Smooth Startup Problem for Innovative Fast Reactor Working in Nuclear Burning Wave Regime

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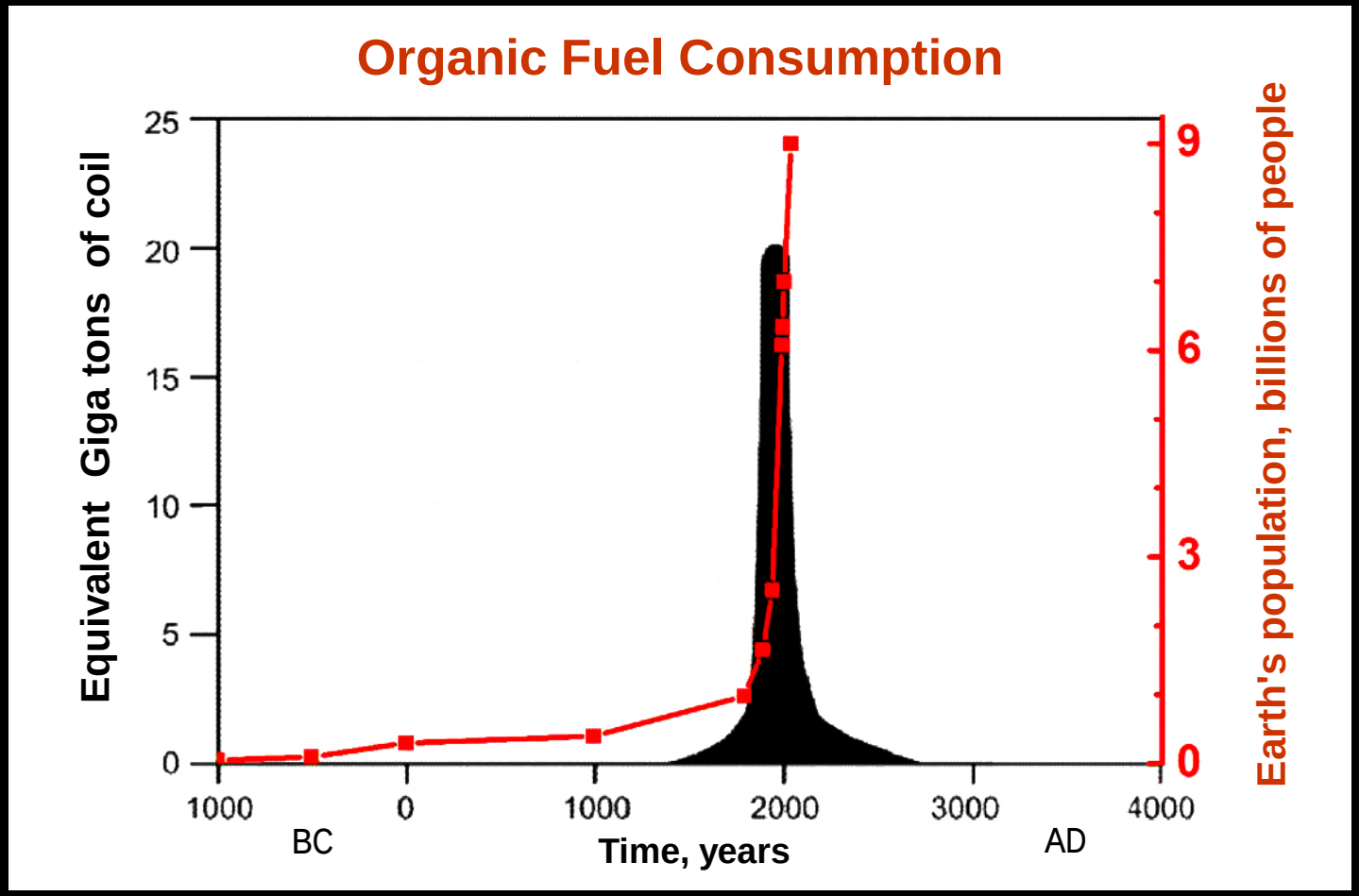
Civilization & Power Consumption

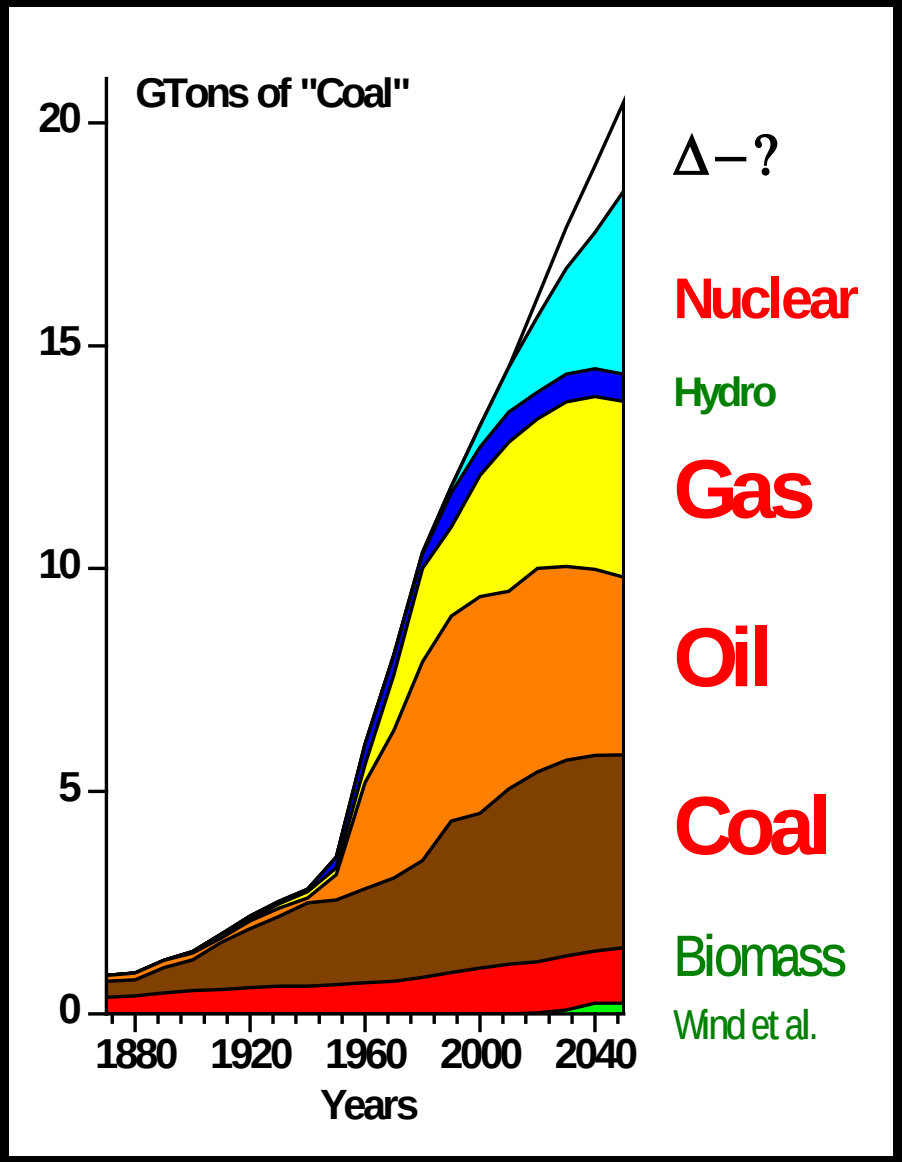
First cave-fire ~ 500 000 years ago : "Chinese Prometheus"

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



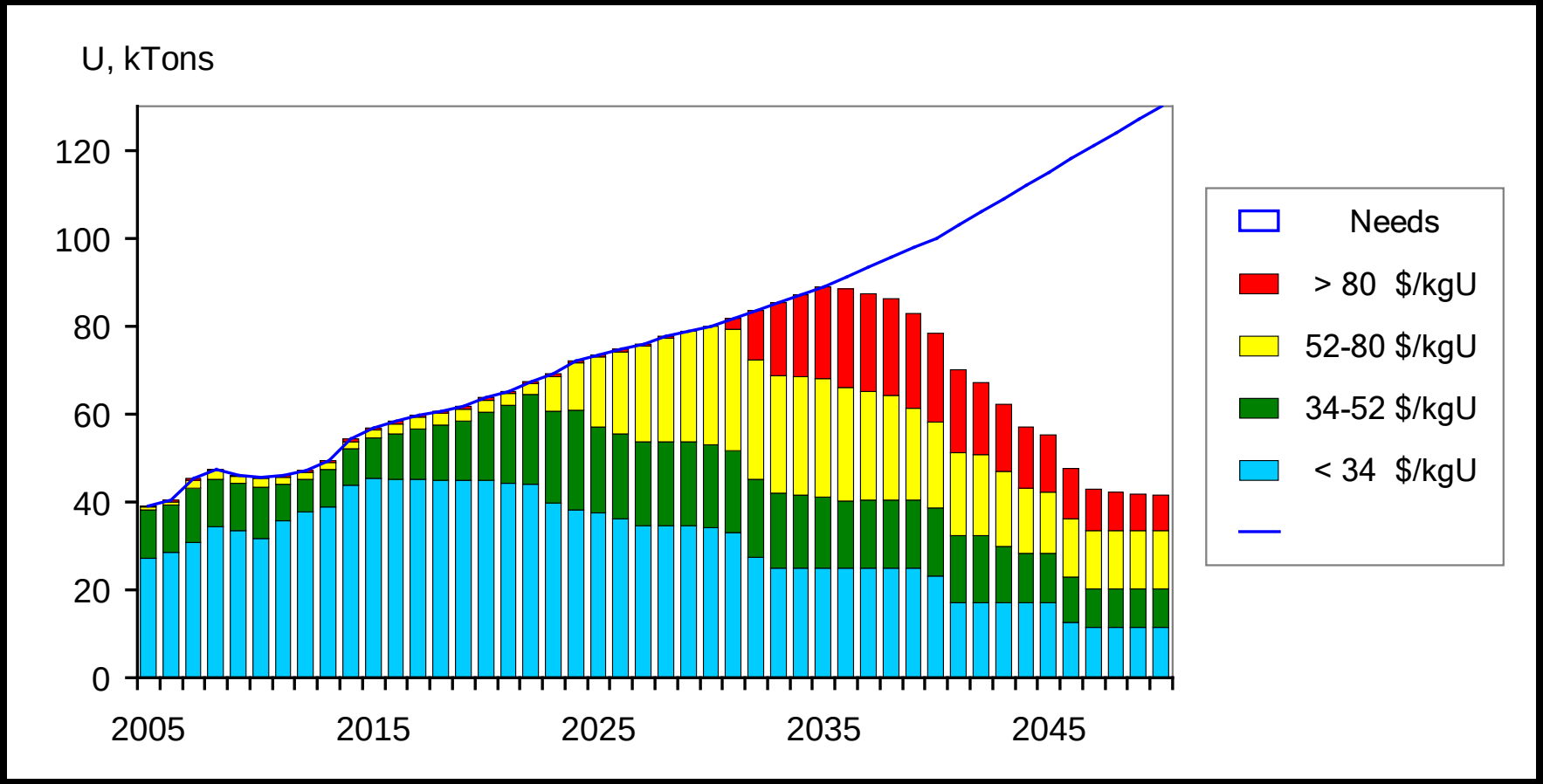
CURRENT USE (2012)

Source	EJ/y	%
Oil	170	33.2
Coal	139	27.2
Gas	109	21.3
Biomass	51	9.96
Uranium	30	5.86
Hydro	12	2.34
Wind	0.72	0.14
Geotherm	0.23	0.045
Solar	0.04	0.007
Ocean	0.002	0.0004
Total:	512	100%
Fossil	448	87.5
Renewable	64	12.5

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

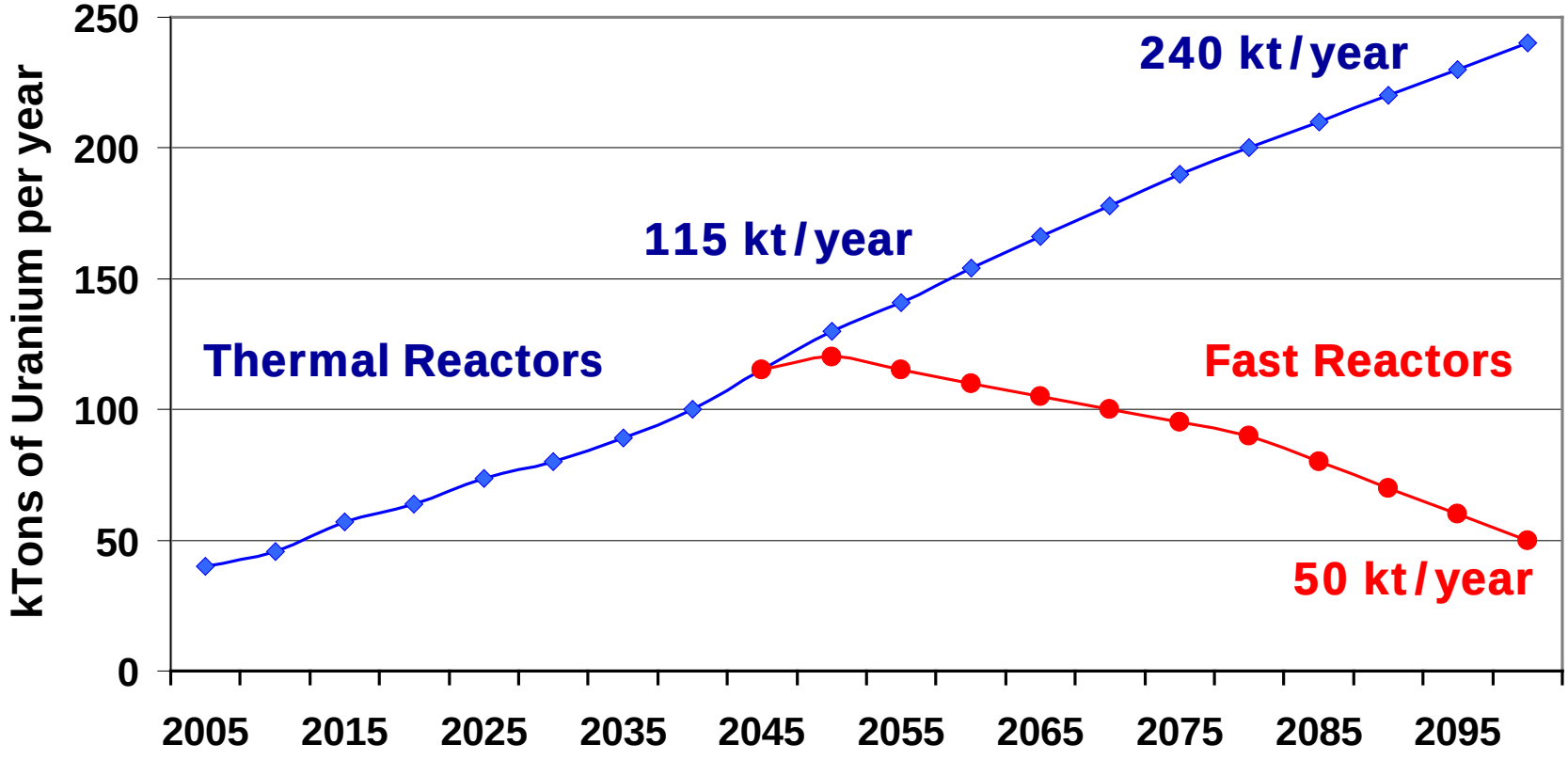
www.elsevier.com/locate/energy - “Energy”, 2012

Explored Earth reserves of Uranium



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

Forecast world demand for Uranium up to 2100

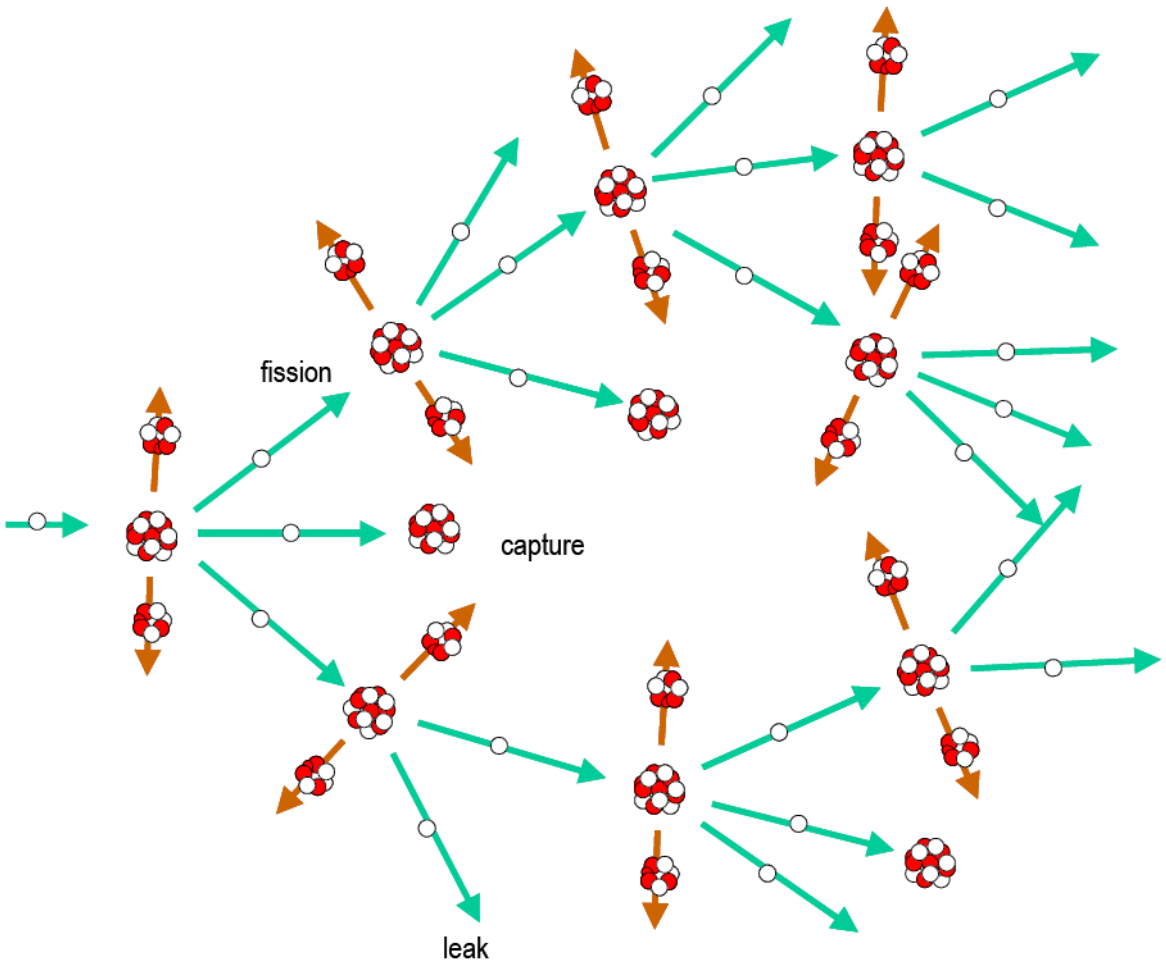


Nuclear Power Problems

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 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

$k_{eff} = 1$!!!

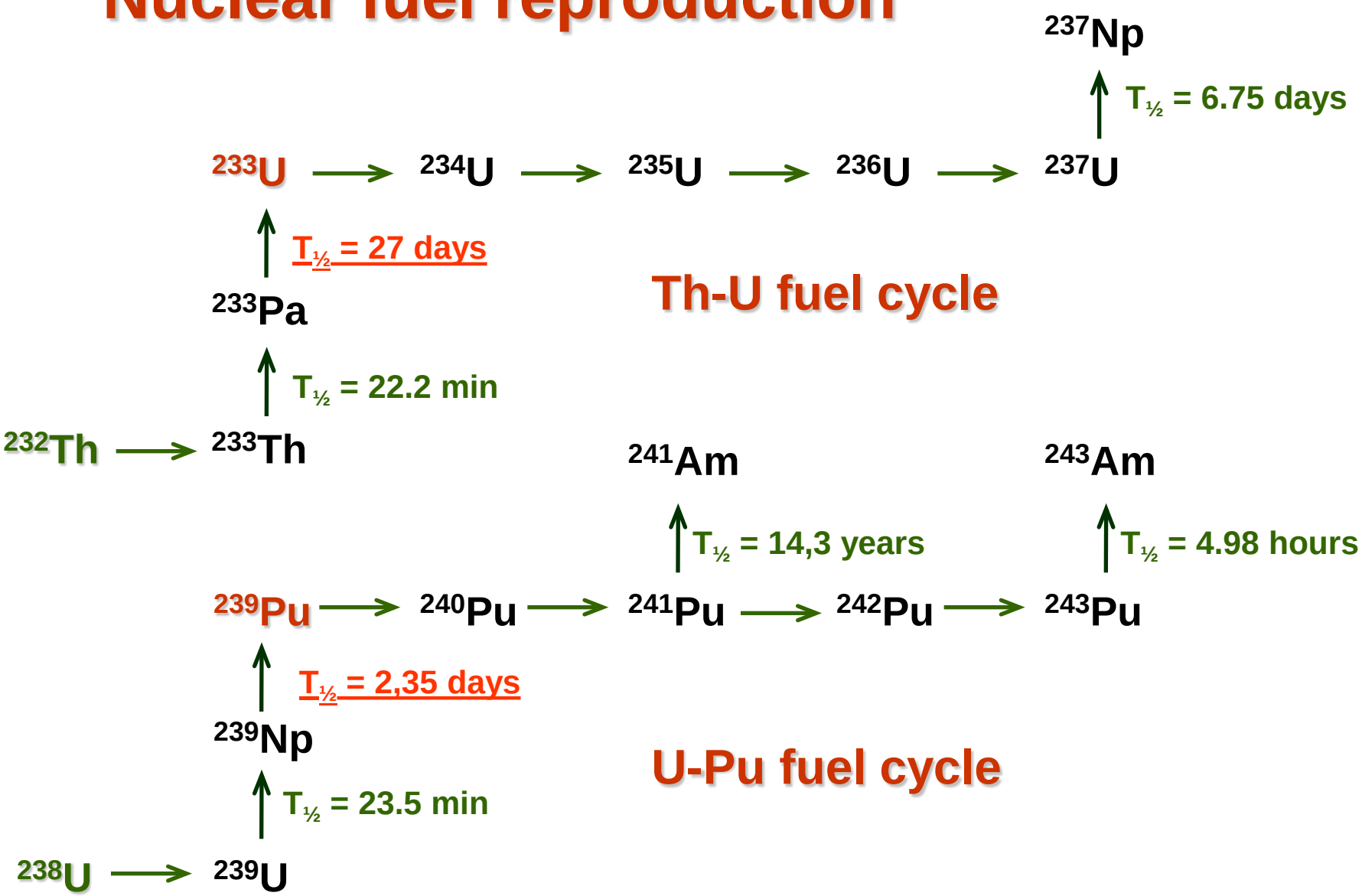
Reactivity

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

Total «nuclear burning» of 1g U ~ 5 tons of coal

NPP W = 500 MW 315 kg/d U ~ 7 000 tons of coal per day

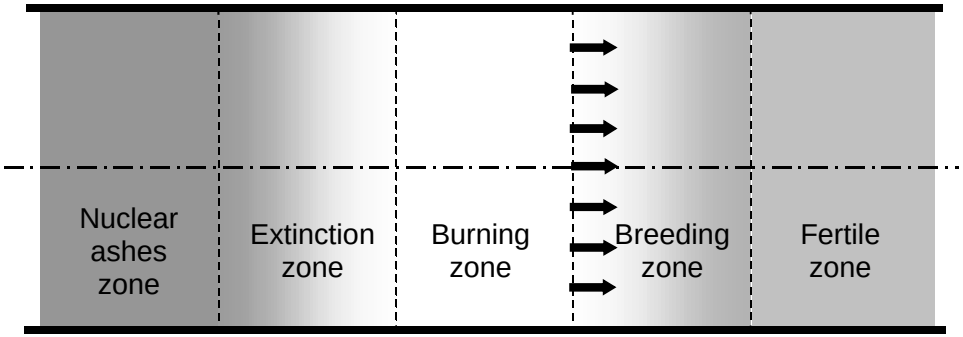
Nuclear fuel reproduction



Lev Feoktistov (USSR, 1988):

Nuclear Burning Wave

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



Concept & Analytical approach

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

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

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

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

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

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

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

$$x = z + Vt$$

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

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

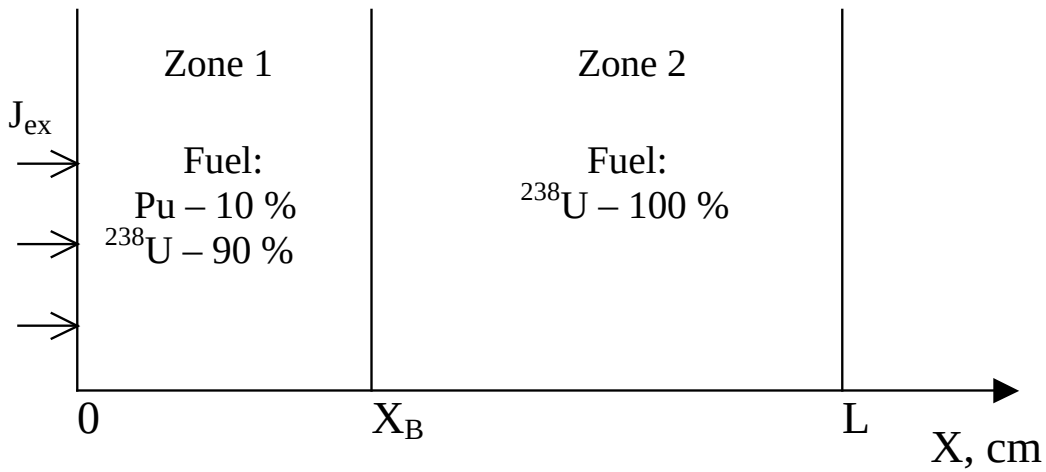
Hiroshi Sekimoto (Japan, 2001): **CANDLE** **Deterministic approach**

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

V. Goldin, D. Anistratov (IAM, Moscow) 1992 : Non-stationary problem !

V. Goldin, D. Anistratov,. Preprint IAM AS USSR, # 43, 1992; Mathematical Modelling, 7 (1995) 12.

Composition: U-Pu fuel - 40 %, Na – 25 % Fe – 35 %



1d one-group approaximation

(U-Pu fuel cycle)

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

$$C_l^i(x, t=0) = C_{0l}^i(x)$$

$$\frac{1}{v}\frac{\partial \Phi}{\partial t} - \frac{\partial}{\partial x}\left(D\frac{\partial \Phi}{\partial x}\right) + \Sigma_a \Phi - (1-\overline{\beta})(\nu_f \Sigma_f)\Phi = \sum_l \sum_i \lambda_l^i C_l^i$$

$$\overline{\beta} = \sum_l \beta_l (\nu_f \Sigma_f)_l / \nu_f \Sigma_f$$

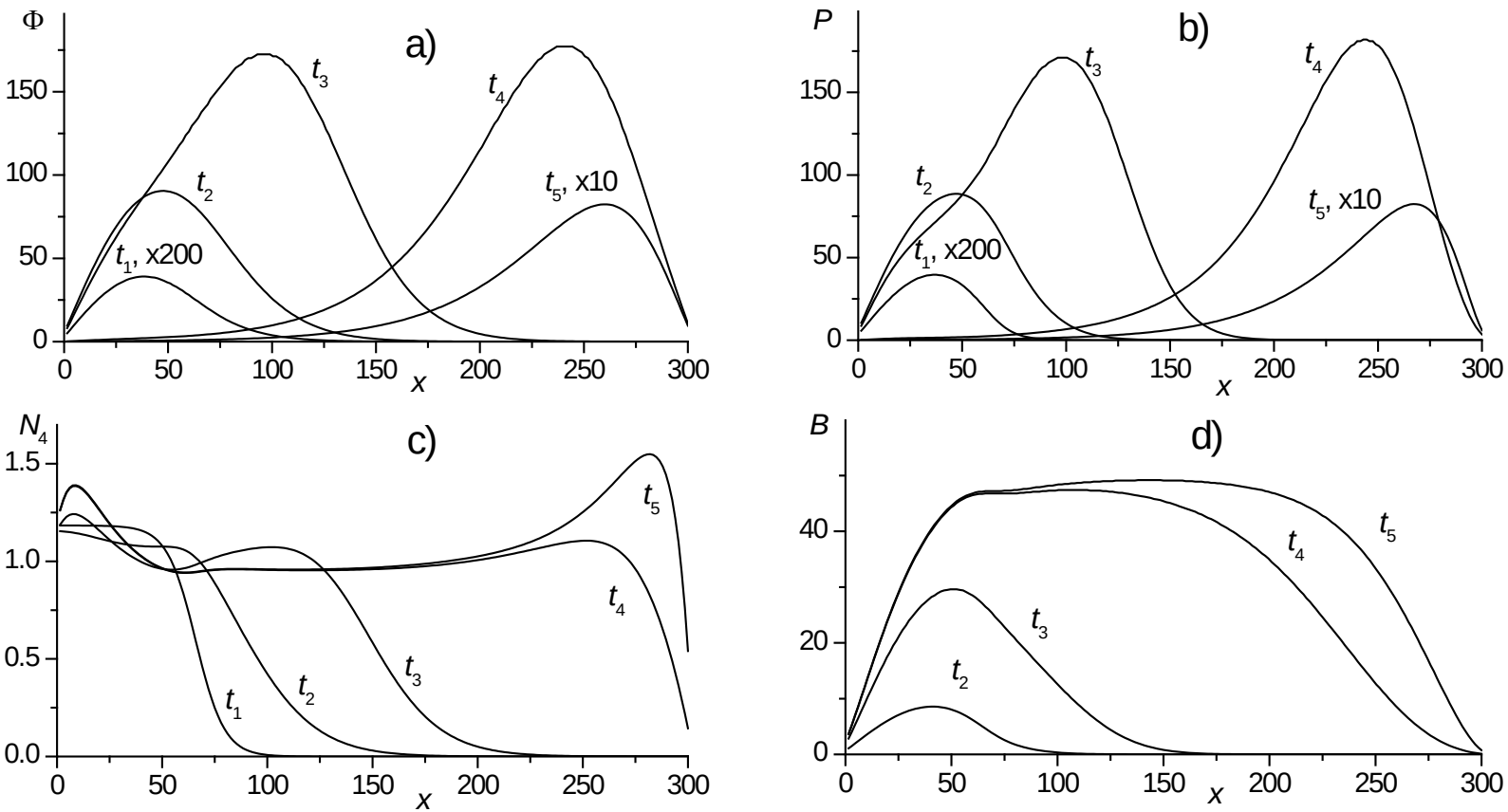
$$D(x) = 1/3\Sigma_{tr}(x) \qquad \Sigma_\alpha(x) = \sum_j \sigma_\alpha^j N^j(x) \qquad \nu_f \Sigma_f = \sum_j \nu_f^j \sigma_f^j N^j(x) \qquad \beta_l = \sum_i \beta_l^i$$

$$\Phi(0) - 2D(0)\left.\frac{\partial \Phi(x)}{\partial x}\right|_{x=0} = 2 j_{ex} \qquad \Phi(L) + 2D(L)\left.\frac{\partial \Phi(x)}{\partial x}\right|_{x=L} = 0 \qquad D^{/}(x)\frac{d\Phi^{/}(x)}{dx} = D^{//}(x)\frac{d\Phi^{//}(x)}{dx}$$

$$\Phi^{/}(x) = \Phi^{//}(x) \qquad \Phi(x, t=0) = 0 \qquad 0 \le x \le L \qquad 0 \le t \le T$$

Nuclear burning wave in FR

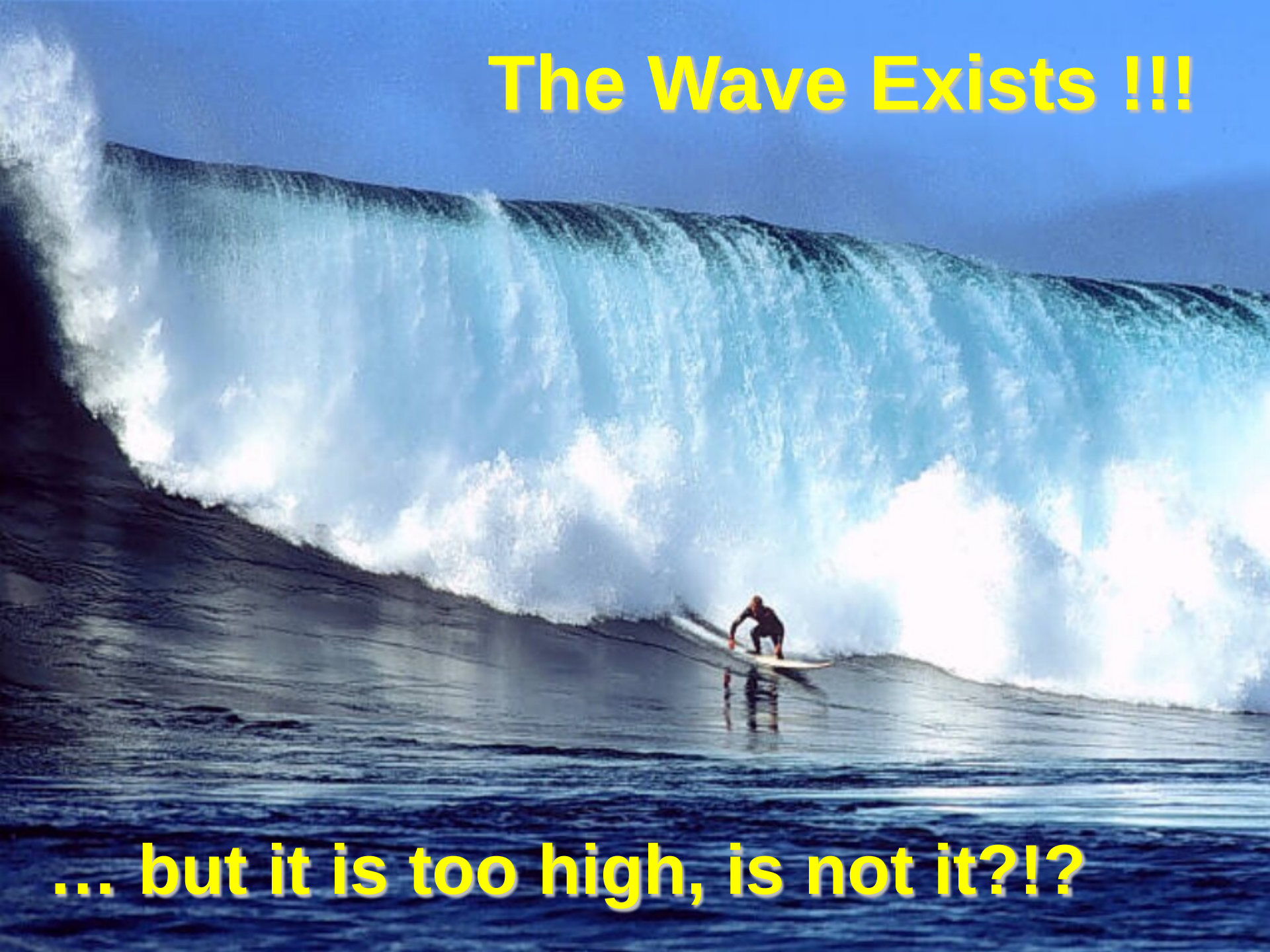
S. Fomin et al., *Annals of Nuclear Energy*, 32 (2005) 1435-1456.



(a) scalar neutron flux ($\times 10^{16}$ cm^{-2} s^{-1}); (b) power density (kW cm^{-3});

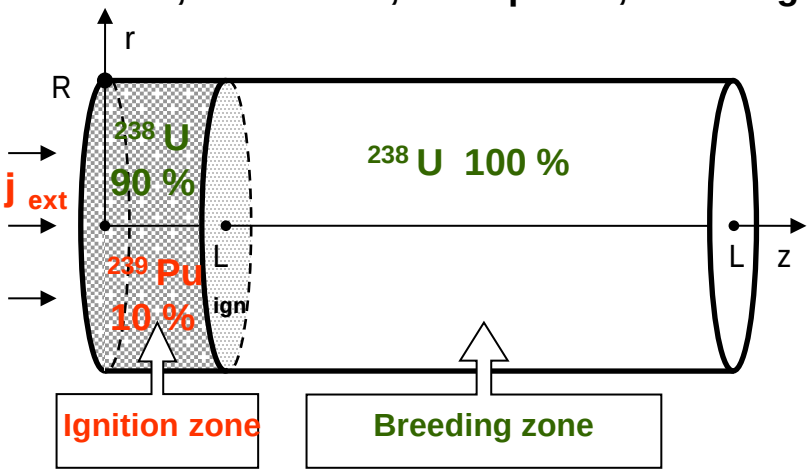
(b) (c) concentration of ^{239}Pu ($\times 10^{21}$ cm^{-3}); (d) depth of fuel burn-up (%)

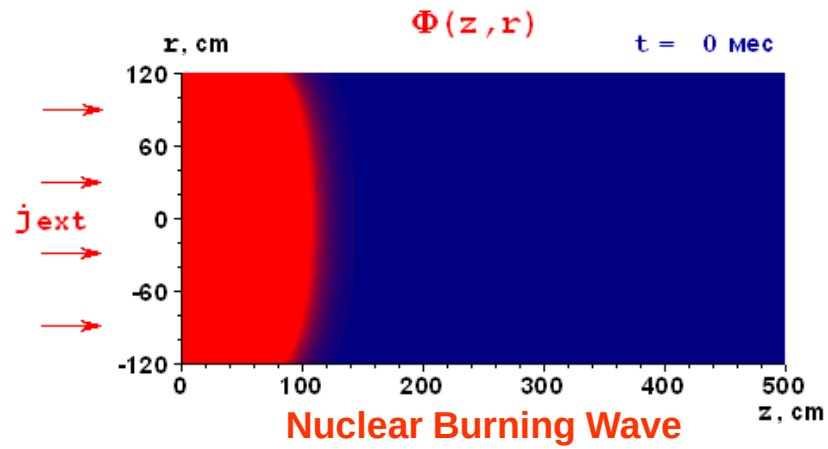
for $t_1 = 1$, $t_2 = 80$, $t_3 = 100$, $t_4 = 140$ and $t_5 = 170$ days. ($0 \le x \le 300$ cm):


The Wave Exists !!!
… but it is too high, is not it?!?

2D Non-Stationary Theory of Nuclear Burning Wave

S. Fomin, Yu. Mel'nik, V. Pilipenko, N. Shul'ga, A. Fomin (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

$$\frac{\partial N_l}{\partial t} = -\left(\sum_g \sigma_{al}^g \Phi^g + \Lambda_l\right) N_l + \left(\sum_g \sigma_{c(l-1)}^g \Phi^g + \Lambda_{(l-1)}\right) N_{(l-1)}, \quad (l = 1 \div 8); \qquad \frac{\partial N_9}{\partial t} = \Lambda_6 N_6$$

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%)

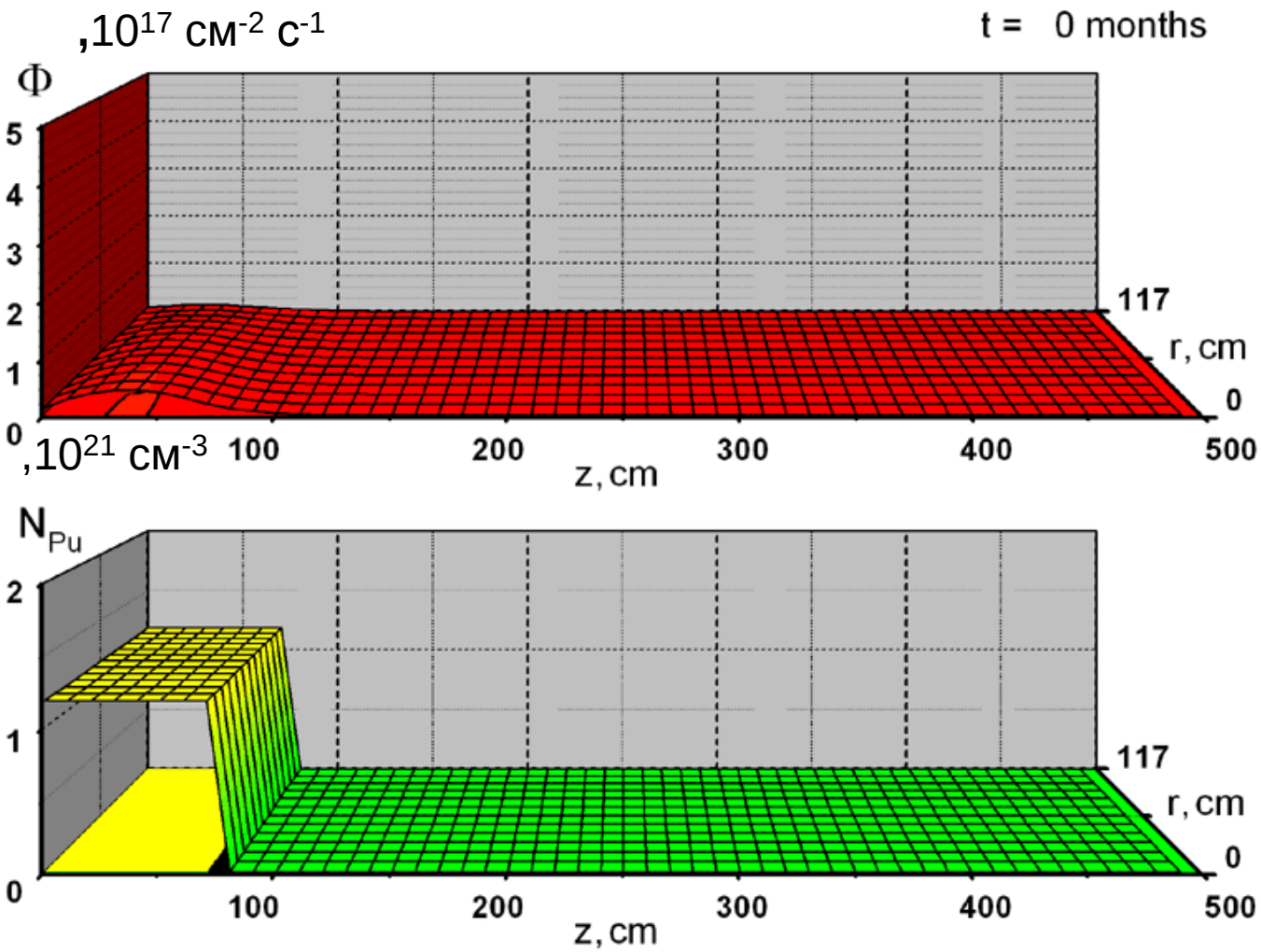
Pb-Bi coolant (36%)

CM - Fe (20%)

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

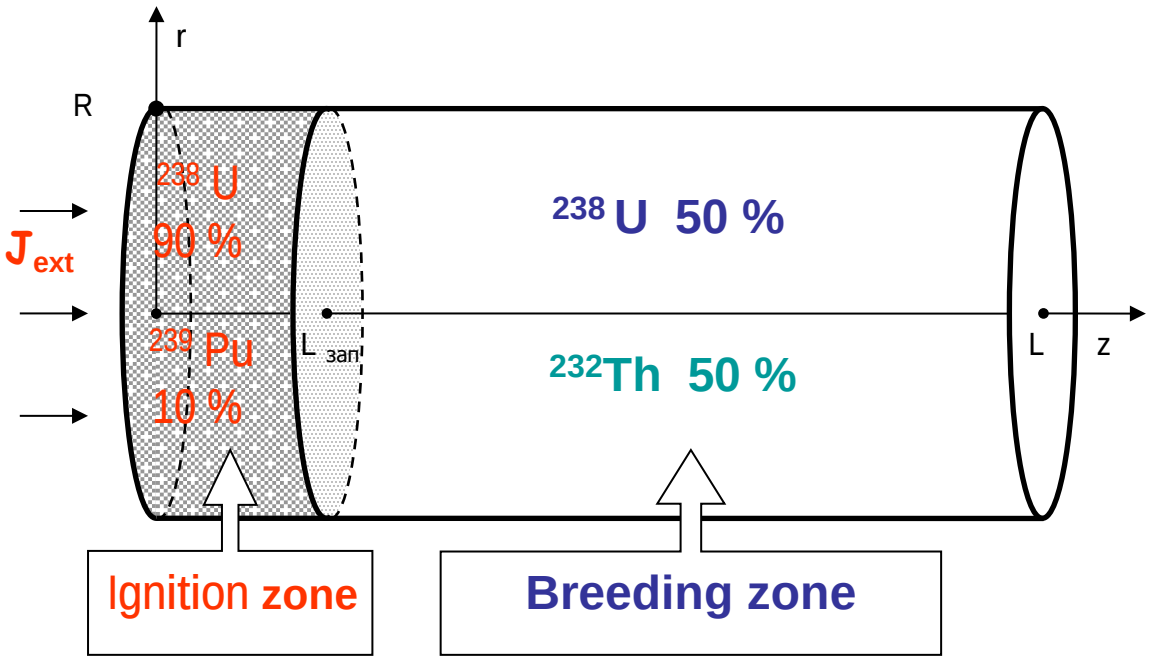
t_{off} = 400 days

Reactor variant: R=117 cm, L = 500 cm (L_{ig}= 71.17 cm), t_{off}=950 days

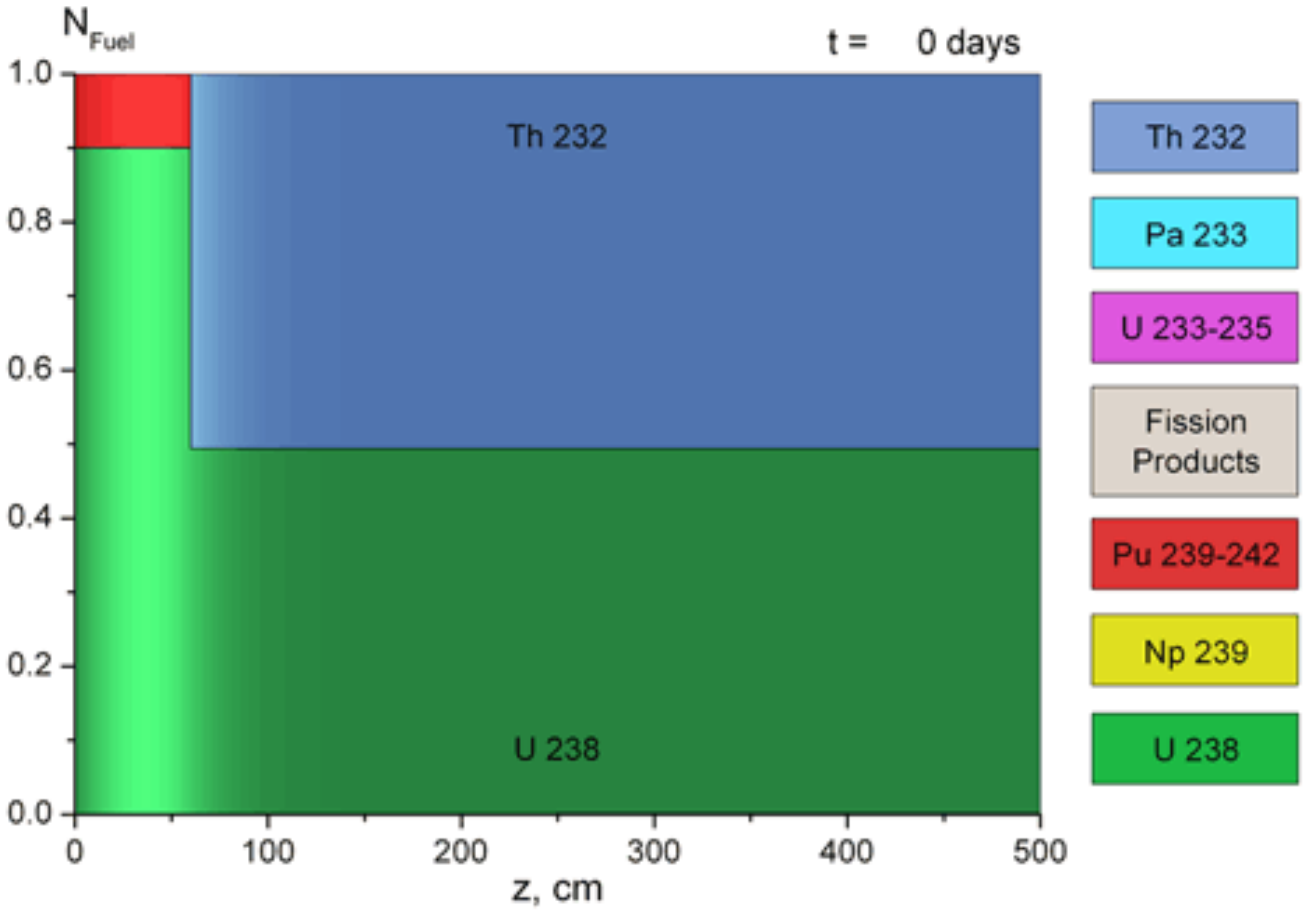


2009: NBW reactor with mixed Th-U-Pu fuel cycle

Example: Metallic fuel ^{232}Th (62%) + ^{238}U (48%) volume fraction = 55%, fuel porosity p = 0.65; Coolant (Pb-Bi eutectic) vol. frac. = 30%, Constr. materials (Fe) vol. frac. = 15%; R = 390 cm



Fuel burn-up for Th-U-Pu cycle

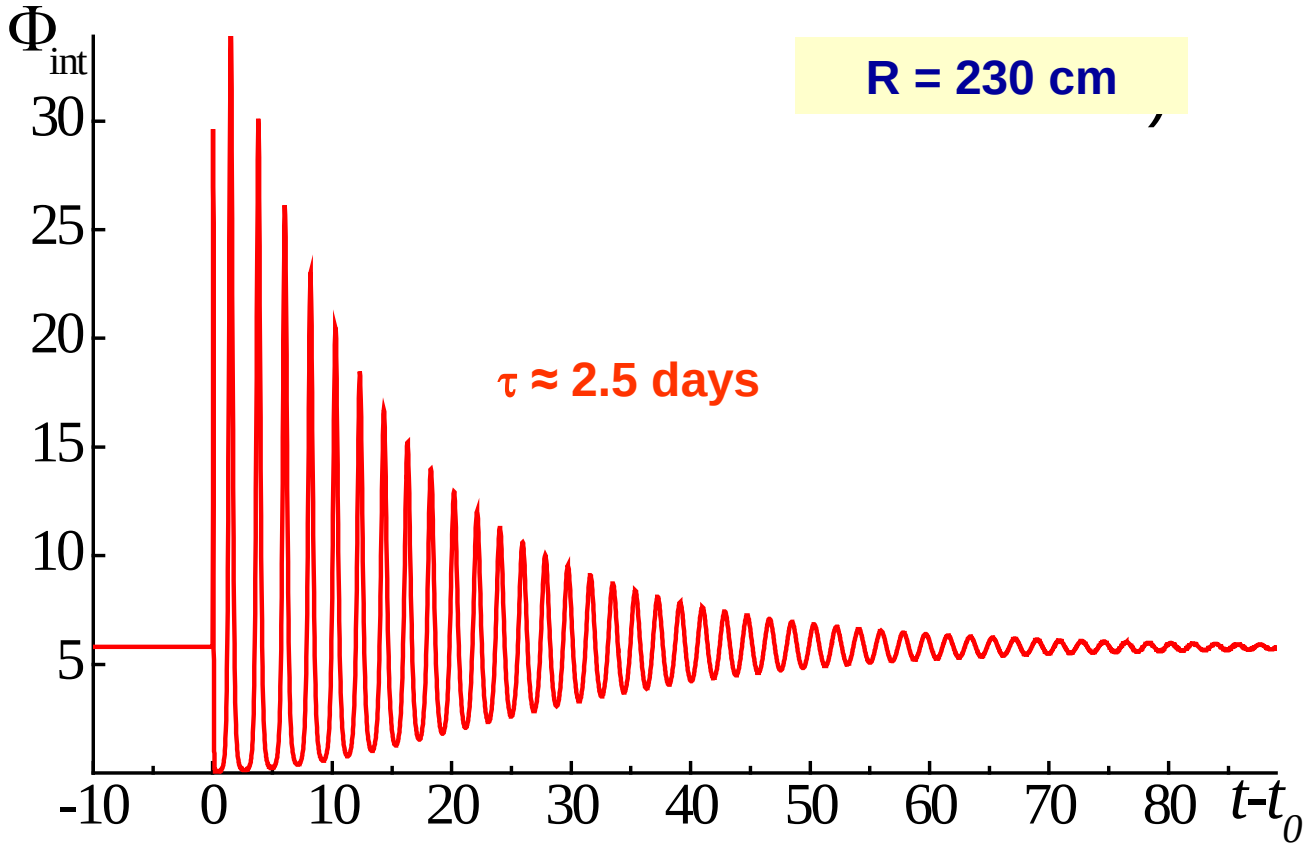


Main features of NBW reactor with mixed Th-U-Pu fuel cycle

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

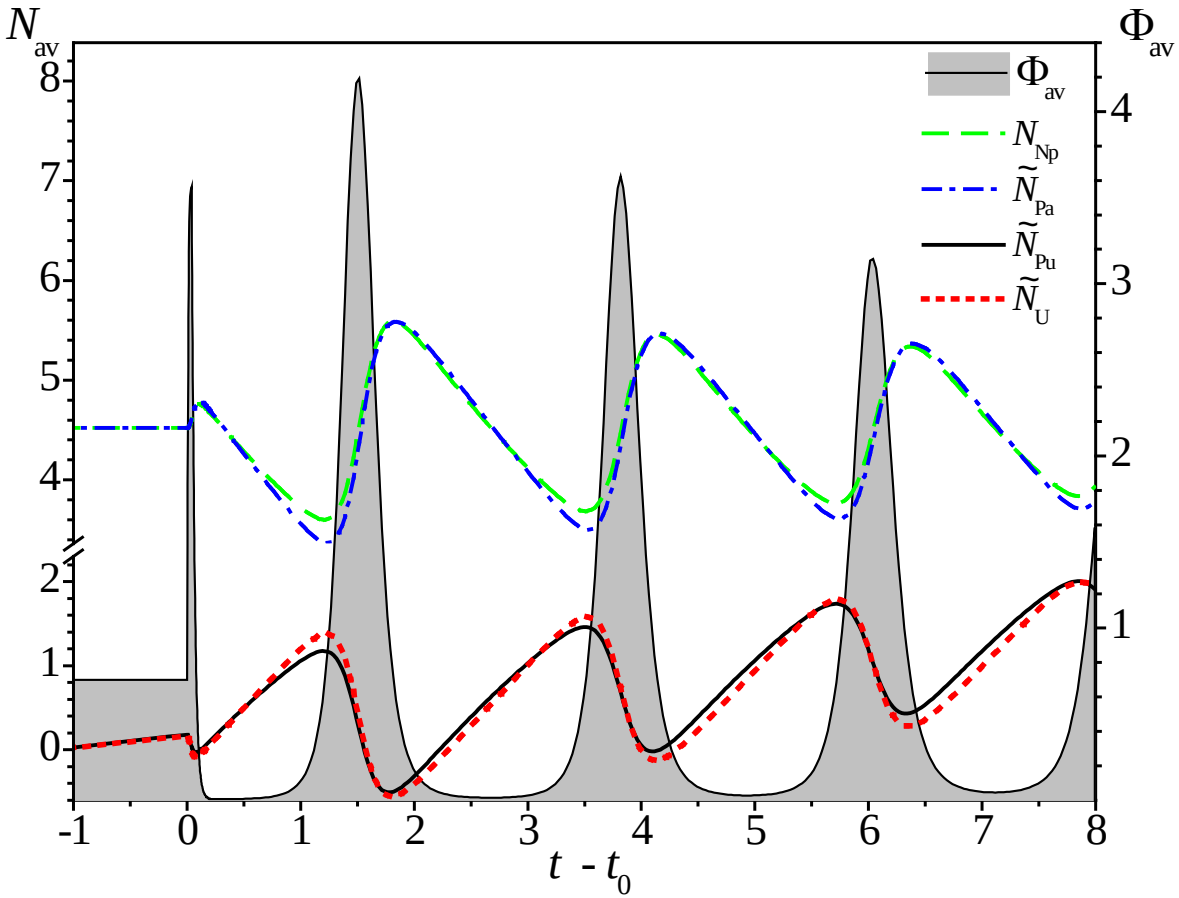
- **negative feedback on reactivity - intrinsic safety**
- **long-term (decades) operation without refueling and external control**
- **possibility of ^{232}Th and ^{238}U utilization as a fuel**
- **fuel burn-up depth for both ^{238}U and ^{232}Th ≈ 50%**
- **neutron flux in active zone ≈ $2\cdot10^{15}$ n/cm^{2}s**
- **neutron fluence during the whole reactor campaign ≈ $3\cdot10^{24}$ n/cm^2**
- **energy production density in active zone ≈ 200 W/cm^3**
- **total power at the steady-state regime ≈ 1.2 GW**
- **wave velocity at the steady-state regime ≈ 2 cm/year**
- **possibility of nuclear waste burn out (expected)**

Stability of the NBW Regime



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 $Q_{ext} = 2\times 10^{11}$ (cm^{-3} s^{-1}) starts at t_0 = 3650 days, lasts during 1 hour and is situated at $160 < z < 170$ cm

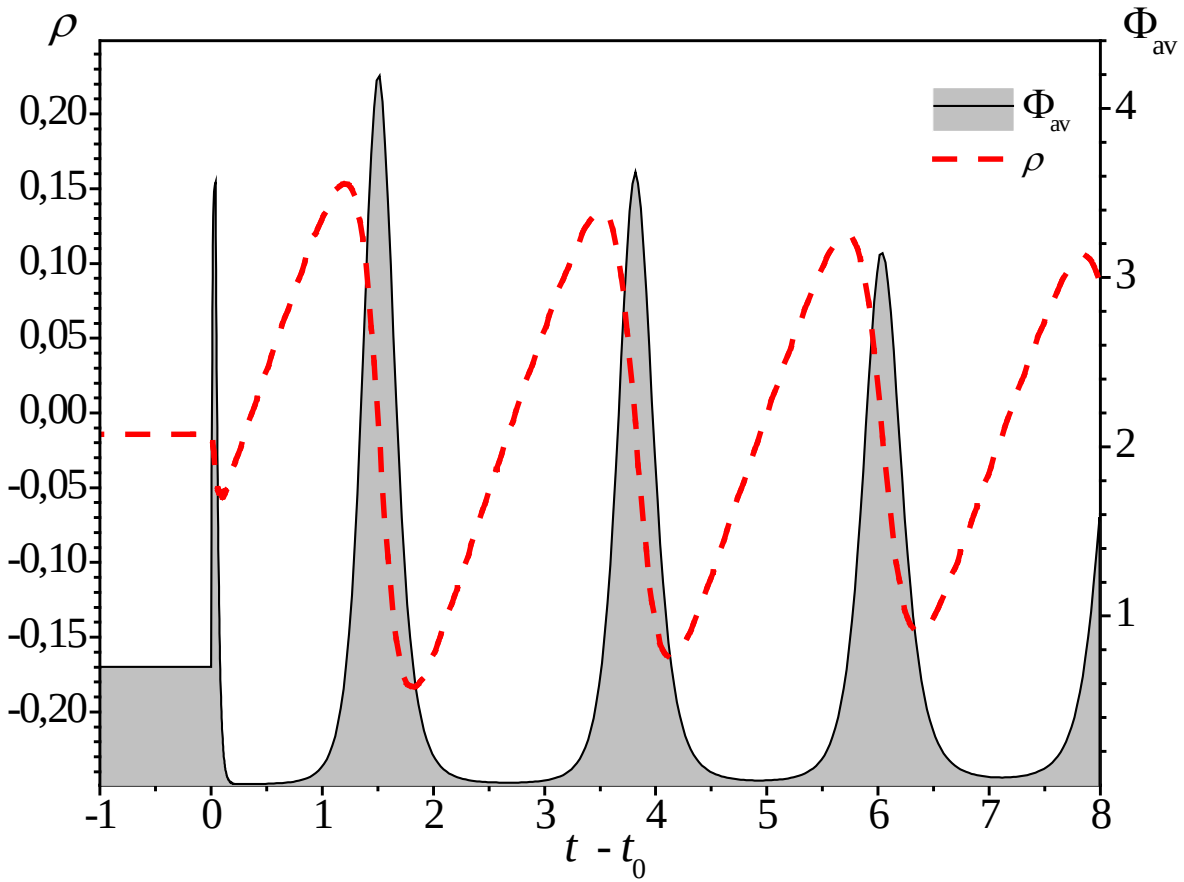
Negative Reactivity Feedback: Stability of the NBW Regime



τ ≈ 2.5 days

Evolution of the volume-averaged neutron flux F_{av} ($\times 10^{15}$ см$^{-2}$ с$^{-1}$) and concentrations N_{av} ($\times 10^{17}$ cm^{-3}) of the main fissile and intermediate nuclides in the fuel of mixed ThUPu 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, $N_{Pa} = N_{Pa} - 53.1 \cdot 10^{17}$ cm^{-3}, $\tilde{N}_{Pu} = N_{Pu} - N_{Pu}|_{t_0-1}$ is for ^{239}Pu , $\tilde{N}_{U} = N_{U} - N_{U}|_{t_0-1}$ is for ^{233}U.

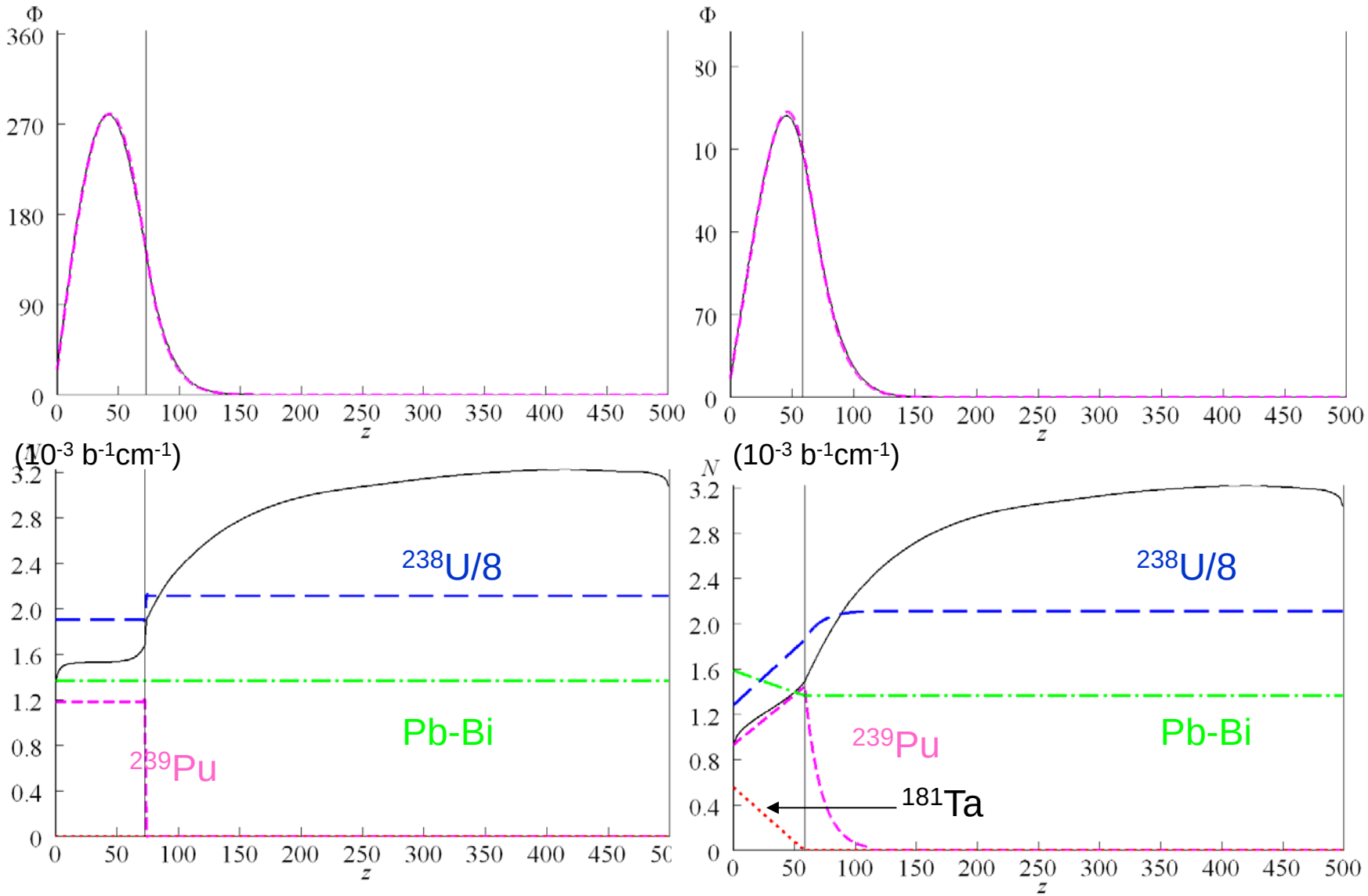
Negative Reactivity Feedback: Stability of the NBW Regime



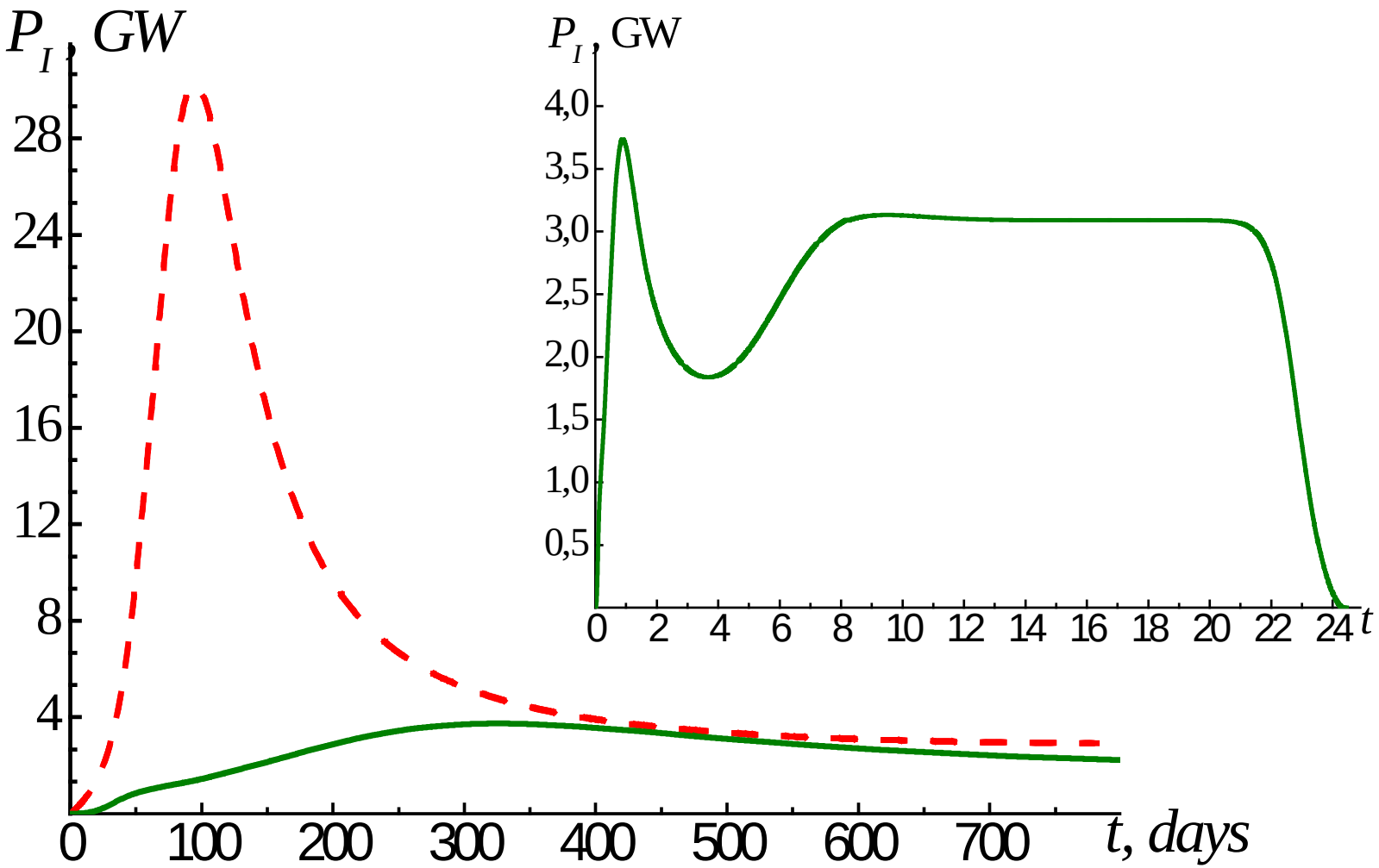
Variation of the reactivity ρ (dollars) with time *t* (days)
along the variation of the volume-averaged neutron flux F_{av} ($\times 10^{15}$ см$^{-2}$ с$^{-1}$)

Startup problem of the NBW Reactor

Neutron flux Φ, $b^{-1}day^{-1}$



Smooth Startup of the NBW Reactor



I believe that we will tame the Feoktistov wave !

… and Nuclear Burning Wave reactor will becomes a “Prometheus of the 3rd Millennium”!

Our publications:

S. Fomin et al., *Annals of Nuclear Energy*, 32 (2005) 1435-1456.

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

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

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

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., *Progress in Nuclear Energy, 52* (2011) 800-805.

Our conference activity:

2005 - ICENES (Brussels, Belgium) IC058; NATO-ARW NSSE (Yalta, Ukraine); IAEA-RCM ADS (Minsk, Belarus)

2006 - ICAPP'06 (Reno, USA) paper 6157; NPAE (Kiev); QEDSP'06 (Kharkov); INES-2 (Yokohama, Japan)

2007 - ICAPP'07 (Nice, France) paper 7499; WS PINP (St-Perersburg, Russia); IAEA-RCM ADS (Roma, Italy)

2008 - Channeling'08 (Erice, Italy); NATO-ARW SNE (Yalta, Ukraine) | NPQCD (Dnepropetrovsk, Ukraine)

2009 - IAEA-RCM ADS (Vienna, Austria), ANIMMA (Marseille, France); Global 2009 (Paris, France) paper 9456

2010 - IAEA-RCM ADS (Mumbai, India); PINP WS (St-Perersburg, Russia); ICAPP (San Diego, USA) paper 10302
NPAE (Kiev); IAEA-TWG-FR (Brussels, Belgium); 19 ICPRPRMS (Alushta, Ukraine); INES-3 (Tokyo, Japan)

2011 - IAEA-TWG-FR (Beijing, China); NSC KIPT SS (Alushta, Crimea); QEDSP'11 (Kharkov, Ukraine);
IAEA-TWG-FR (Chinnai, India); IAEA-TWG-FR (Vienna, Austria)

2012 - IAEA-TWG-FR (Vienna, Austria); IAEA-TWG-FR (Argonne, USA); NPAE-4(Kiev , Ukraine); …

2013 – FR13 (Paris, France)