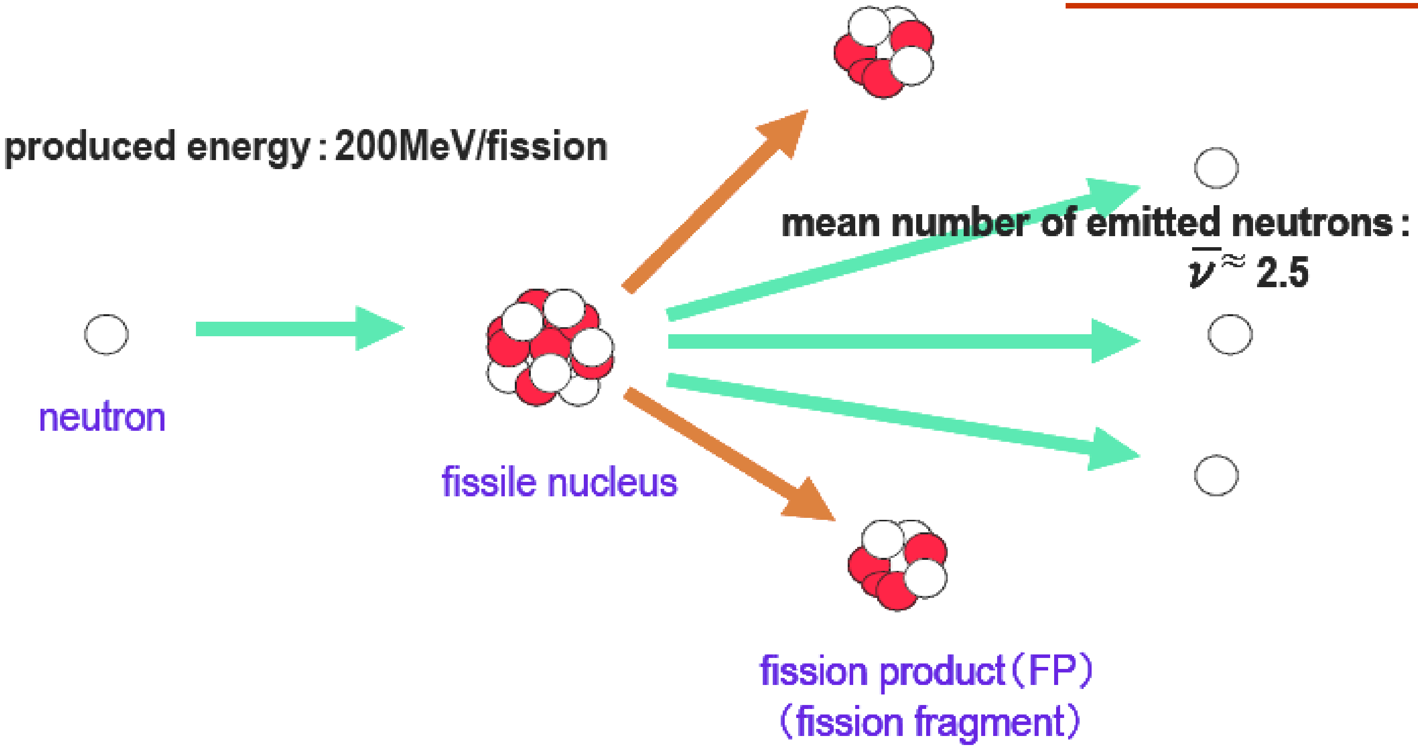
Ernest Walton
Nobel Prize 1951

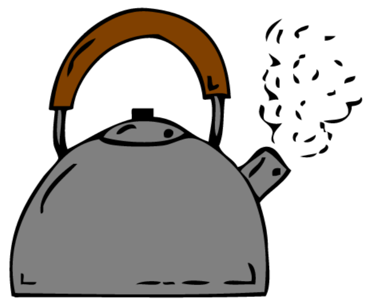
Different kinds of "Energy sources"

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. <u>10^8 times more !!!</u> than at oxidation of 1 carbon atom



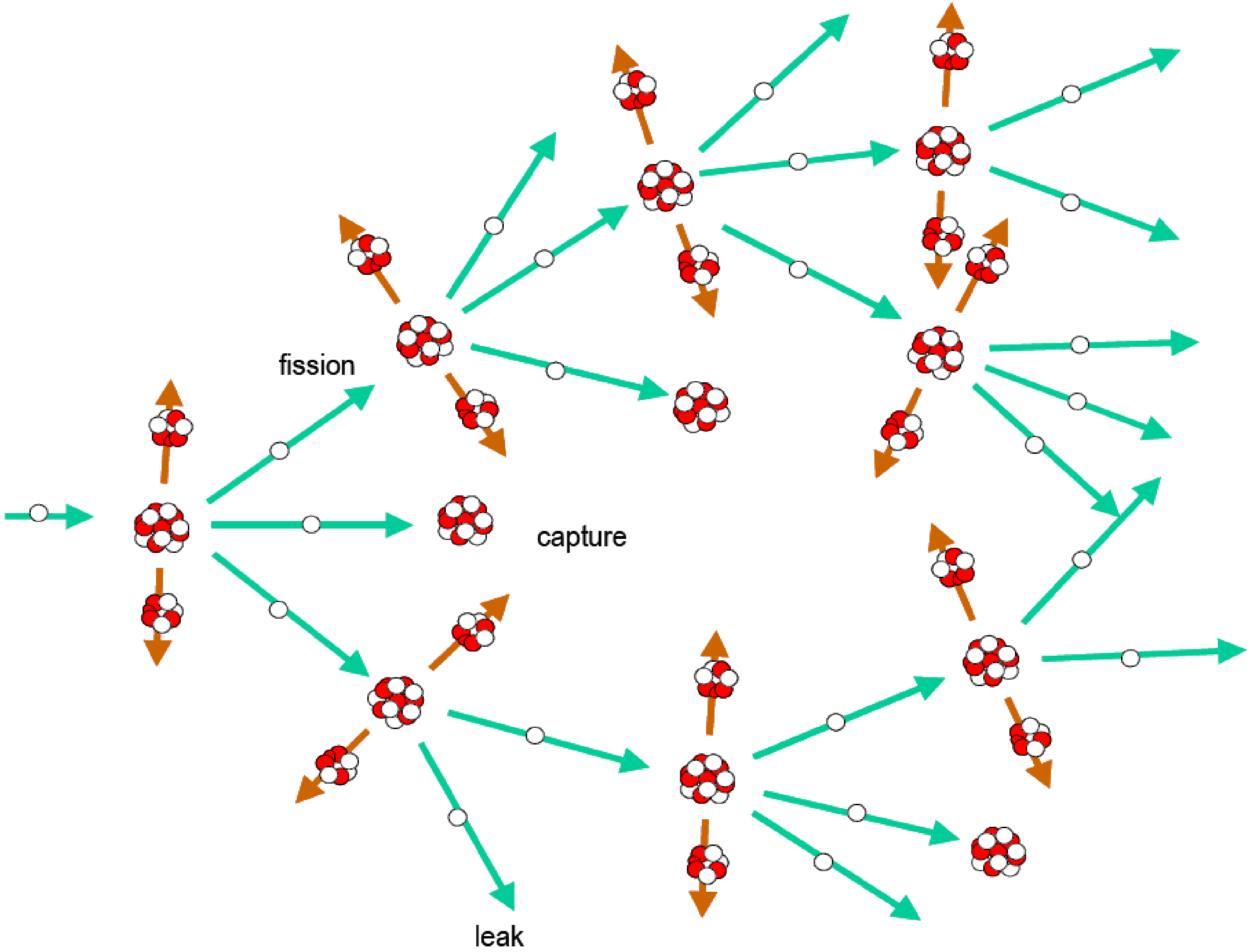


To boil 1 liter of water ~ 0.1 kWh

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

$\tau \sim 10^{-7}$s – fast n

$\tau \sim 10^{-4}$ s – thermal n

Delayed neutrons

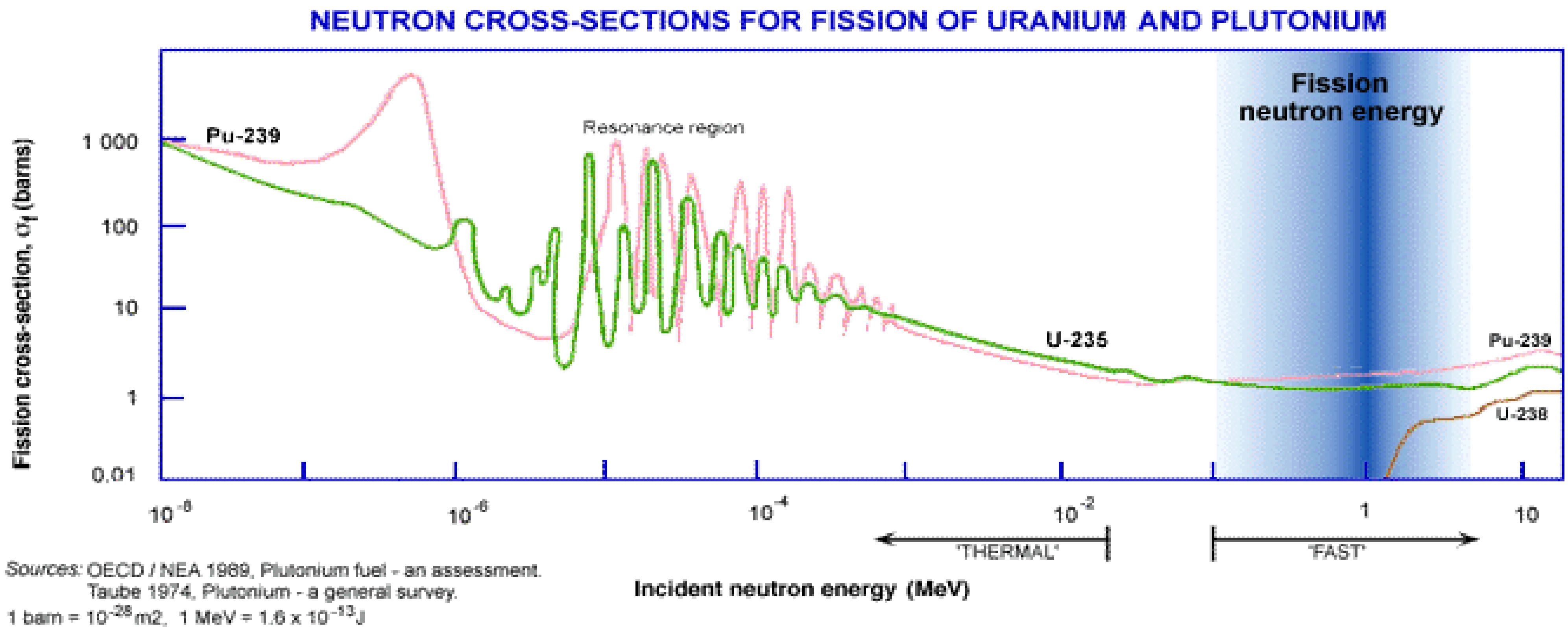
$N_d < 1\%$, $\Delta t \sim 10$ s

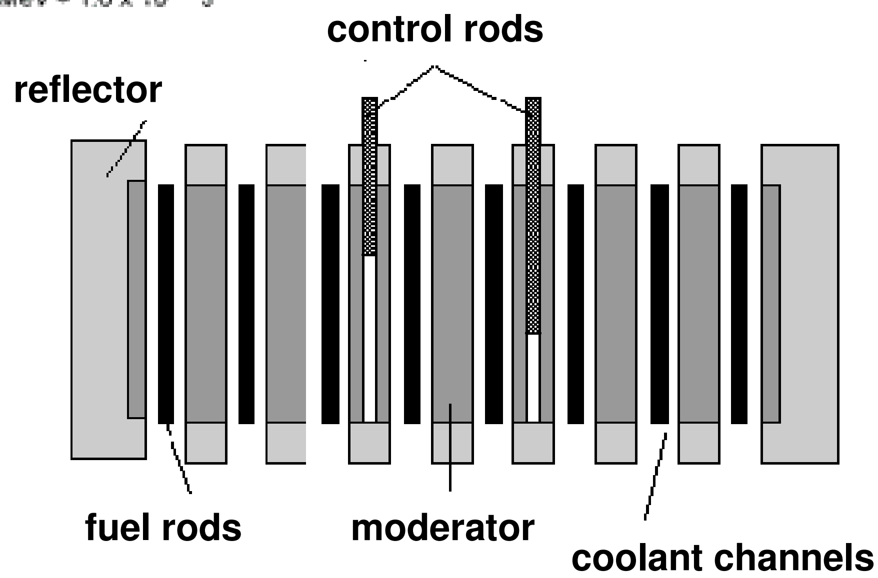
Neutron multiplication coefficient

$k_{eff} = 1$!!!

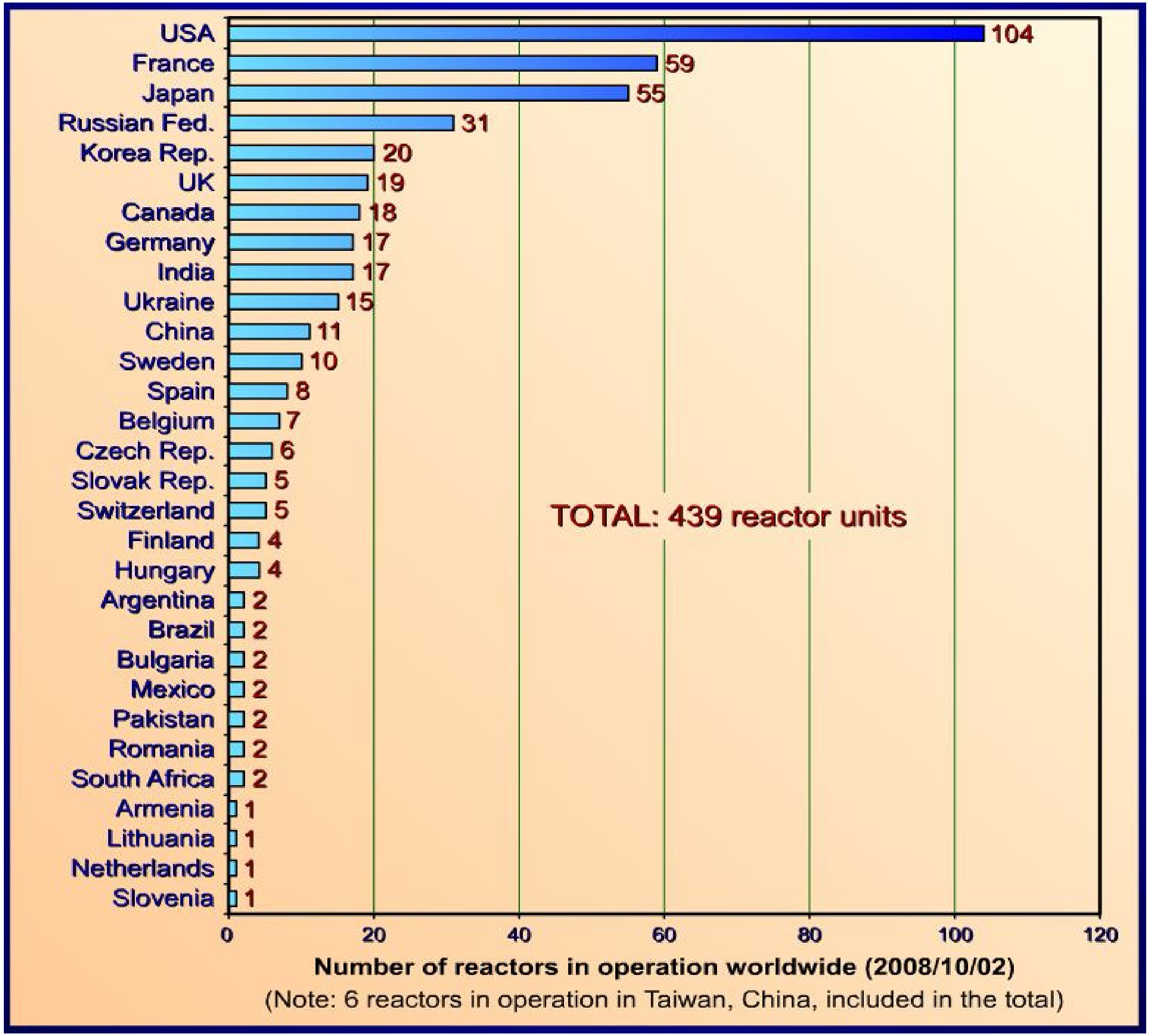
Reactivity

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

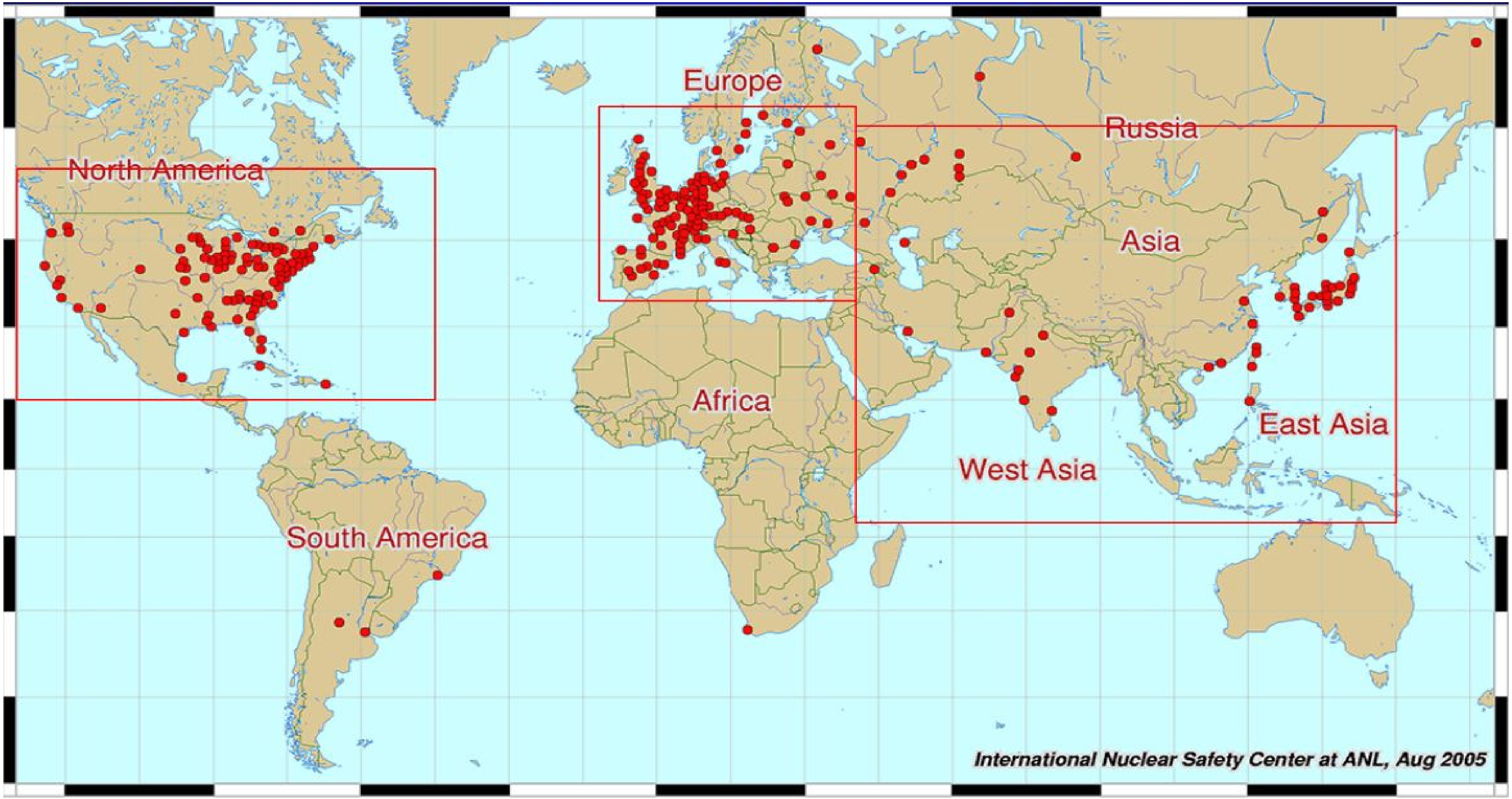

NEUTRON CROSS-SECTIONS FOR FISSION OF URANIUM AND PLUTONIUM
Fission cross-section, σ_f (barns)
1 000
100
10
1
0,01
Pu-239
Resonance region
Fission neutron energy
U-235
Pu-239
U-238
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10
'THERMAL'
'FAST'
Incident neutron energy (MeV)
Sources: OECD / NEA 1989, *Plutonium fuel - an assessment.*
Taube 1974, *Plutonium - a general survey.*
1 barn = 10^{-28} m2, 1 MeV = 1.6 x 10^{-13} J


control rods
reflector
fuel rods
moderator
coolant channels

Nuclear Power (2019: Total = 450 reactor units)



Nuclear Power Today



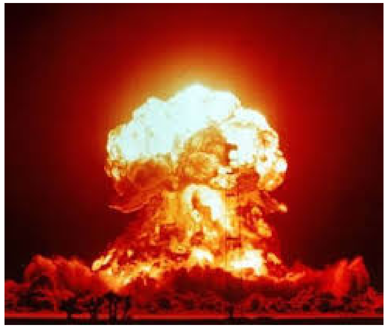
Nuclear Energy in Ukraine

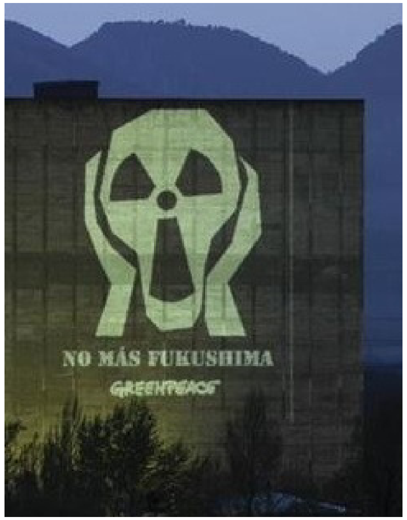
Electricity production by nuclear plants is ≥ 50% of total

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

Total Electric Power – 13,835 MWe.

Nuclear Power Problems

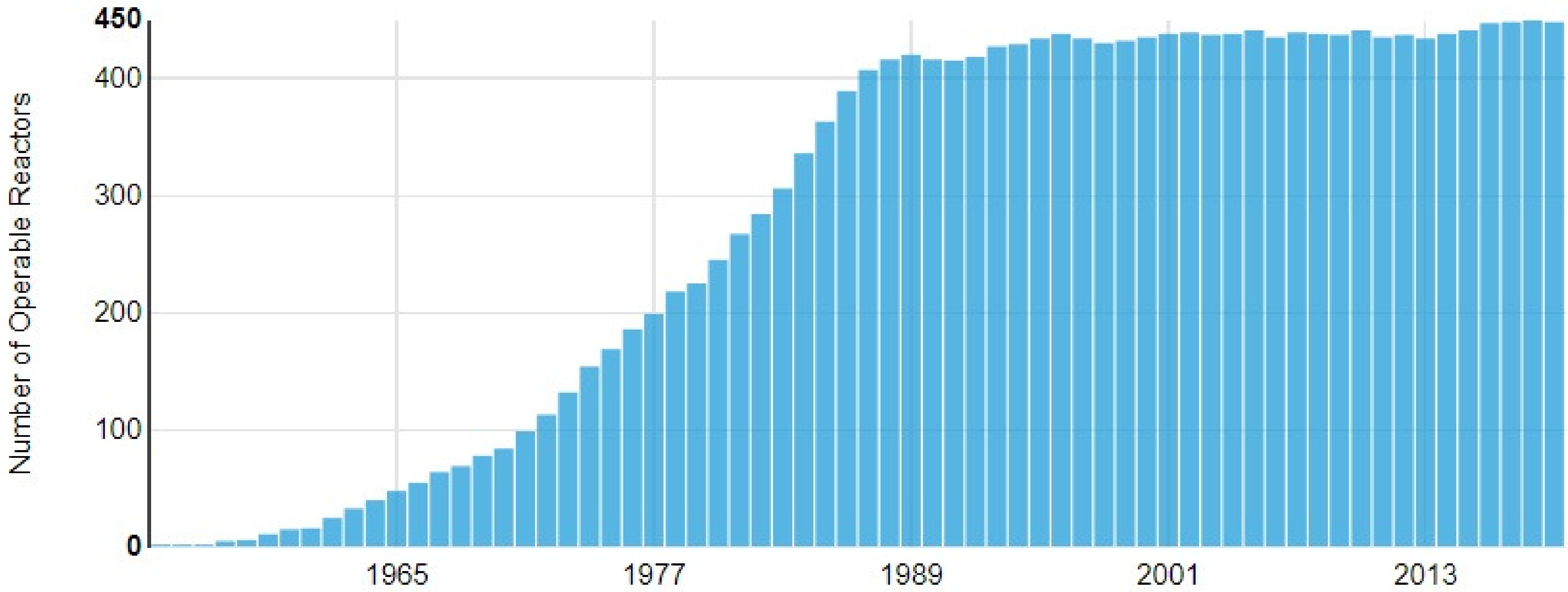




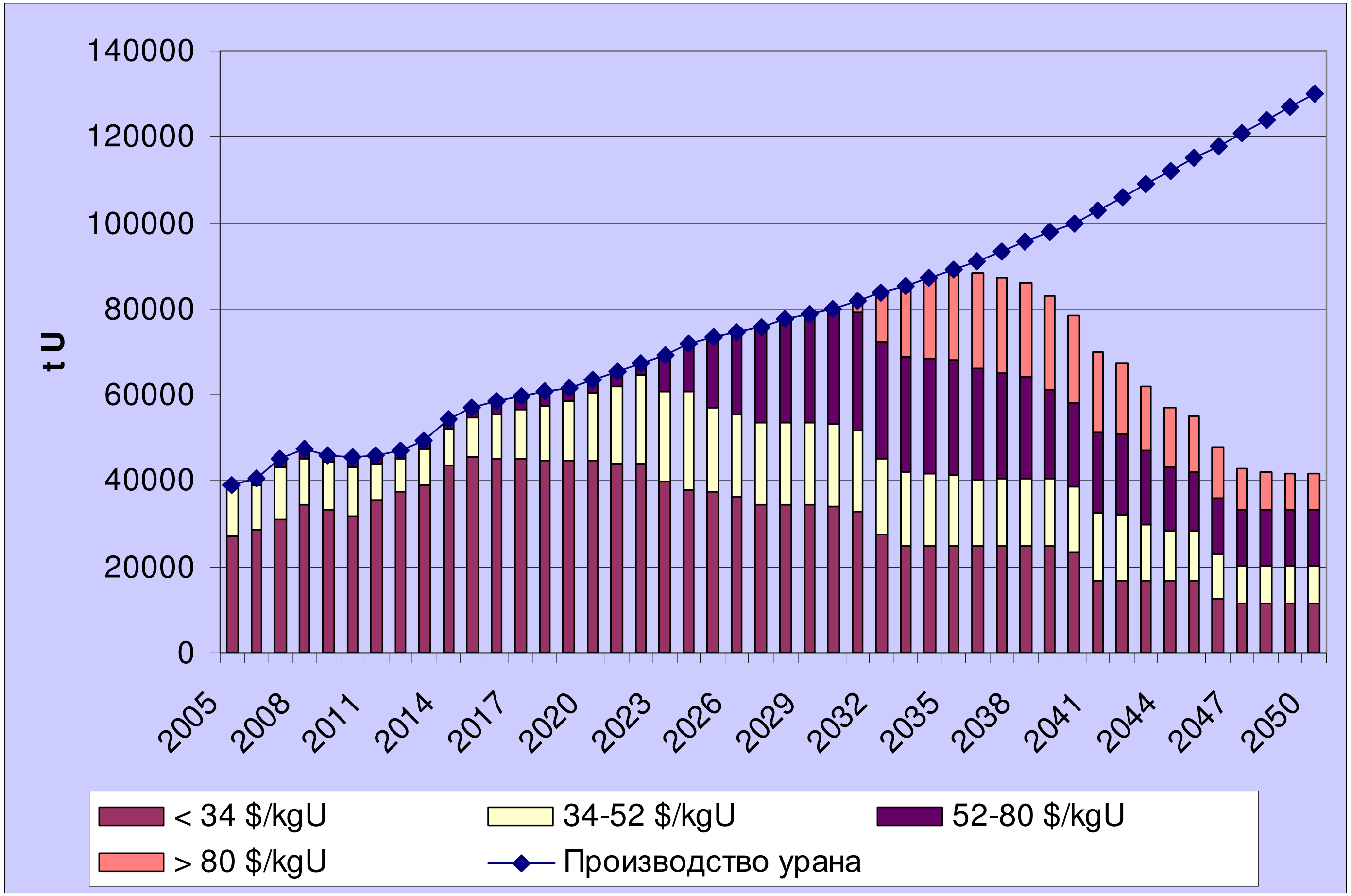
Atomic Bomb House, Hiroshima

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

Nuclear Power 2019

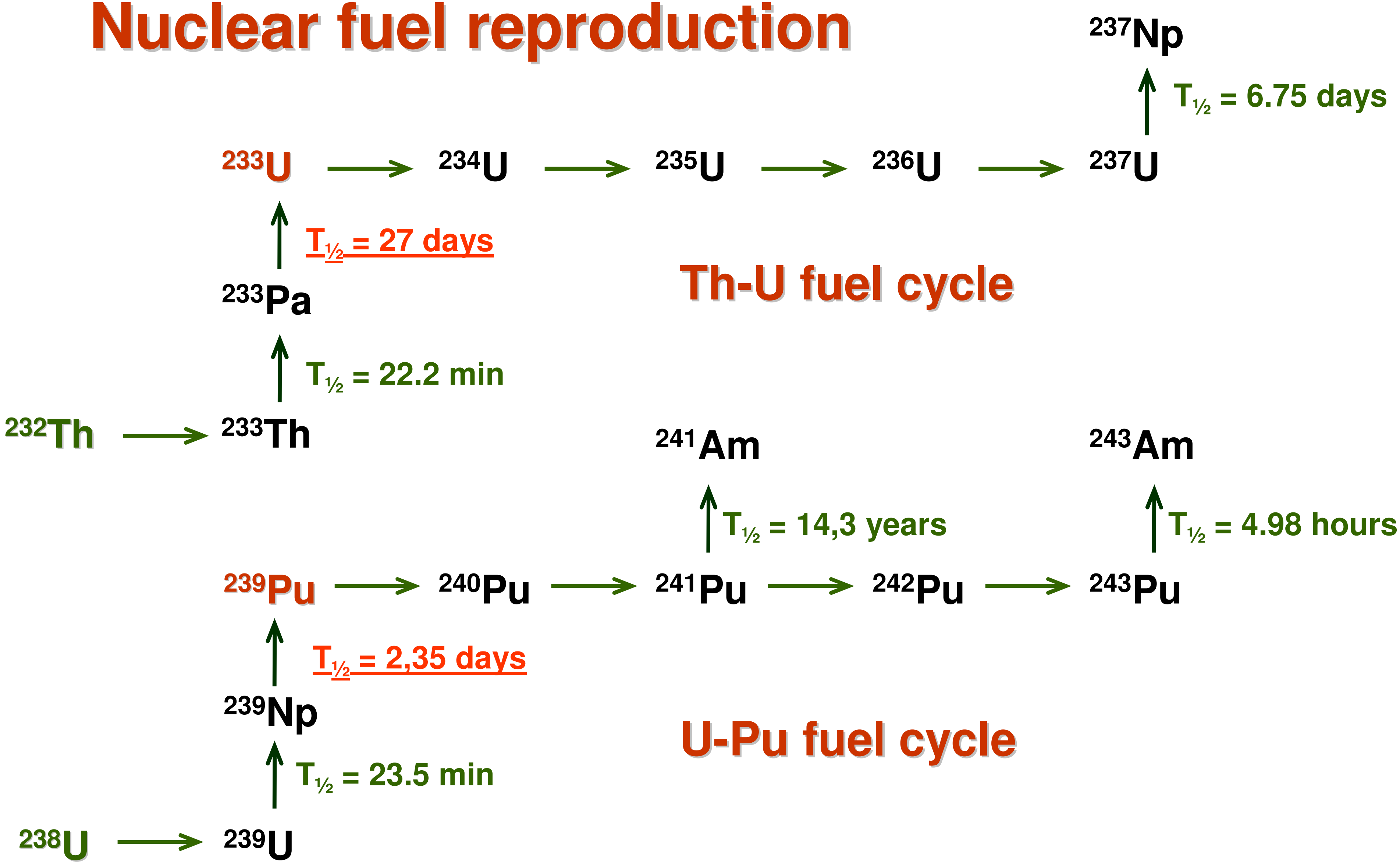


Explored Earth reserves of Uranium

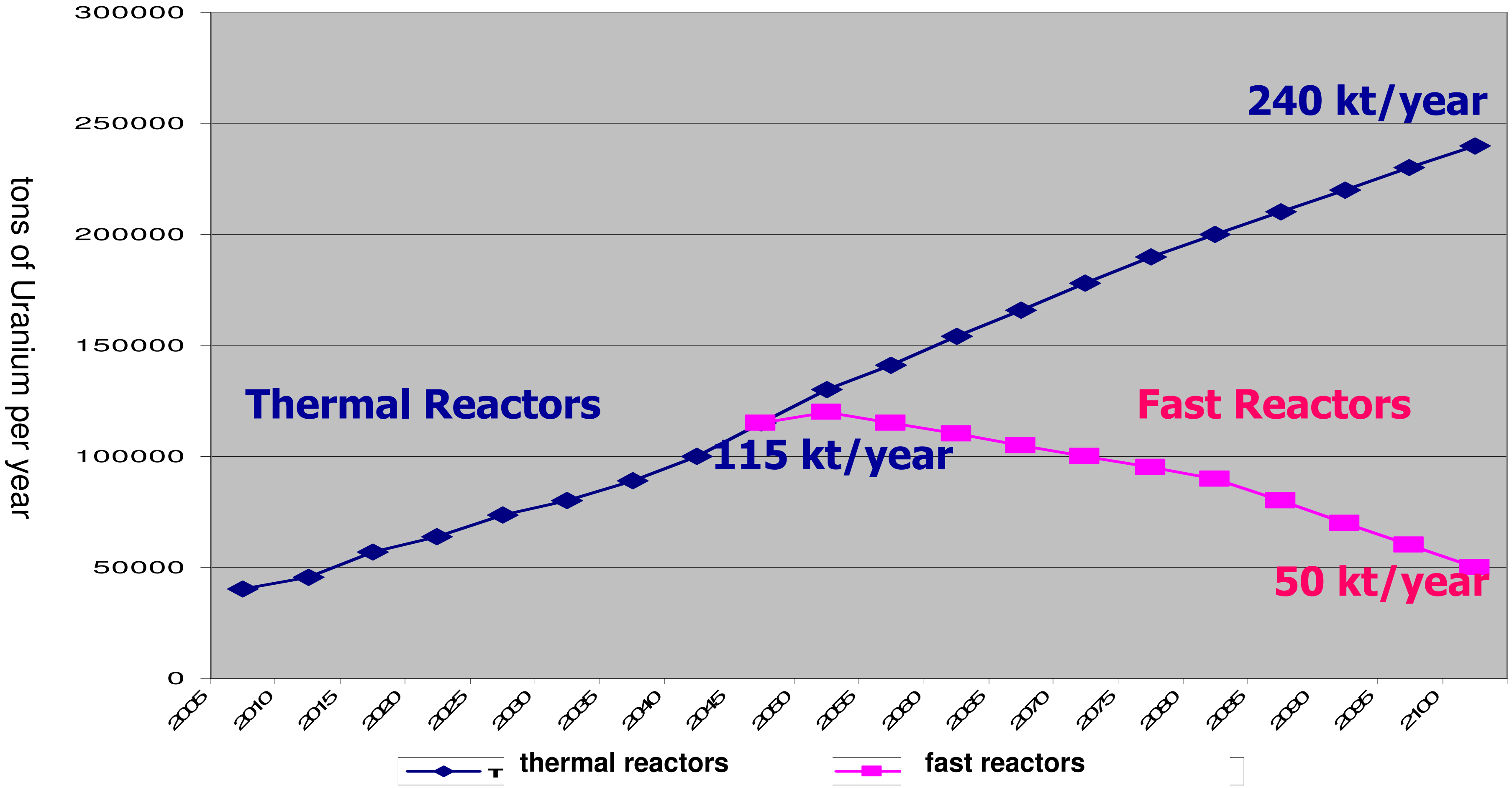


Nuclear plants are provided with Uranium-235 only until 2035!

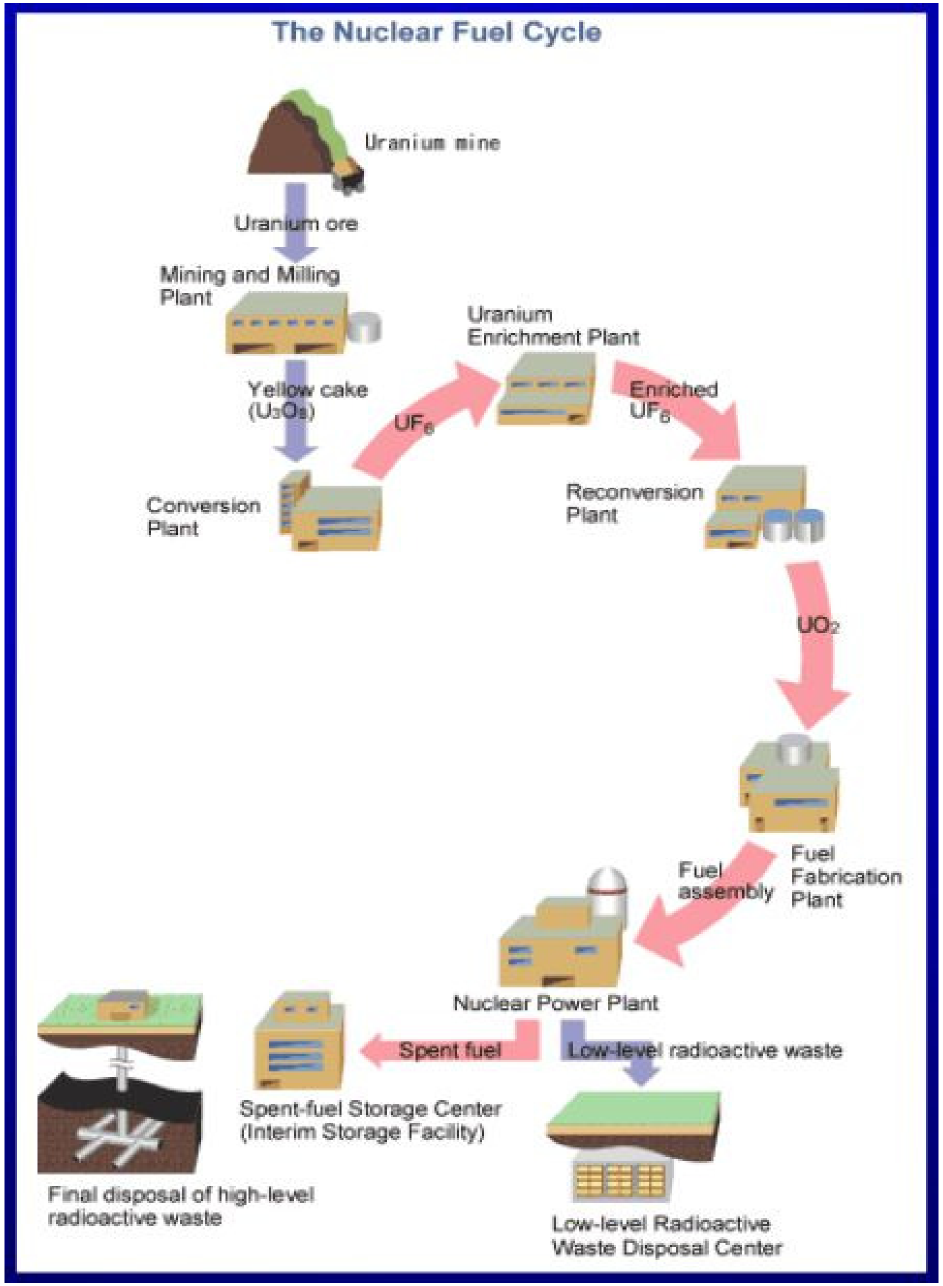
Nuclear fuel reproduction

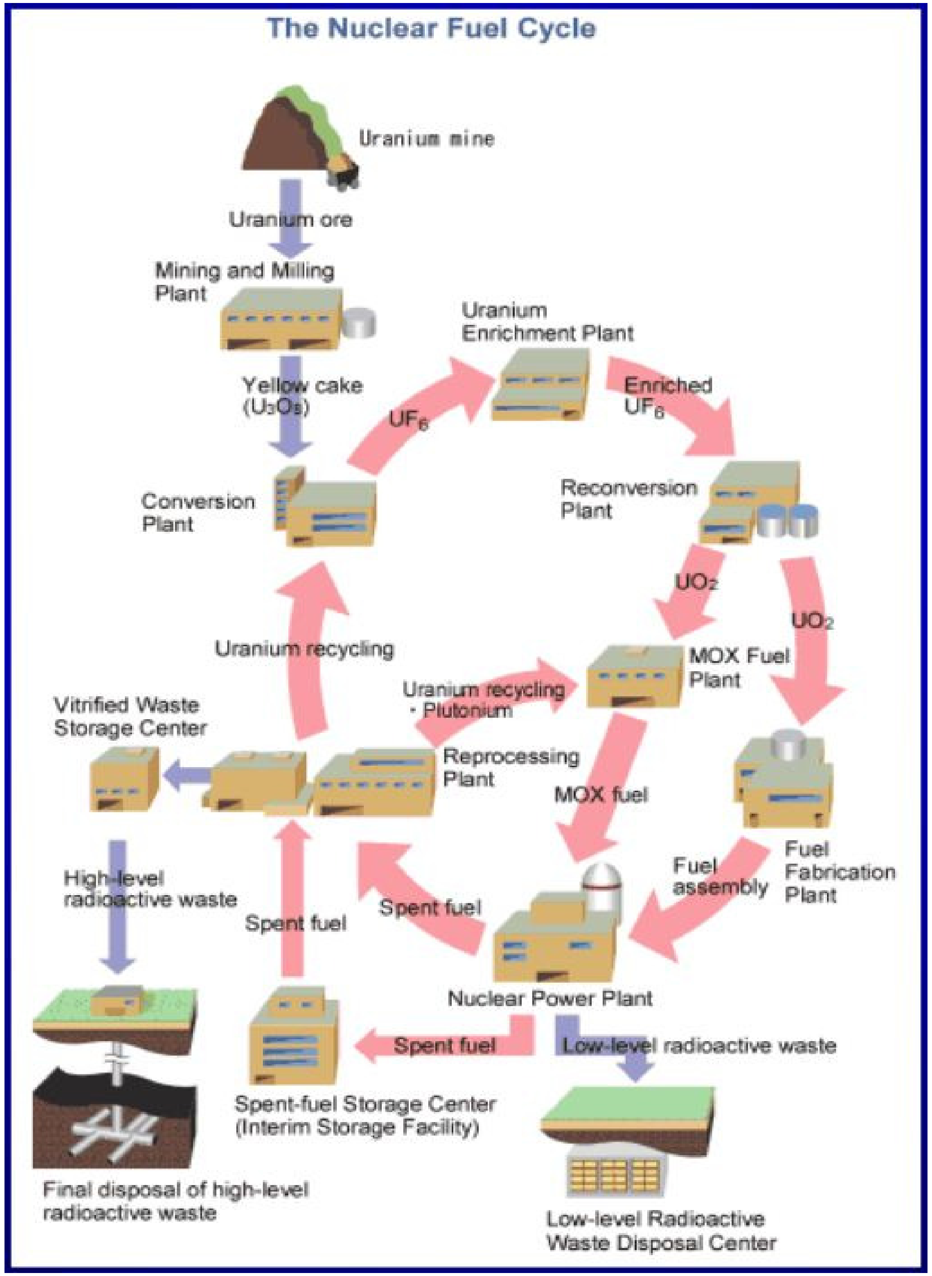


Forecast world demand for Uranium up to 2100

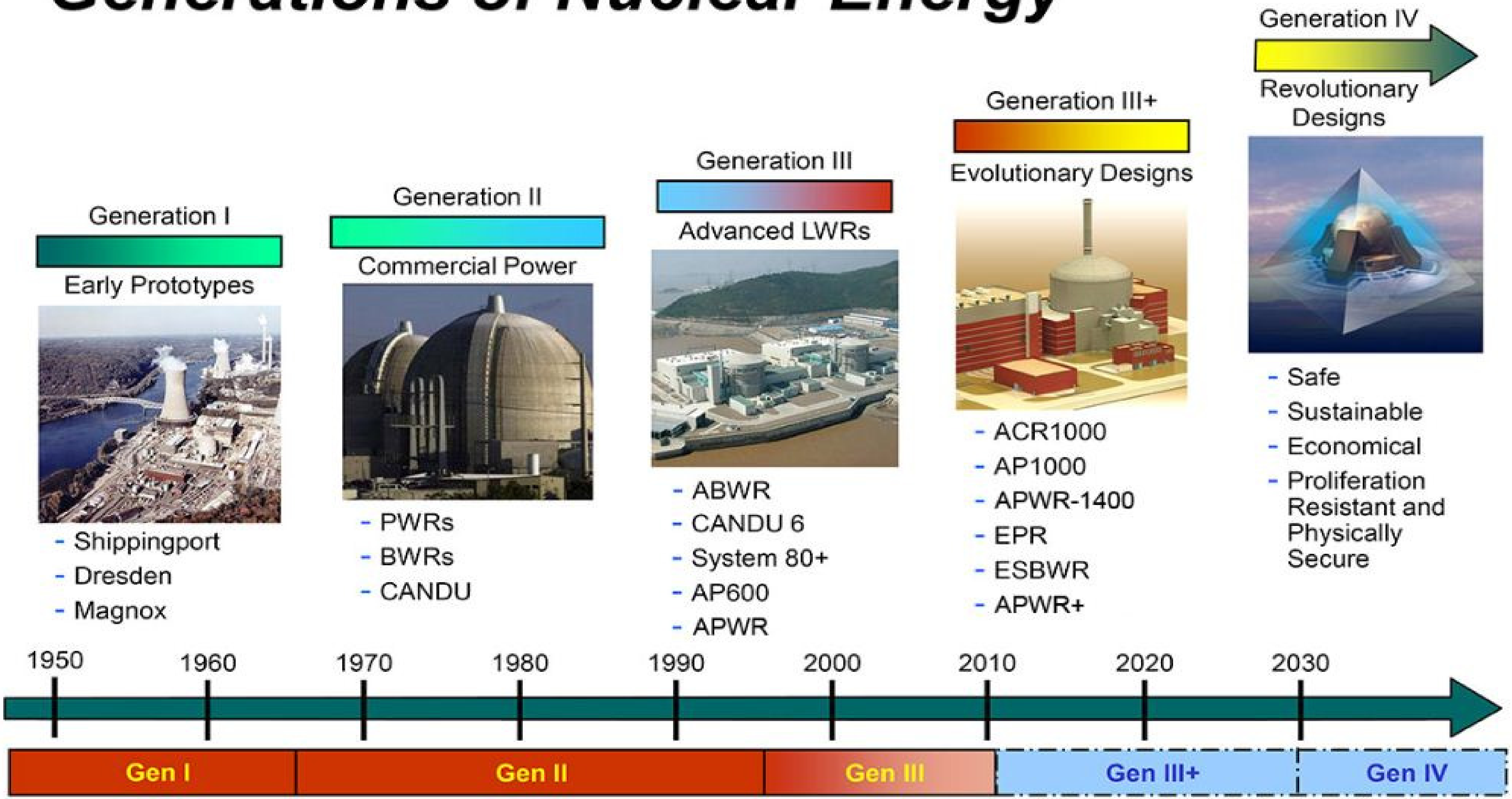


Opened and closed nuclear fuel circles

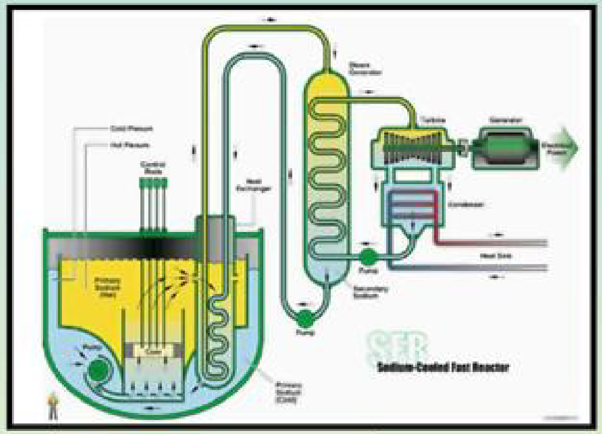




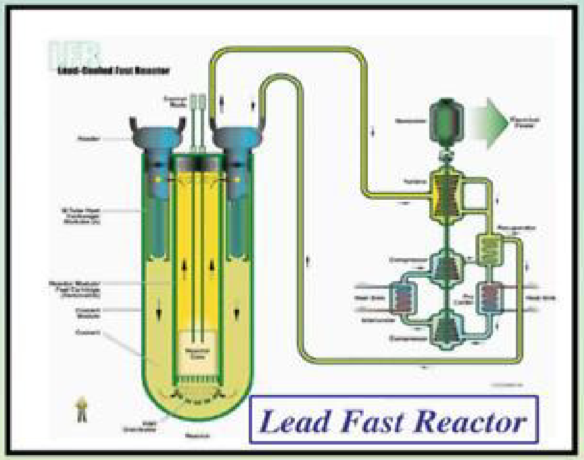
Generations of Nuclear Energy



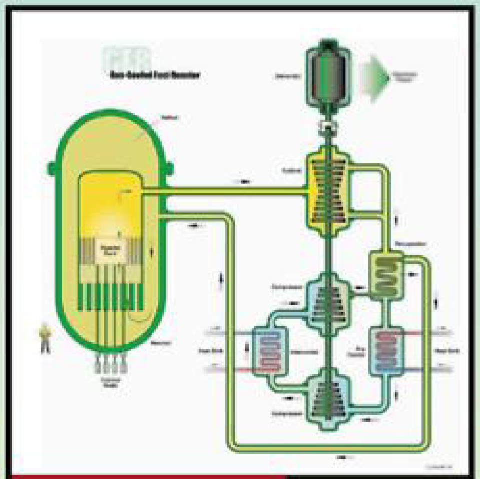
Generation IV Reactors



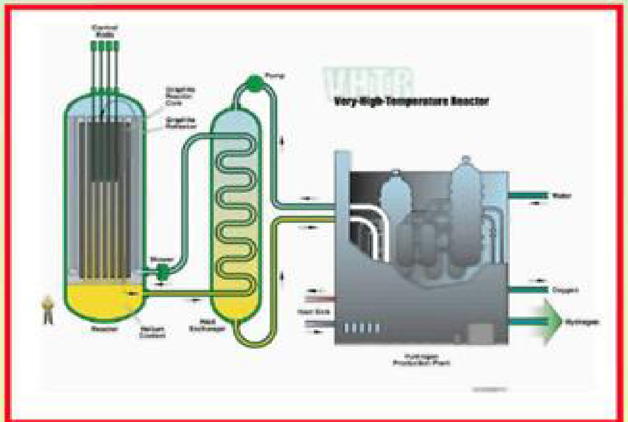
Sodium Fast Reactor



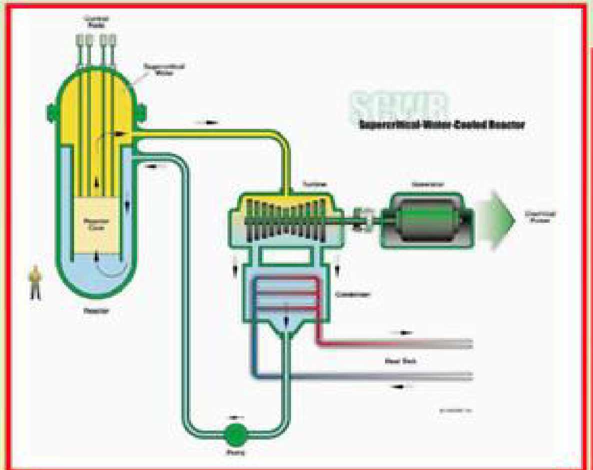
Lead Fast Reactor



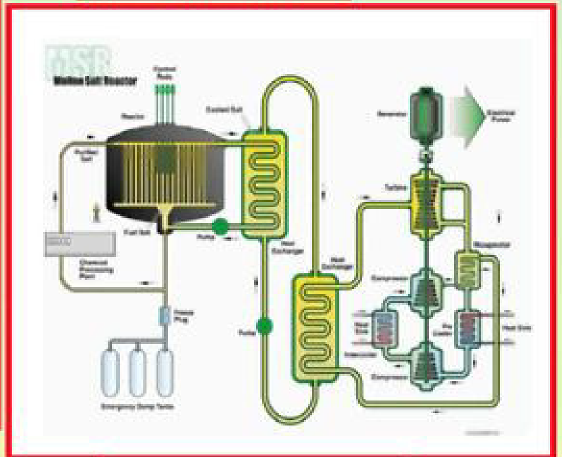
Gas Fast Reactor



Very High Temperature Reactor

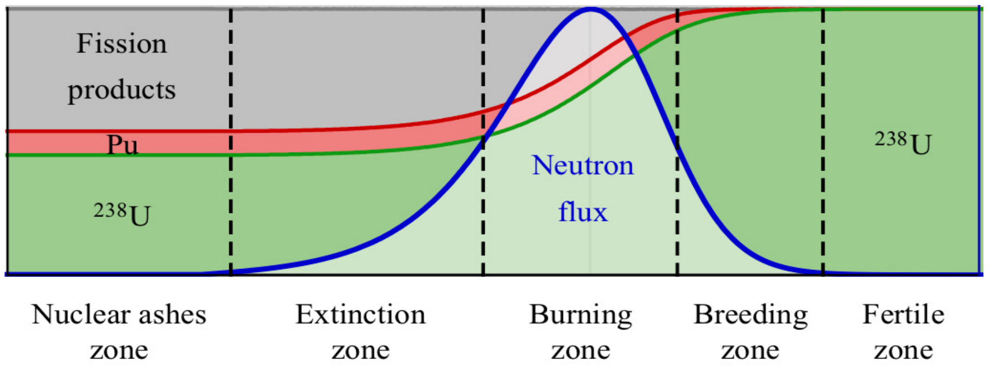


Supercritical Water-cooled Reactor



Molten Salt Reactor

Nuclear Burning Wave concept



Lev Feoktistov (USSR, 1988):

L.P. Feoktistov. Preprint IAE-4605/4, 1988.
L.P. Feoktistov. *Sov. Phys. Doklady*, 34 (1989) 1071.

^{238}U (n,γ) → ^{239}U (β) → ^{239}Np (β) → ^{239}Pu (n,fission) ...

$T_{1/2} \approx 2.35$ days

Concept & Analytical approach

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial z^2} + vn\left(\sigma_{a8}N_8 - \left(\sigma_a + \sigma_f\right)_{\mathrm{Pu}} N_{\mathrm{Pu}}\right)$$

$$\frac{\partial N_8}{\partial t} = -vn\sigma_{a8}N_8 \; ; \qquad \frac{\partial N_9}{\partial t} = vn\sigma_{a8}N_8 - \frac{1}{\tau_\beta}N_9$$

$$\frac{\partial N_{\mathrm{Pu}}}{\partial t} = \frac{1}{\tau_\beta}N_9 - vn\left(\sigma_a + \sigma_f\right)_{\mathrm{Pu}} N_{\mathrm{Pu}}$$

$$N_{cr}^{Pu} = \frac{\sum_i \sigma_{ai} N_i}{(\nu - 1)\sigma_f^{Pu}}$$

$$N_{eq}^{Pu} = \frac{\sigma_{a8}N_8}{\sigma_f^{Pu} + \sigma_a^{Pu}}$$

$$x = z + Vt$$

$$N_{eq}^{Pu} > N_{cr}^{Pu}$$

Feoktistov criterion

Goldin & Anistratov (USSR, 1992): Nuclear Burning Wave — **Deterministic approach**

V. Goldin, D. Anistratov. Preprint IMM RAS # 43, 1992. — **U-Pu fuel cycle** — **1d non-stationary problem**

Edward Teller (USA, 1997): Traveling Wave Reactor — **Monte Carlo simulation**

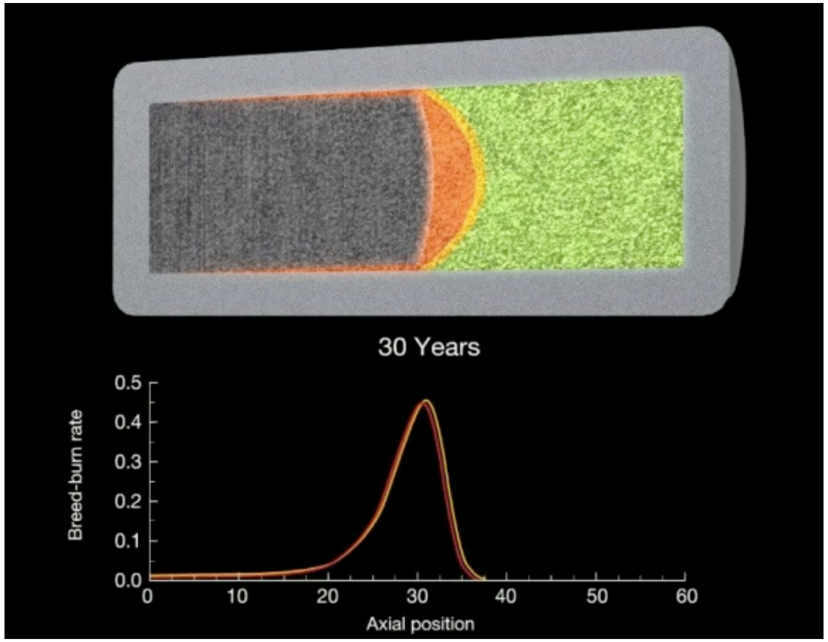
_E.Teller. Preprint UCRL-JC-129547, LLNL,1997. — **Th-U** fuel cycle

Hiroshi Sekimoto (Japan, 2001): CANDLE — **Deterministic approach**

H.Sekimoto et al., Nucl. Sci. Eng., 139 (2001) 306. — **U-Pu** fuel cycle, — **Stationary problem**: $x = z + Vt$

"A New Nuclear Evangelist"

http://www.ted.com/talks/bill_gates.html



TerraPower + Toshiba + China + Korea Rep. = TWR (2026)

The Evolution of the Traveling-Wave Concept

1958 Saveli M. Feinberg proposes a "breed-burn" reactor in which unenriched fuel is moved around the core to sustain fission

1979 Michael J. Driscoll and others at MIT further evaluate breed-burn reactor ideas

1988 Lev Feoktistov works on the concept in Russia and publishes an analysis of a concept of a physically safe reactor

1996 Edward Teller, Lowell Wood (now at Intellectual Ventures), and others at Lawrence Livermore Lab detail ways to make breed-burn waves travel through a stationary fuel supply

2000 Hugo van Dam publishes mathematical analyses of waves of fission moving inside nuclear fuels

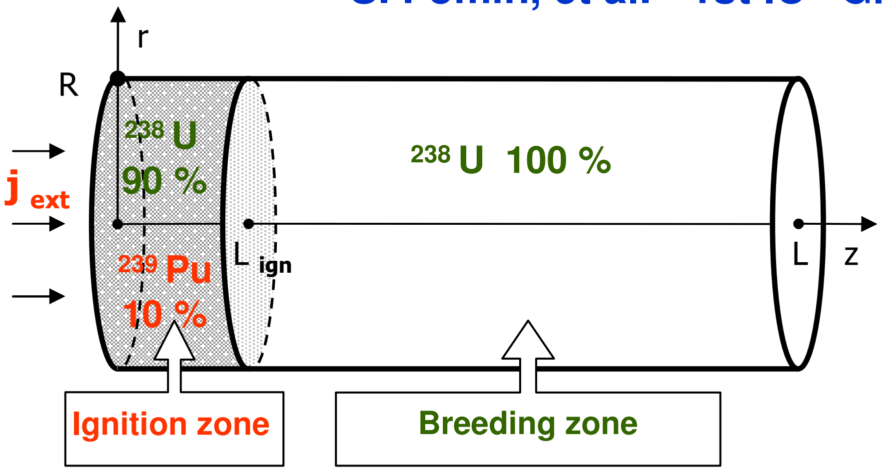
2001 Hiroshi Sekimoto begins a series of conceptual studies of various kinds of TWRs

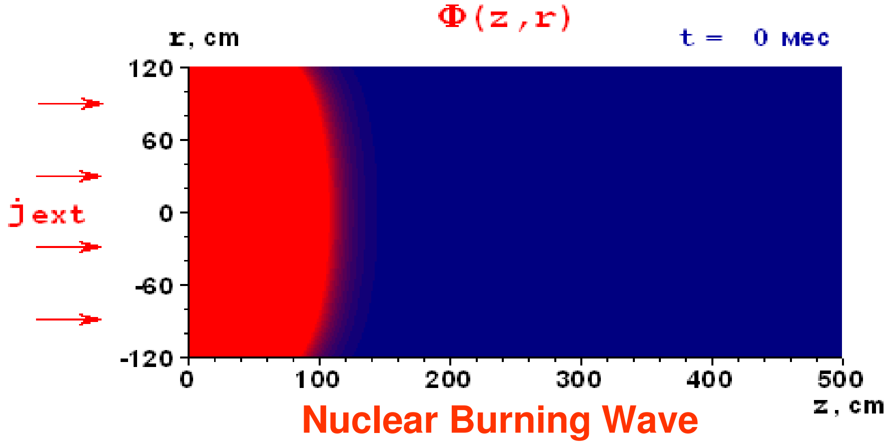
Early 2000s Sergii Fomin and N. Shul'ga study the burning wave in fast reactors in the Ukraine

2006 Intellectual Ventures begins detailed physics and engineering studies of the feasibility, cost, and features of various TWR designs

2D Non-Stationary Theory of Nuclear Burning Wave

S. Fomin, et al. - 1st IC “Global 2009”, Paris, paper 9456.





Non-Stationary Nonlinear Multi-Group Diffusion Equation of Neutron Transport

$$\frac{1}{v^g}\frac{\partial \Phi^g}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r} r D^g \frac{\partial \Phi^g}{\partial r} - \frac{\partial}{\partial z} D^g \frac{\partial \Phi^g}{\partial z} + \left(\Sigma_a^g + \Sigma_{in}^g + \Sigma_{mod}^g - \Sigma_{in}^{g\to g}\right)\Phi^g - \Sigma_{mod}^{g-1}\Phi^{g-1} =$$

$$= \chi_f^g \sum_{g'=1}^{G} (\nu_f\Sigma_f)^{g'}\Phi^{g'} - \sum_j \chi_d^j \sum_l \beta_l^j \sum_{g'=1}^{G}(\nu_f\Sigma_f)_l^{g'}\Phi^{g'} + \sum_j \chi_d^j \sum_l \lambda_l^j C_l^j + \sum_{g'=1}^{g-1}\Sigma_{in}^{g'\to g}\Phi^{g'}$$

Together with Fuel Burn-up Equations and Equations of Nuclear Kinetics

$$\frac{\partial N_l}{\partial t} = -\left(\sum_g \sigma_{al}^g\Phi^g + \Lambda_l\right)N_l + \left(\sum_g \sigma_{c(l-1)}^g \Phi^g + \Lambda_{(l-1)}\right)N_{(l-1)} \quad , (l = 1\div 8);$$

$$\frac{\partial N_9}{\partial t} = \Lambda_6 N_6$$

of Precursor Nuclei of Delayed Neutrons

$$\frac{\partial N_{10}}{\partial t} = \sum_{l=1,4,5,6,7}\left(\sum_g \sigma_{fl}^g\Phi^g\right)N_l$$

$$\frac{\partial C_l^j}{\partial t} = -\lambda_l^j C_l^j + \beta_l^j \sum_g (\nu_f^g\Sigma_f^g)_l\Phi^g$$

Metal fuel (44%)

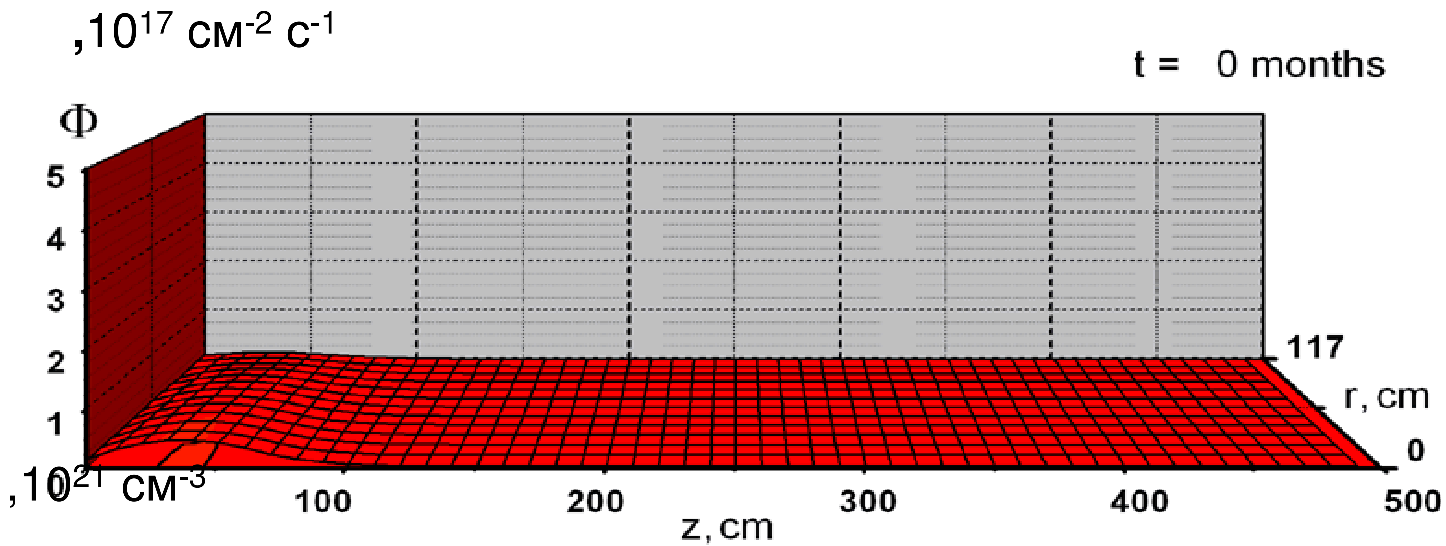
Pb-Bi coolant (36%)

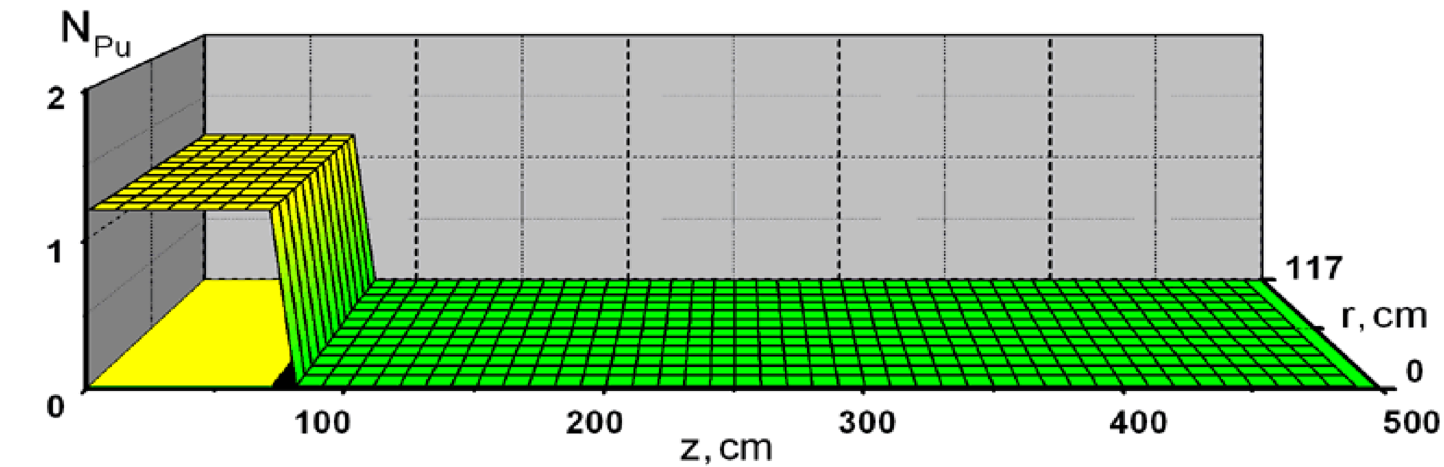
CM - Fe (20%)

$j_{ext} \sim 10^{15}$ cm^{-2} s^{-1}

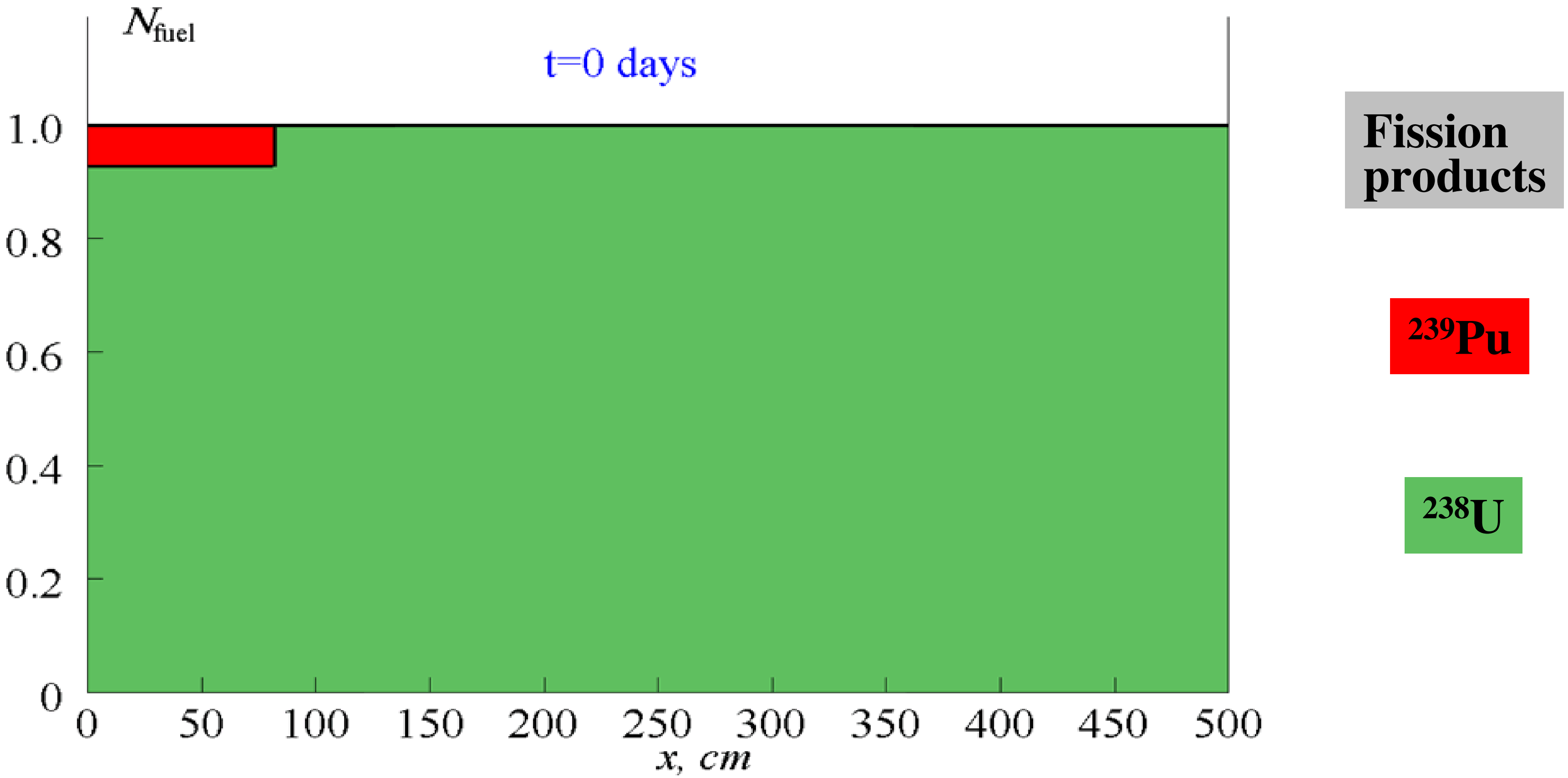
t_{off} = 400 days

NBW Reactor : R=117 cm, L = 500 cm , t_{off} = 950 days





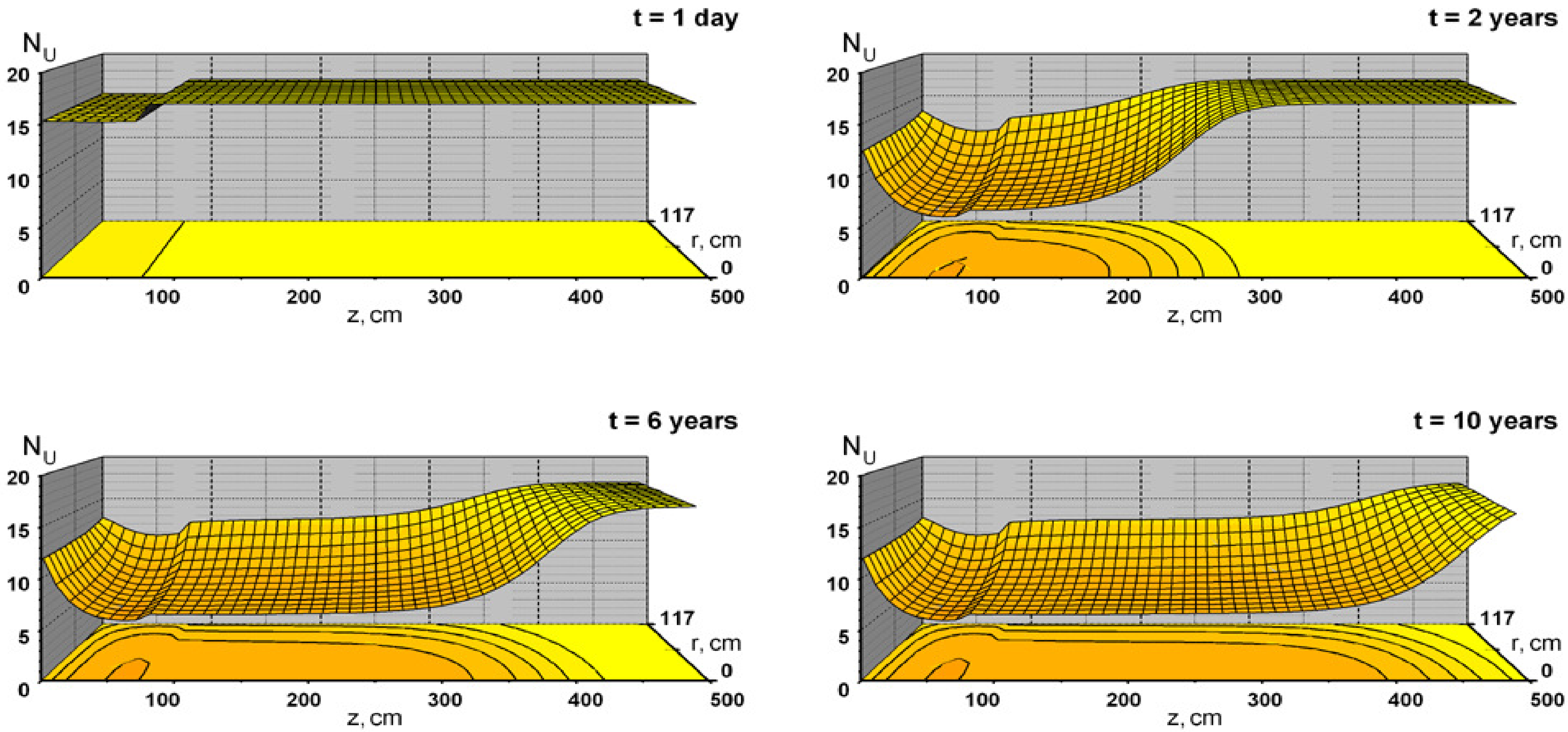
Fuel burn-up



N_{fuel}
t=0 days
1.0
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
x, cm
Fission products
^{239}Pu
^{238}U

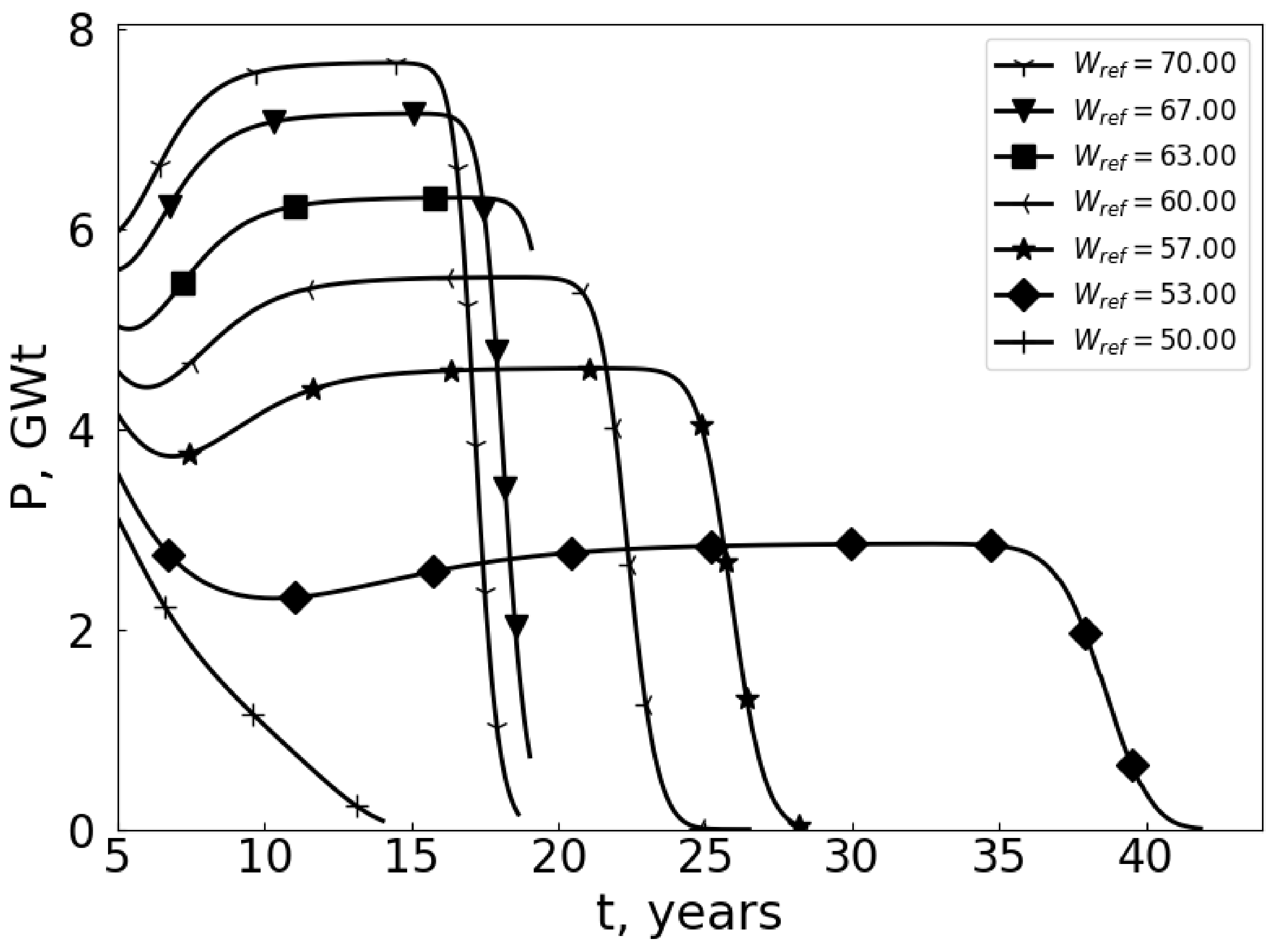
The 2D-distribution $N_U(r,z)$ ($\times 10^{21}$ cm^{-3}) of the ^{238}U isotope

in the NBW regime at different time moments

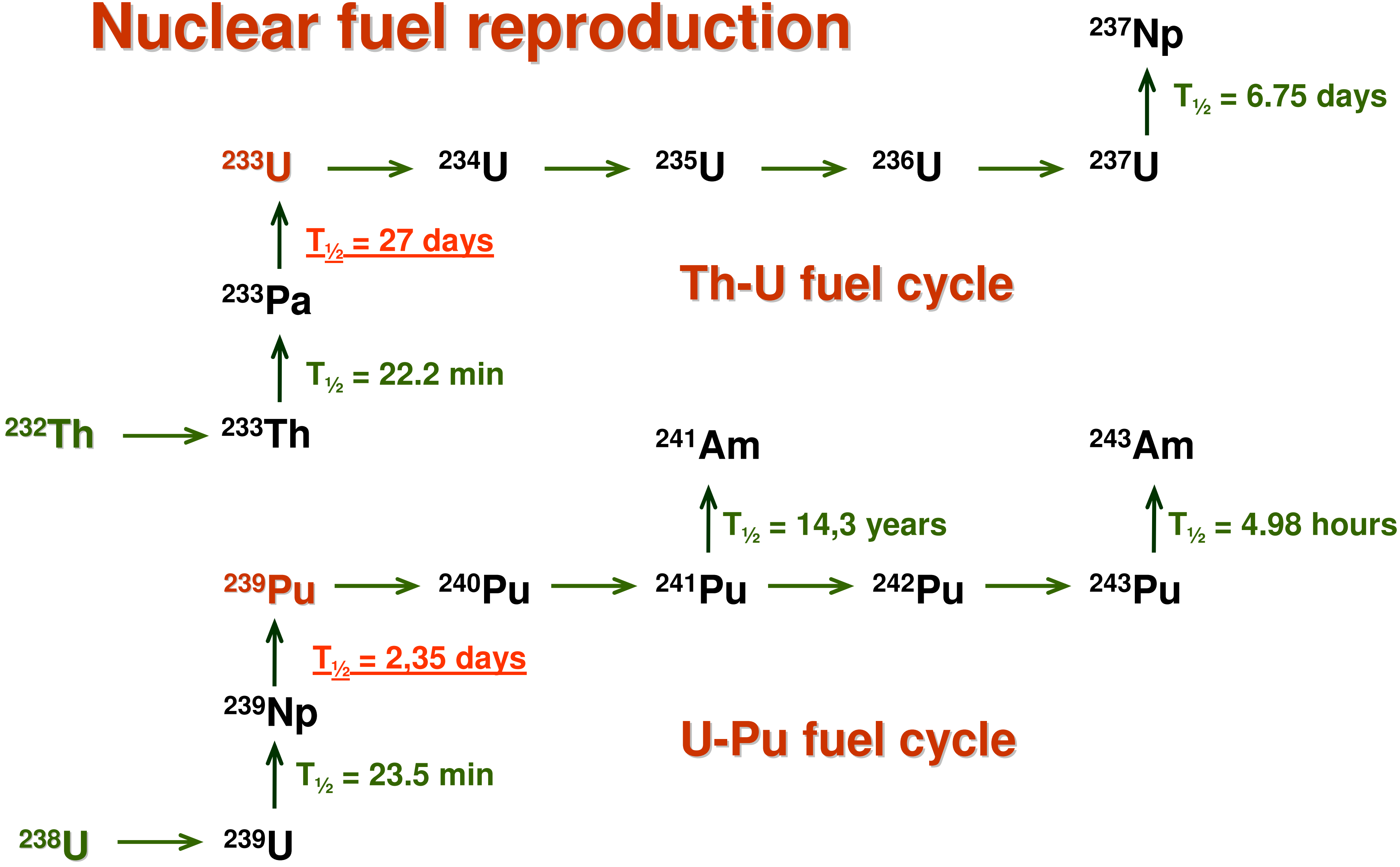


Reactor Power Control by Reflector Efficiency

S. Fomin et al., Annals of Nuclear Energy, (2020) in print.

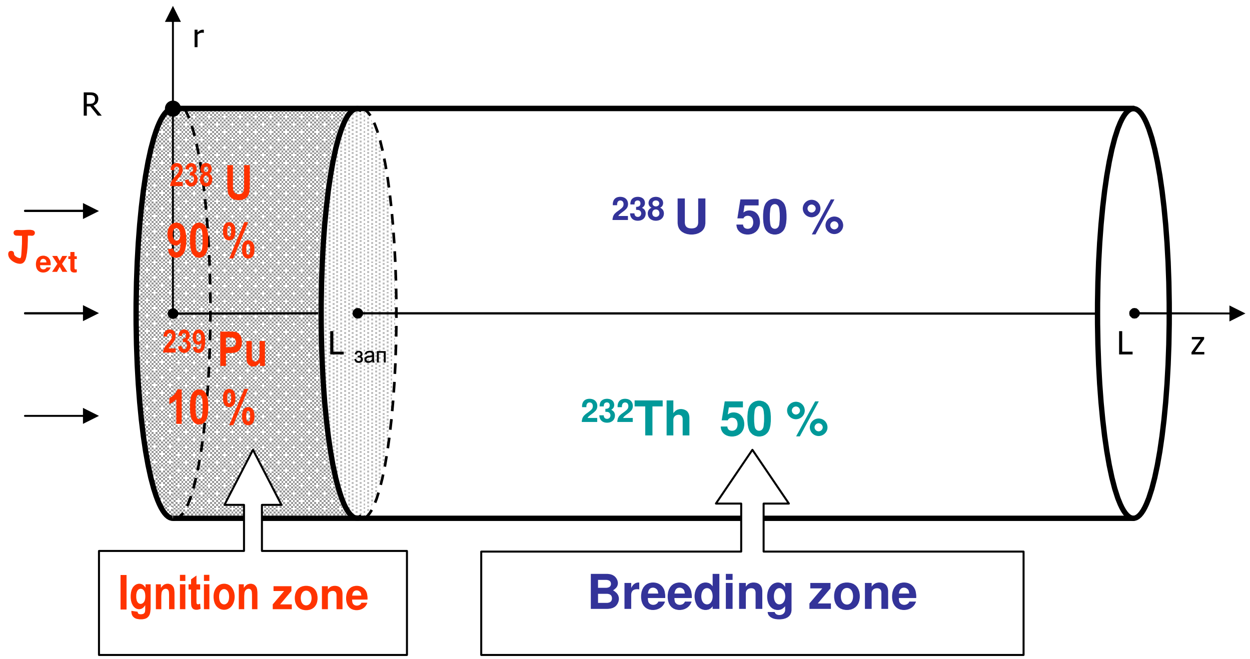


Nuclear fuel reproduction



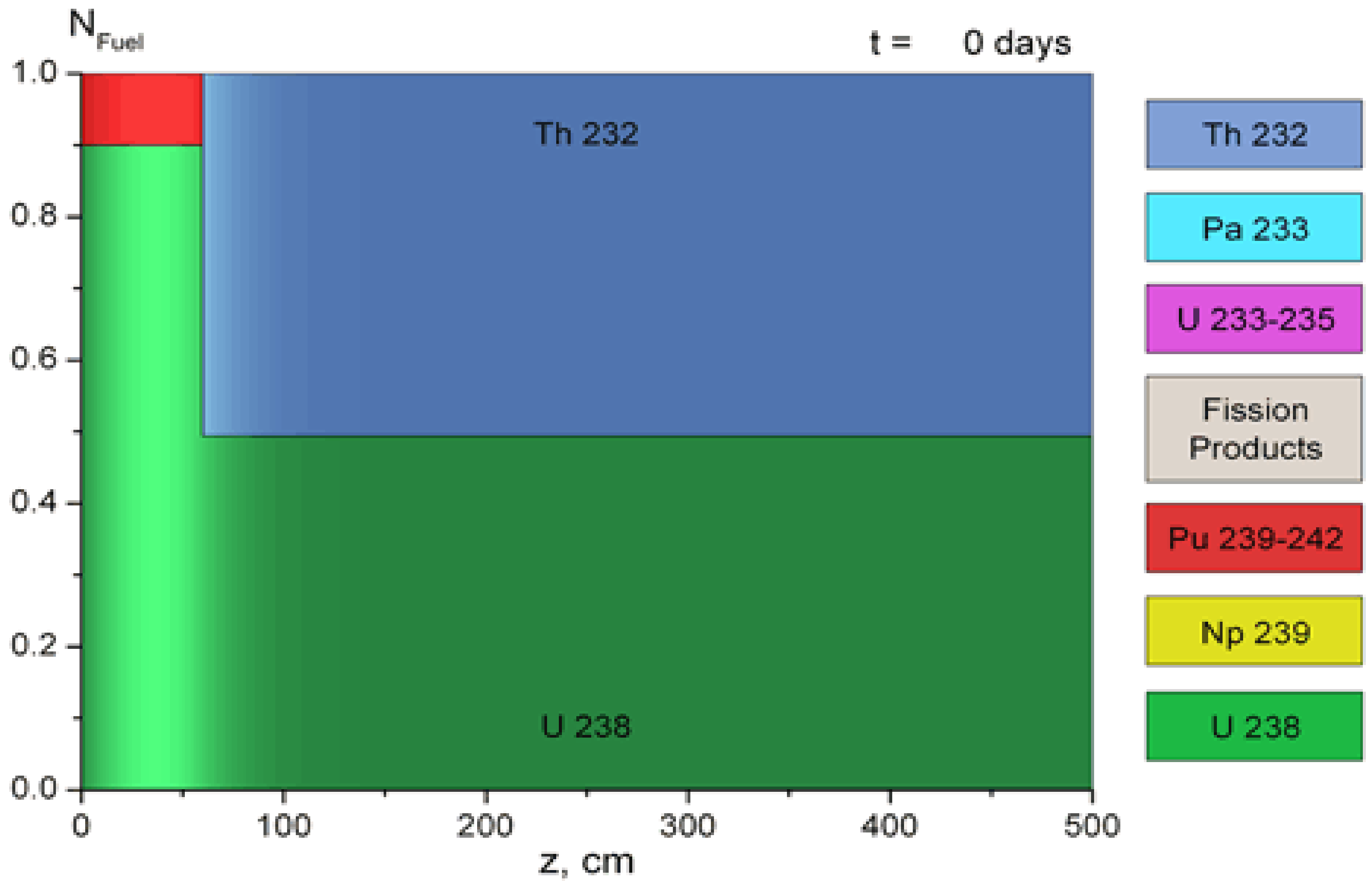
NBW reactor with mixed Th-U-Pu fuel

S. Fomin et al., ICAPP 2010 (San Diego, USA) paper 10302.
S. Fomin et al., Progress in Nuclear Energy, 52 (2011) 800-805.



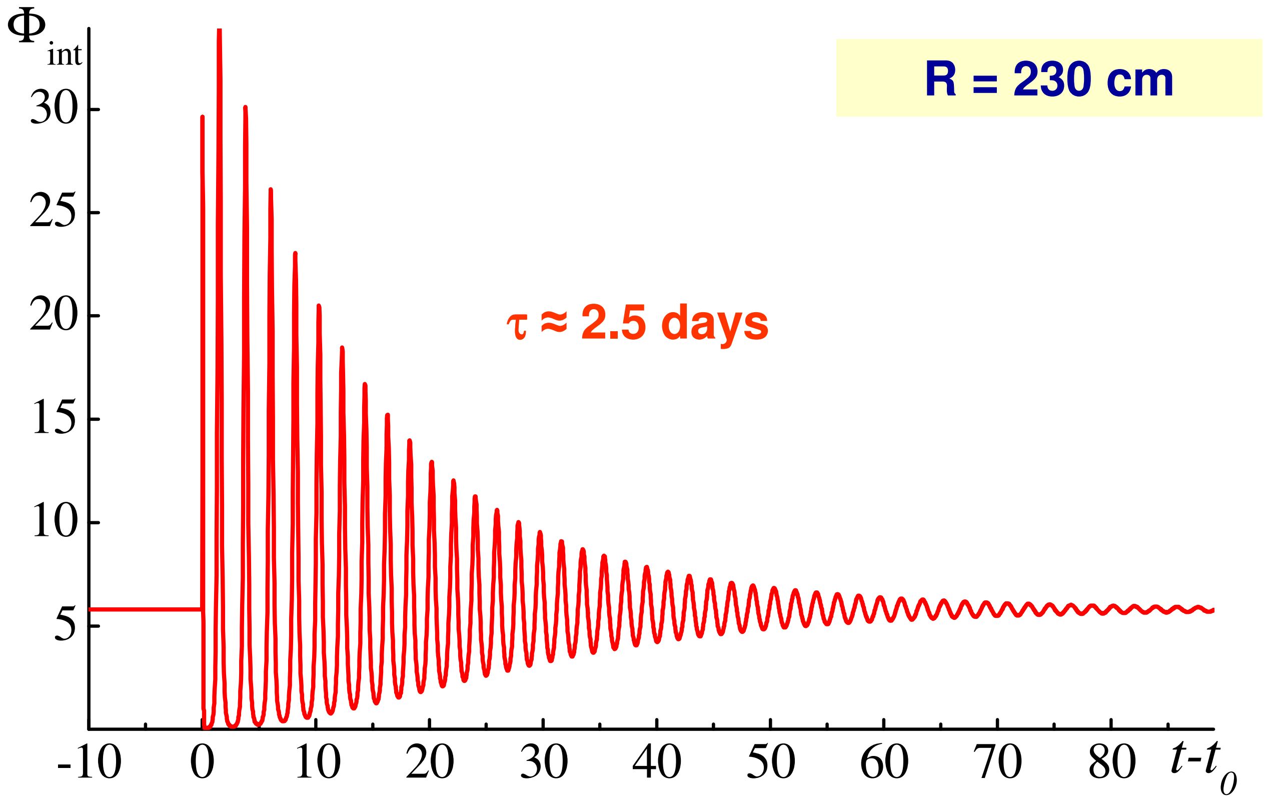
Example: Metallic fuel ^{232}Th (62%) + ^{238}U (48%) volume fraction = 55%, fuel porosity p = 0.35; Coolant (Pb-Bi eutectic) vol. frac. = 30%, Constr. materials (Fe) vol. frac. = 15%; R = 390 cm

Fuel burn-up for Th-U-Pu cycle



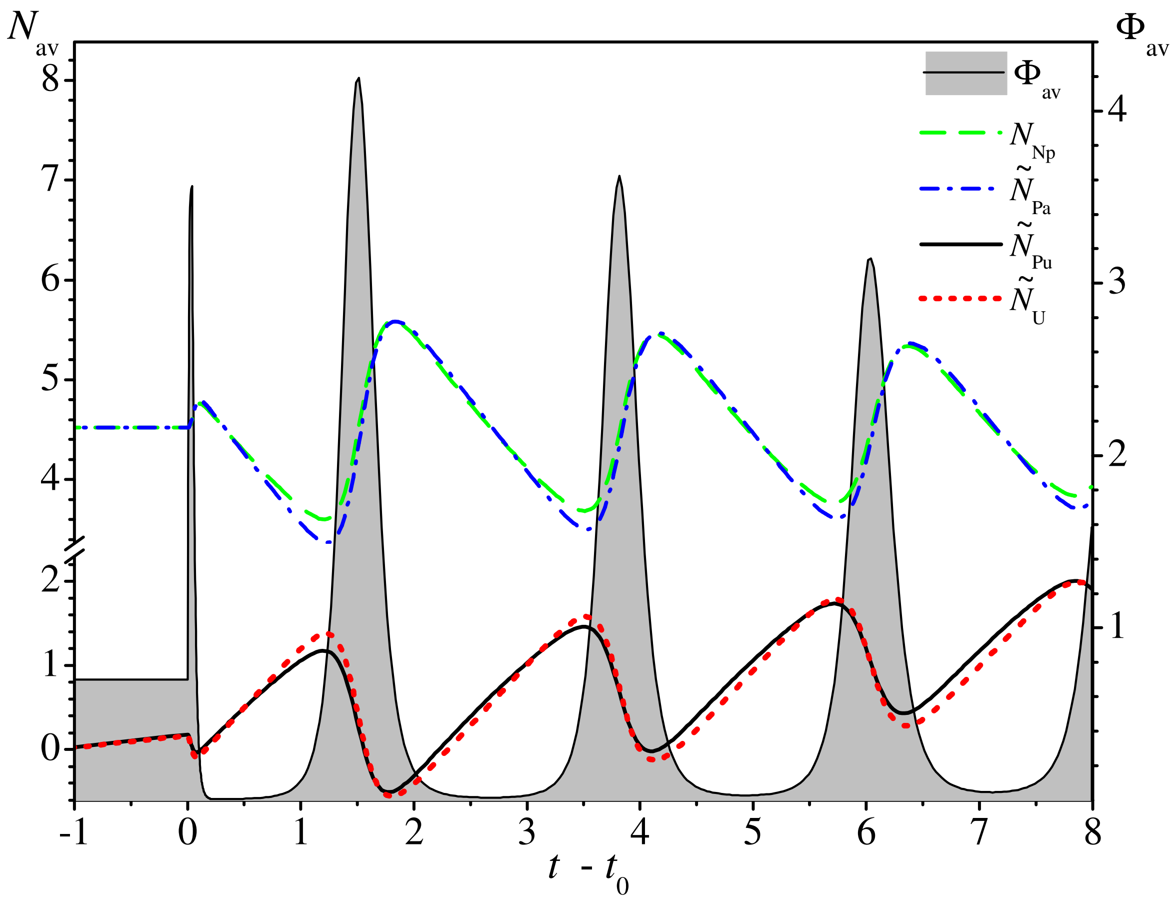
Stability of the NBW Regime

S. Fomin et al., Int. Conf. "Fast Reactors 2013" (Paris, France) paper CN-199-457.



Perturbation of integral neutron flux F_{int} ($\times 10^{22}$ cm/s) caused by an external neutron source via time *t* (days). The source with intensity $Q_{ext} = 2\times10^{11}$ (cm^{-3} s^{-1}) starts at t_0 = 3650 days, lasts during 1 hour and is situated at 160 < *z* < 170 cm

Negative Reactivity Feedback: Stability of the NBW Regime

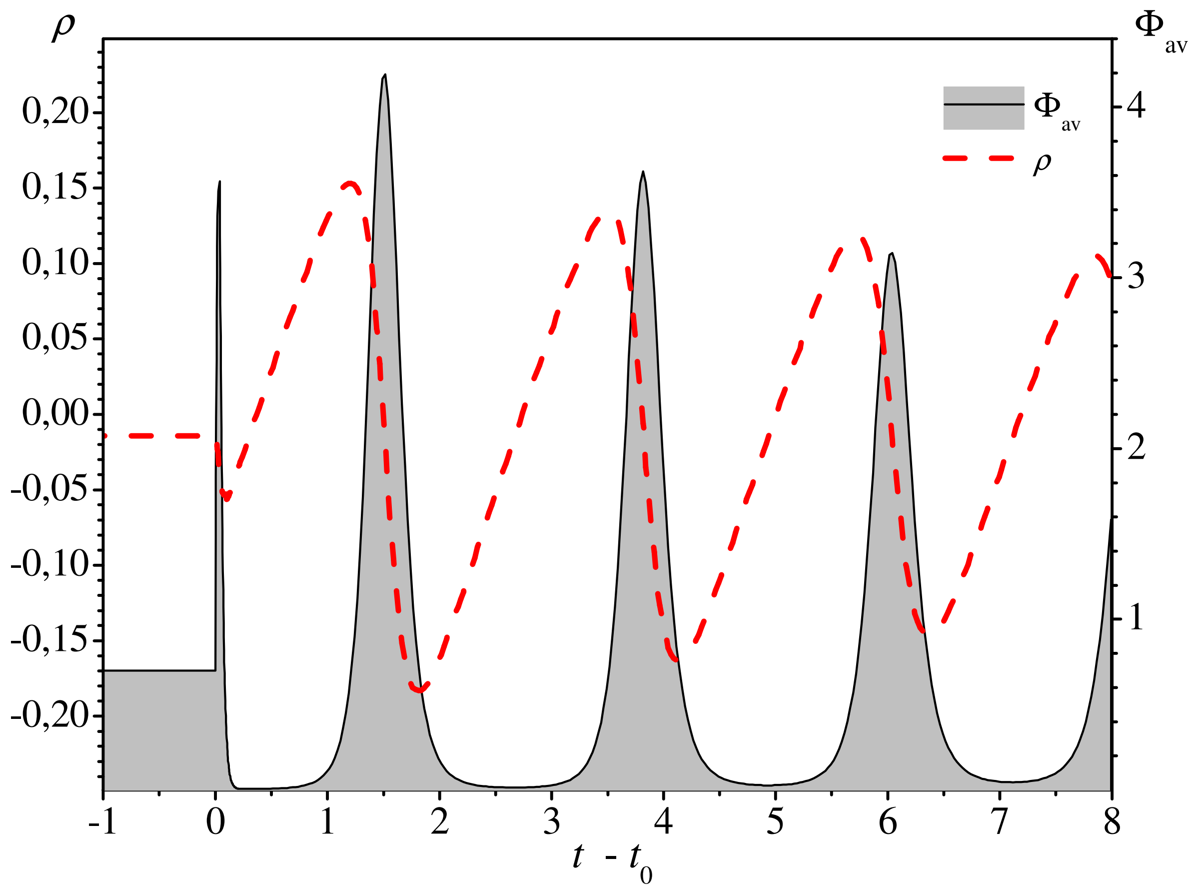


τ ≈ 2.5 days

Evolution of the volume-averaged neutron flux F_{av} (×10^{15} см$^{-2}$ с$^{-1}$) and concentrations N_{av} (×10^{17} cm^{-3}) of the main fissile and intermediate nuclides in the fuel of mixed Th-U-Pu cycle with time t (days) at the initial stage of the neutron flux perturbation t_0 = 3650 days. The averaged nuclide concentrations: N_{Np} is for ^{239}Np, $N_{Pa} = N_{Pa}$ - 53.1·10^{17} cm^{-3}, $\tilde{N}_{Pu} = N_{Pu} - N_{Pu}\big|_{t_0-1}$ is for ^{239}Pu, $\tilde{N}_{U} = N_{U} - N_{U}\big|_{t_0-1}$ is for ^{233}U.

Negative Reactivity Feedback: Stability of the NBW Regime

$$\rho = \frac{k_{eff} - 1}{k_{eff}} : \; 10^{-5} \;\; !!!$$



Variation of the reactivity ρ (dollars) with time *t* (days)
along the variation of the volume-averaged neutron flux F_{av} ($\times 10^{15}$ см$^{-2}$с$^{-1}$)

Main features of NBW reactor with mixed Th-U-Pu fuel cycle

Reactor composition (vol. frac.):
Fuel = 55% (F_{Th} = 62%, p = 0.20), Coolant = 30%, CM = 15%, **R = 215 cm**

- **negative feedback on reactivity - intrinsic safety (!!!)**
- **long-term (decades!!) operation without refueling and external control**
- **possibility of ^{232}Th and ^{238}U utilization as a fuel**
- **fuel burn-up depth for both ^{238}U and ^{232}Th ≈ 50% (one through cycle !)**
- **neutron flux in active zone ≈ $2{\cdot}10^{15}$ n/cm^{2}s**
- **neutron fluence during the whole reactor campaign ≈ $3{\cdot}10^{24}$ n/cm^2**
- **energy production density in active zone ≈ 200 W/cm^3**
- **total power at the steady-state regime ≈ 1.2 GWt**
- **wave velocity at the steady-state regime ≈ 2 cm/year**
- **possibility of nuclear waste burn out (expected)**

List of our publications on the NBW reactor :

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S. Fomin et al., *Problems of Atomic Science & Technology*, 6 (2005) 106-113.

S. Fomin et al., ICENES (2005) (Brussels, Belgium) paper IC058.

S. Fomin et al., *Nuclear Science & Safety in Europe*. Springer (2006) 239-251.

S. Fomin et al., ICAPP'06 (2006) (Reno, USA) paper 6157.

S. Fomin et al., *Problems of Atomic Science & Technology*, 3 (2007) 156–163.

S. Fomin et al., ICAPP'07 (2007) (Nice, France) paper 7499.

S. Fomin, *Reactor Physics and Technology*. PINP WS, St-Perersburg, XL-XLI (2007) 154-198.

S. Fomin et al., *Progress in Nuclear Energy*, 50 (2008) 163-169.

Yu.Mel'nik et al., *Atomic Energy*, 107 (2009) 288-295.

S. Fomin et al., *Global 2009* (Paris, France) paper 9456.

S. Fomin et al., *ICAPP 2010* (San Diego, USA) paper 10302.

S. Fomin et al., *Progress in Nuclear Energy,* 52 (2011) 800-805.

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S. Fomin et al., IC "Fast Reactors 2013" (Paris, France) paper CN-199-457.

S. Fomin et al., IC "Global 2015" (Paris, France) paper 5254.

S. Fomin et al., Problems of Atomic Science & Technology, 3 /121/ (2019) 80–85.

S. Fomin et al., Annals of Nuclear Energy, 148 (2020) 107699.

Thank you for attention !

С.П. Фомин. “*Прометей третьего тысячелетия*”
Университеты / Universitates, № 1/56 (2014) 4–17 и № 3/58 (2014) 4-21.
http://alumni.univer.kharkov.ua/zhurnal-universitates-arxiv-nomerov/