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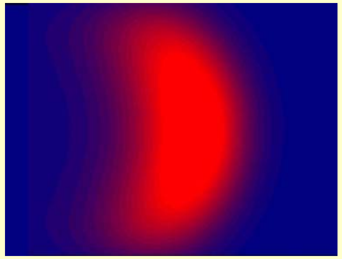

Soliton-like Regime of Neutron Transport in a Multiplying Medium. Physical Ground of Traveling Wave Reactor

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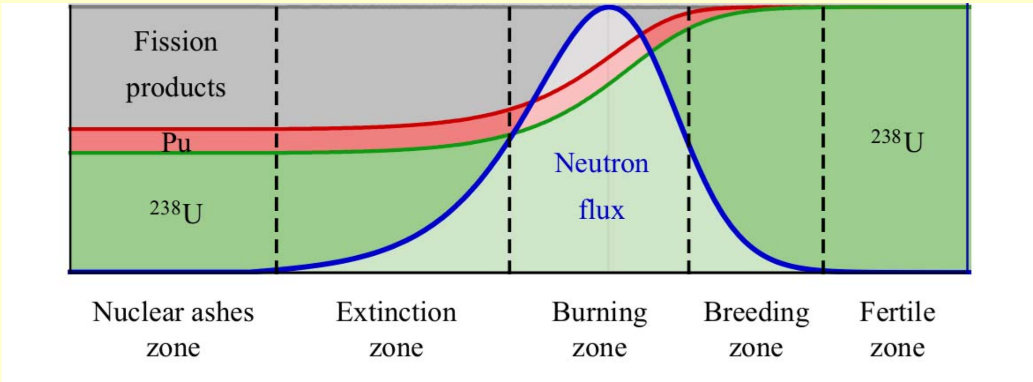
Channeling 2018 23-28 September 2018 Ischia, Italy

Outlook:

- Historical introduction
- Nuclear Burning Wave concept
- Mathematical approach
- Results of our calculations
- Mixed Th-U-Pu fuel cycle
- Stability study of NBW regime
- Negative reactivity feedback (!)
- Transient processes in NBW reactor
- Main features of NBW reactor & possibility to solve the nuclear power problems

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.

Concept & Analytical approach

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

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

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

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

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

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

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

$$x = z + Vt$$

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

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**

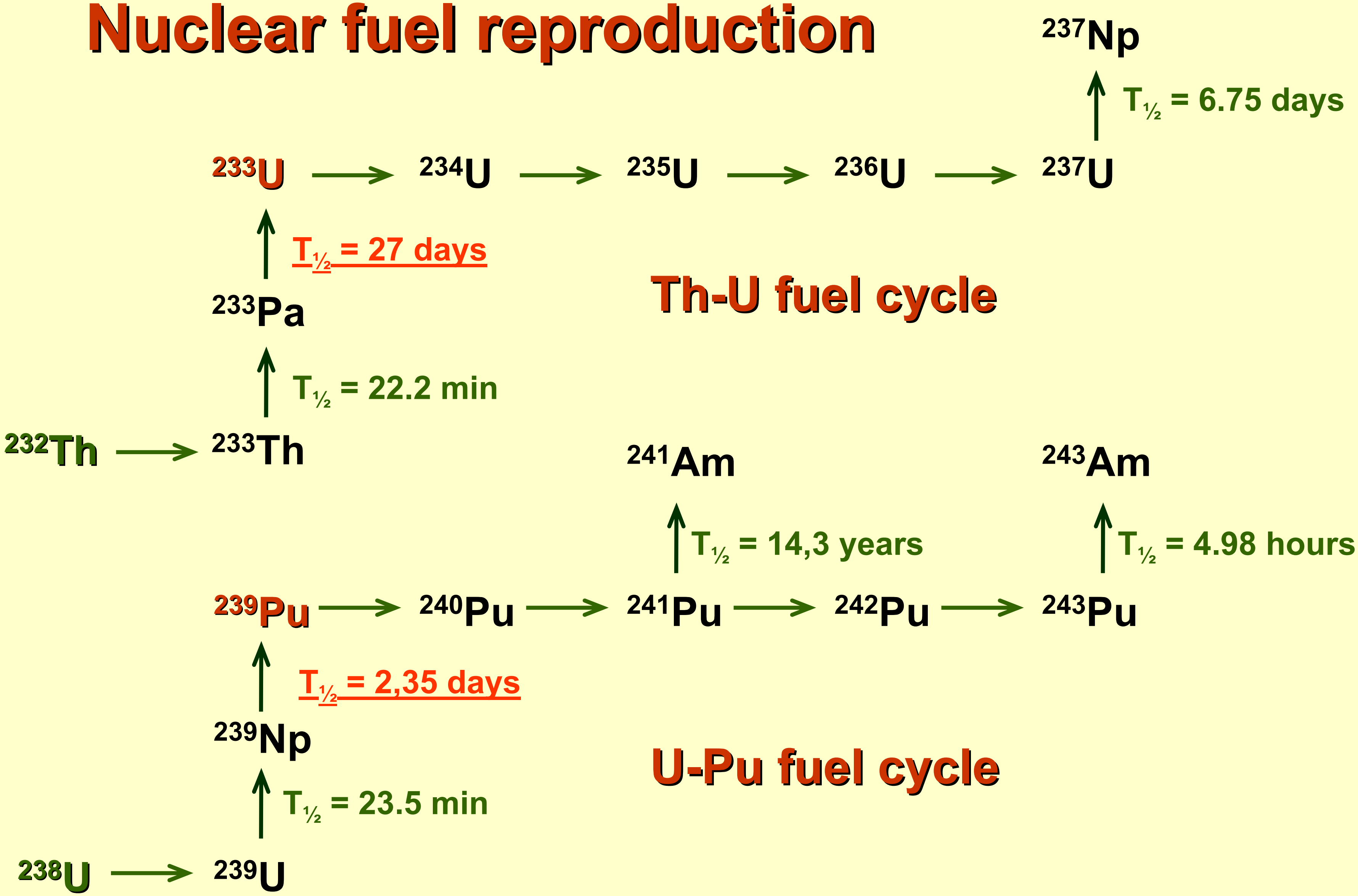
Edward Teller (USA, 1997): **Traveling Wave Reactor** **Monte Carlo simulation**

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

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

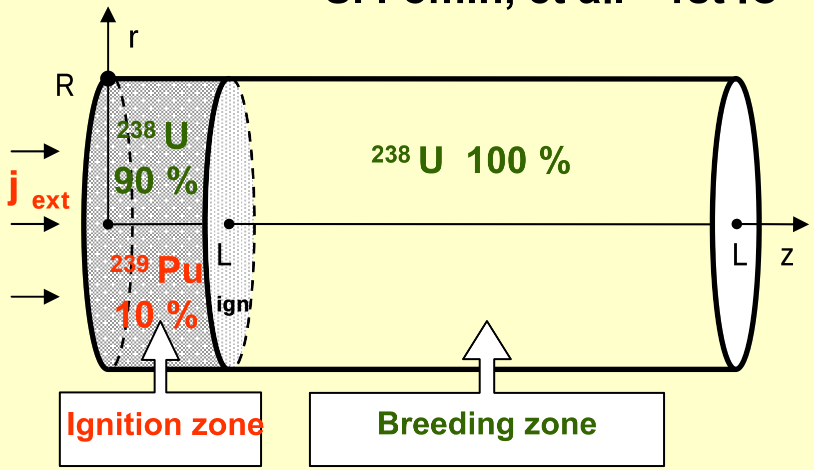
H.Sekimoto et al., Nucl. Sci. Eng., 139 (2001) 306. **U-Pu** fuel cycle, **Stationary problem**: $x = z + Vt$

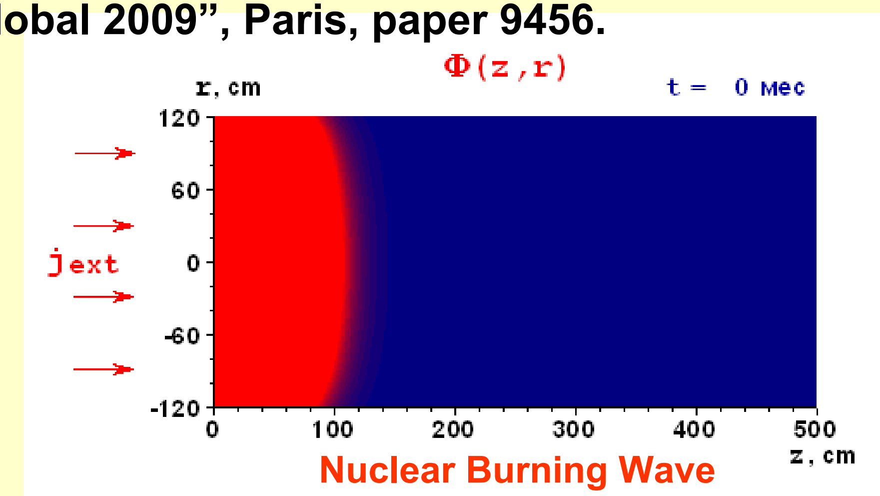
Nuclear fuel reproduction



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

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

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

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

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

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

of Precursor Nuclei of Delayed Neutrons

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

Metal fuel (44%)

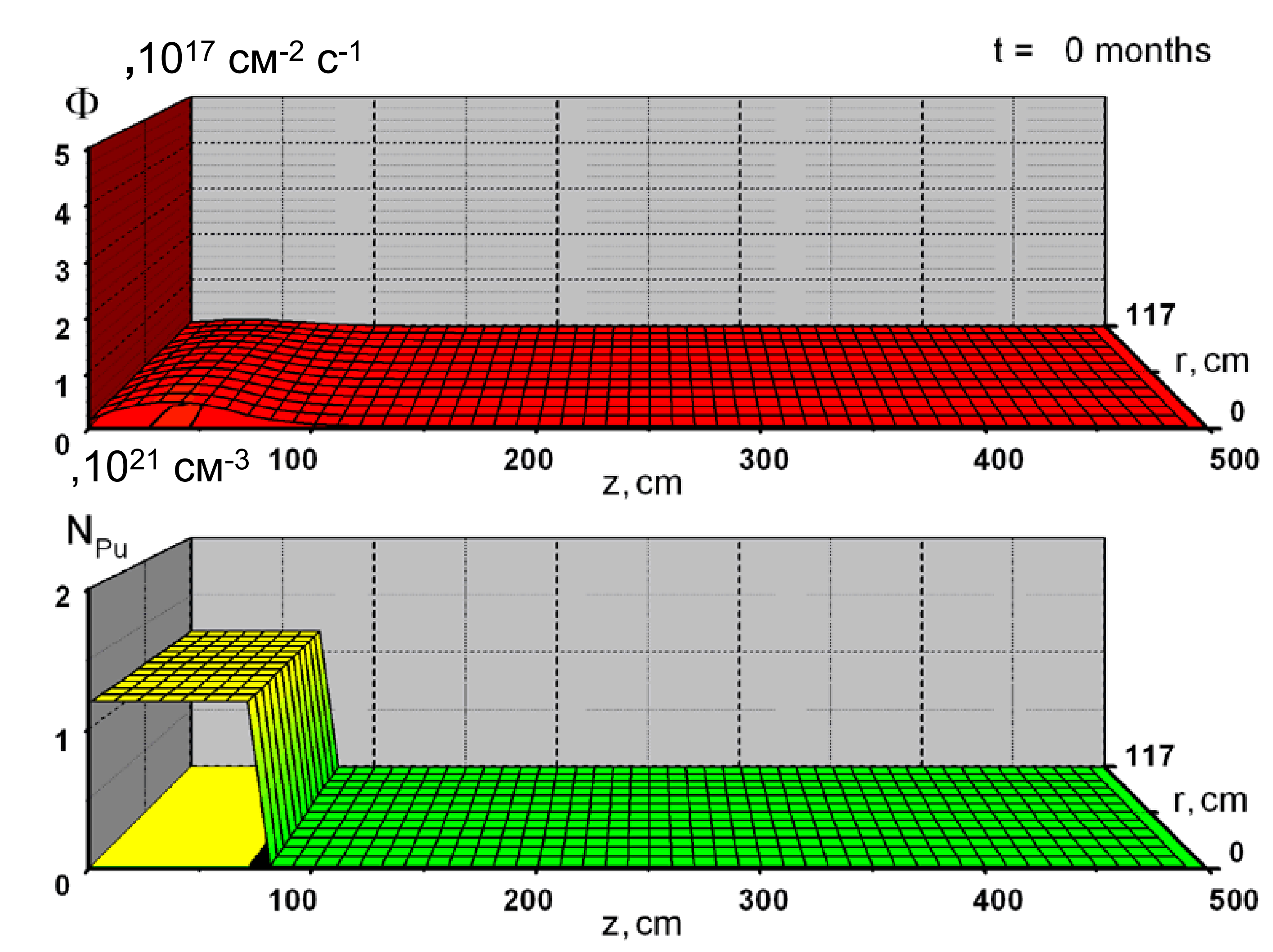
Pb-Bi coolant (36%)

CM - Fe (20%)

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

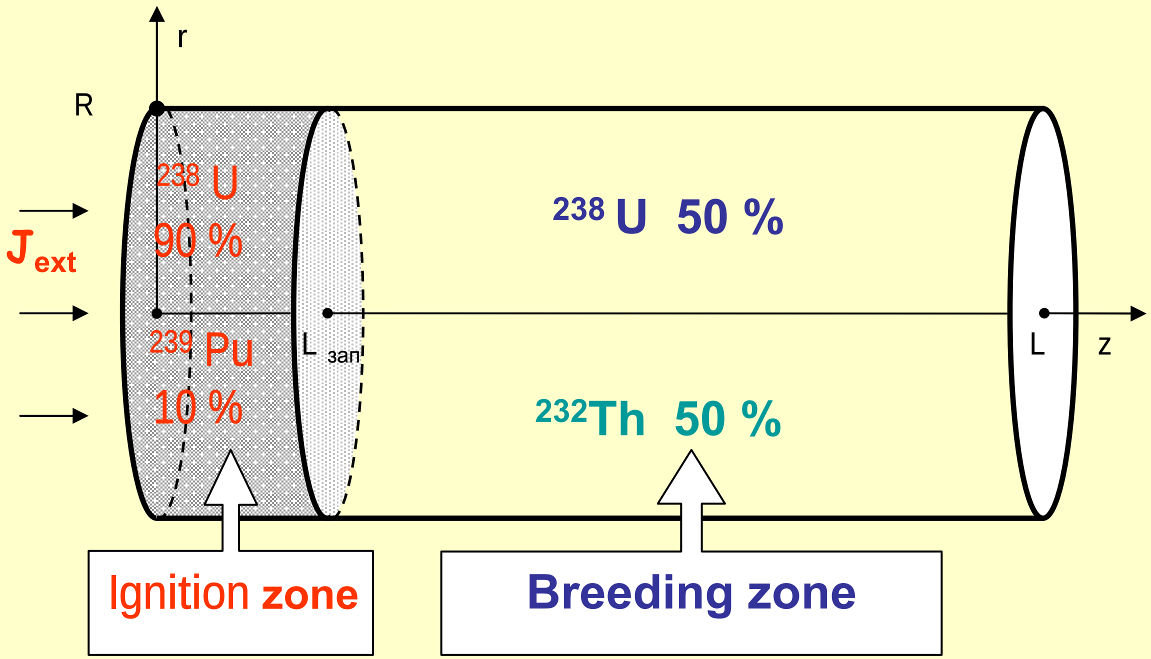
t_{off} = 400 days

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



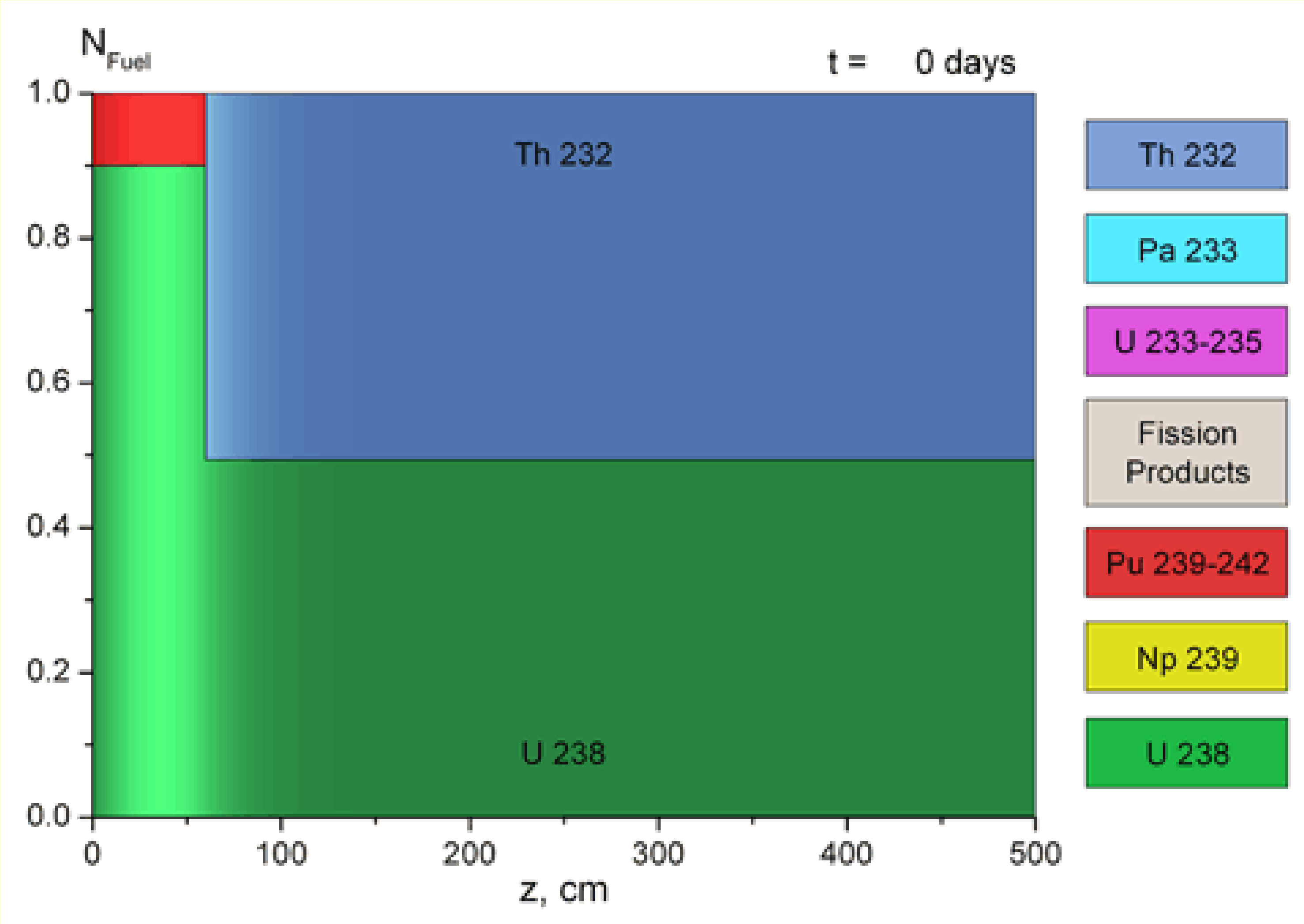
NBW reactor with mixed Th-U-Pu fuel

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

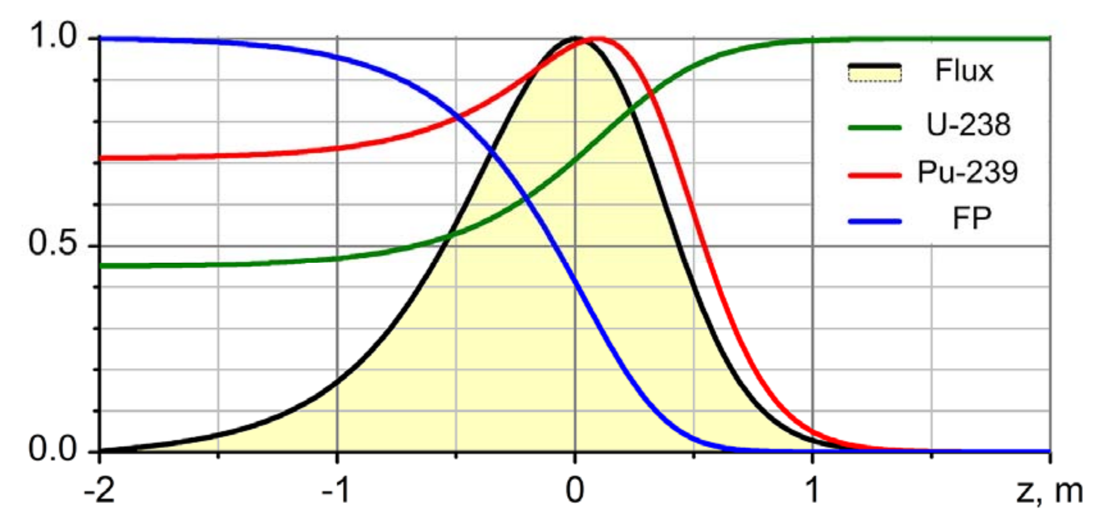


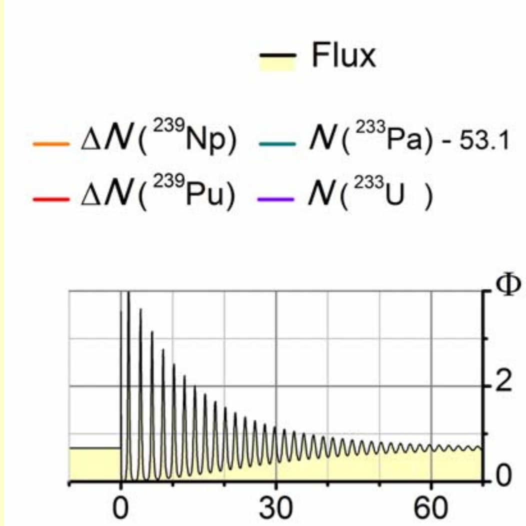
Example: Metallic fuel ^{232}Th (62%) + ^{238}U (48%) volume fraction = 55%, fuel porosity p = 0.35; Coolant (Pb-Bi eutectic) vol. frac. = 30%, Constr. materials (Fe) vol. frac. = 15%; R = 390 cm

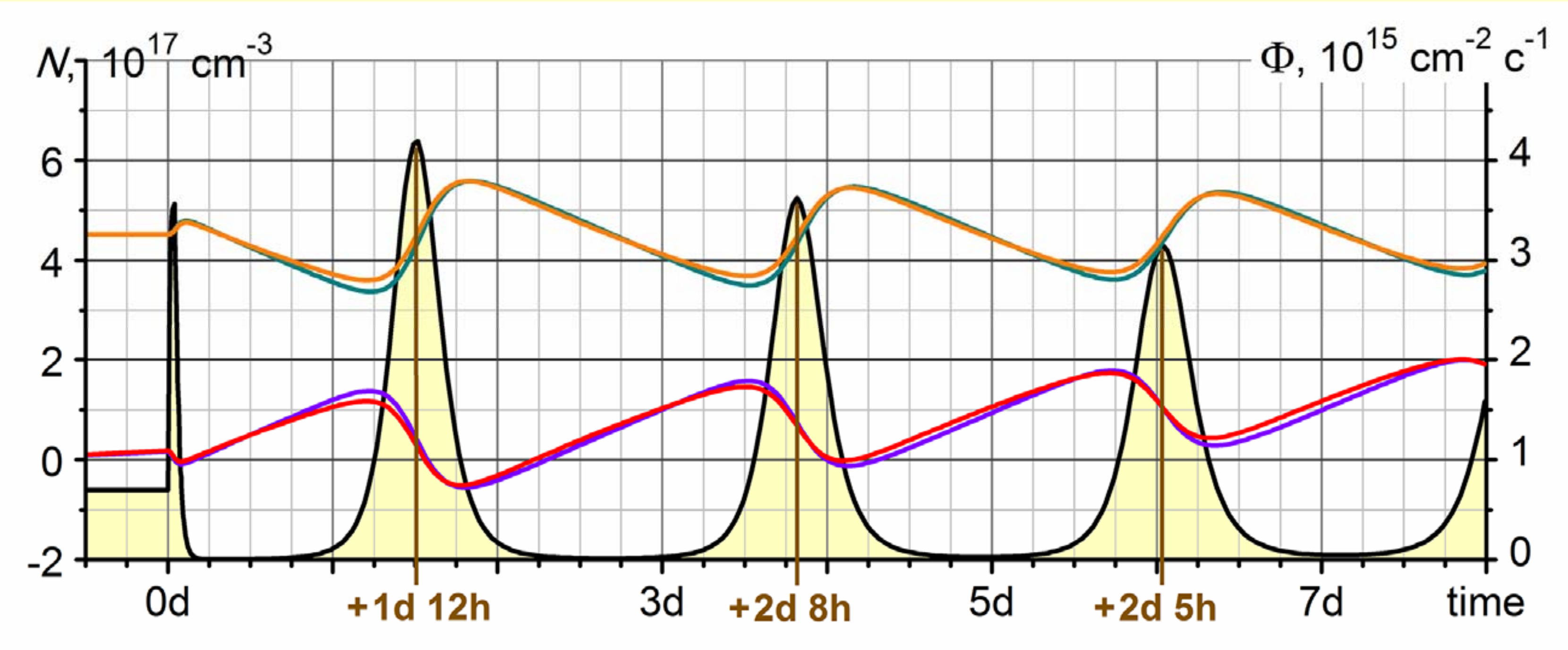
Fuel burn-up for Th-U-Pu cycle



Stability of the NBW Regime - Negative Reactivity Feedback (!)

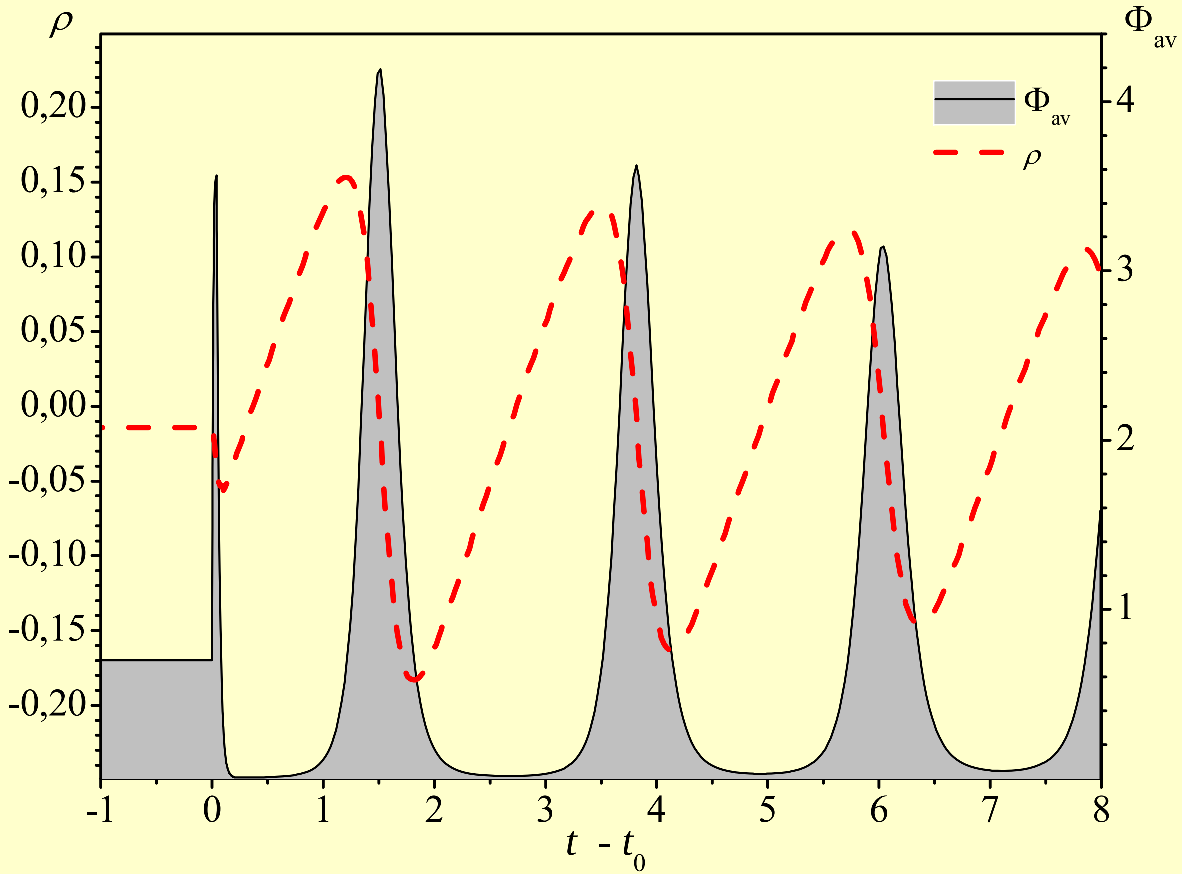






Stability of the NBW Regime - Negative Reactivity Feedback (!)

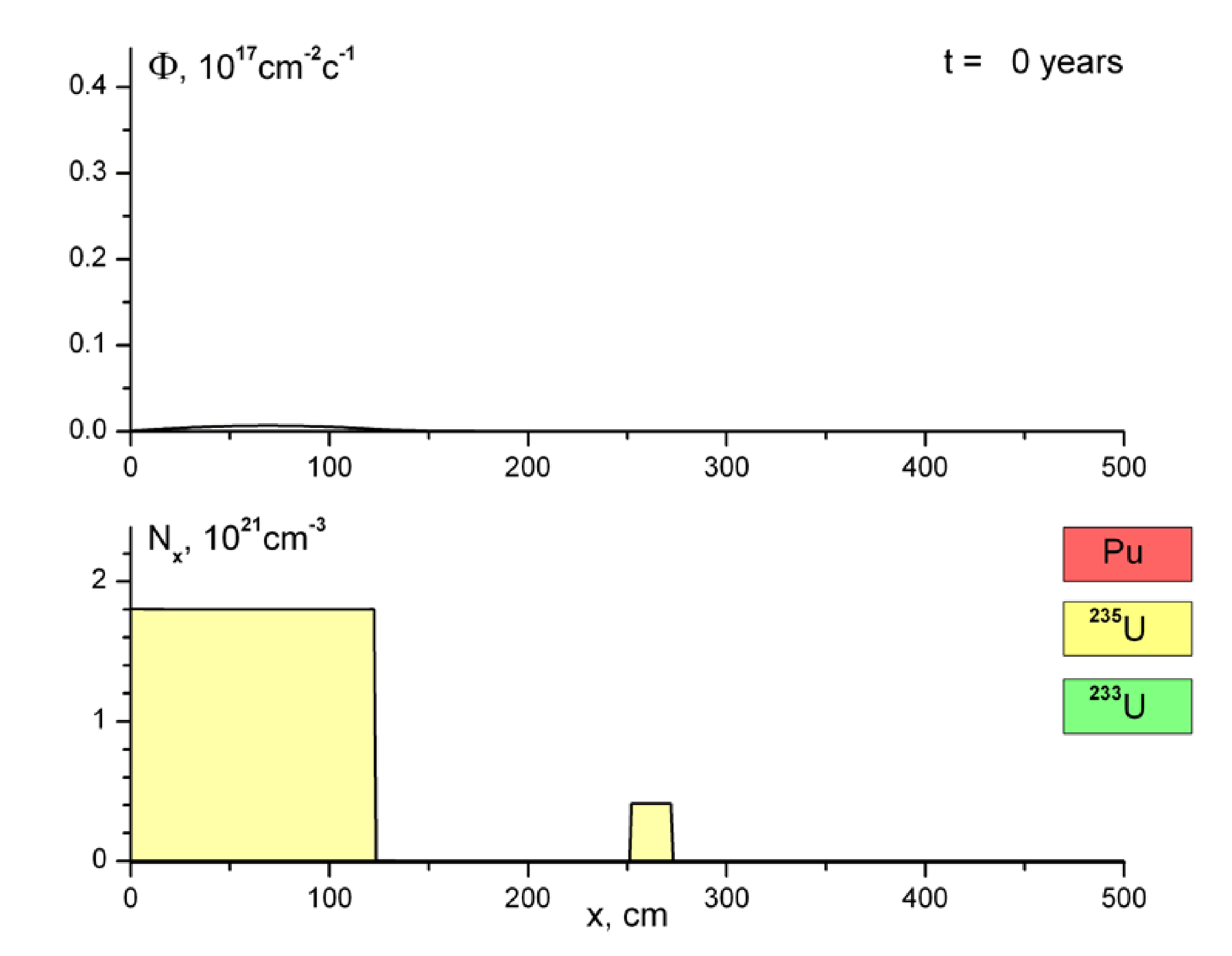
S. Fomin et al., *IC "Fast Reactors 2013"* (Paris, France) paper CN-199-457



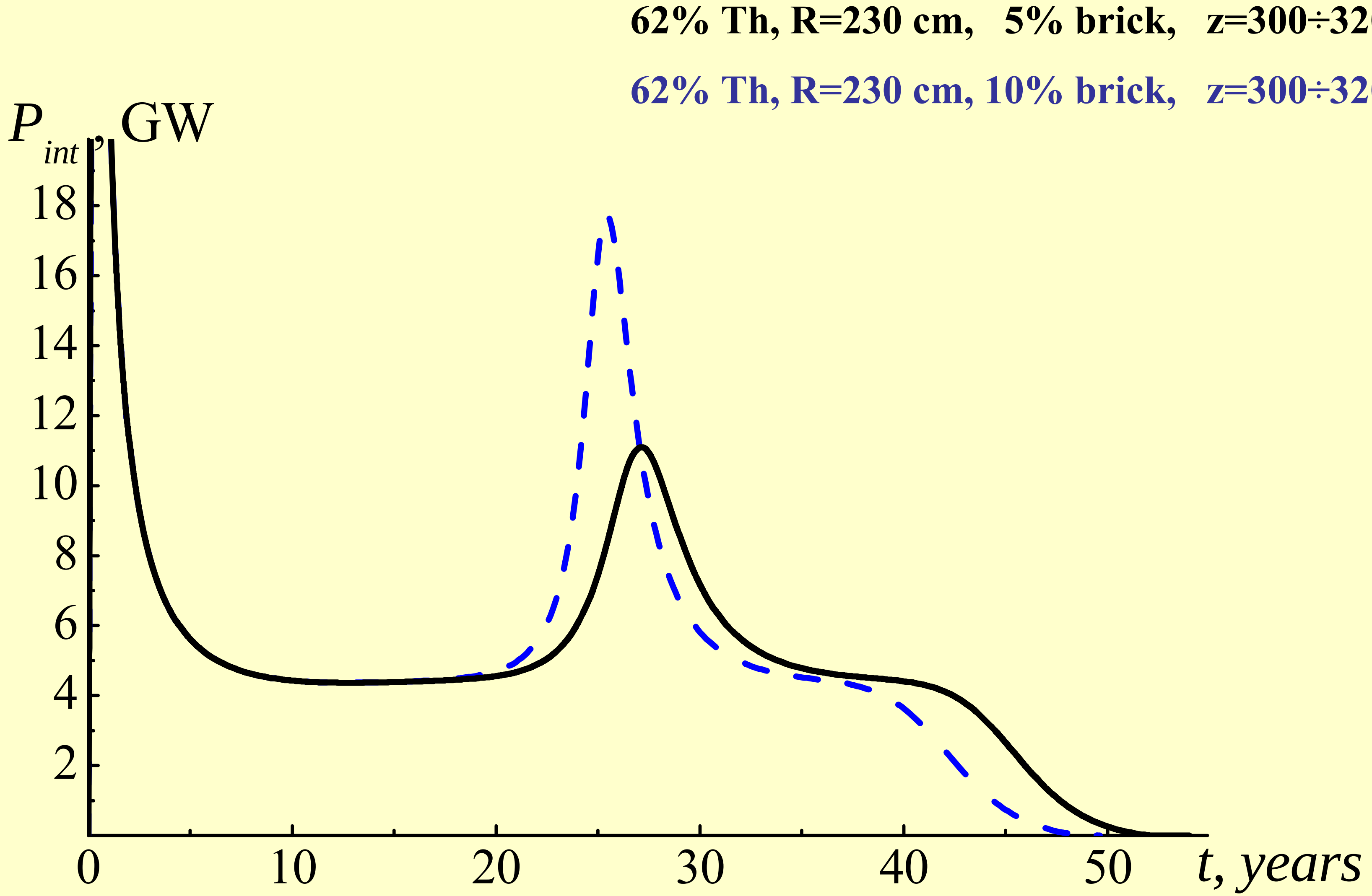
Variation of the reactivity ρ (dollars) with time *t* (days)
along the variation of the volume-averaged neutron flux F_{av} ($\times 10^{15}$ см$^{-2}$ с$^{-1}$)

Stability of the NBW Regime

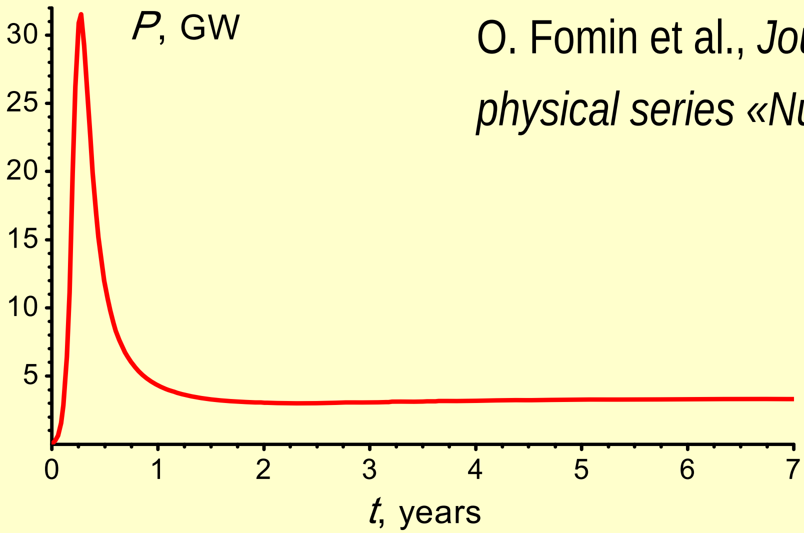
(enriched region in the breeding zoon)



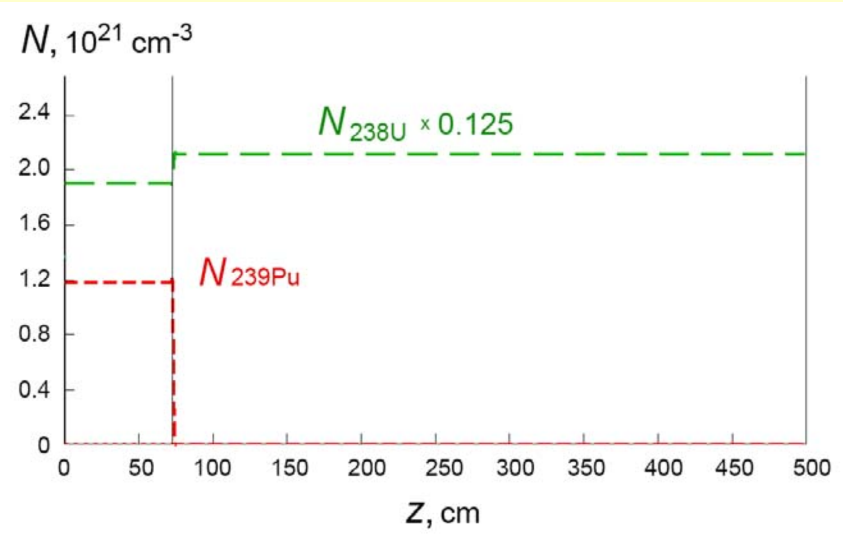
Stability of the NBW Regime



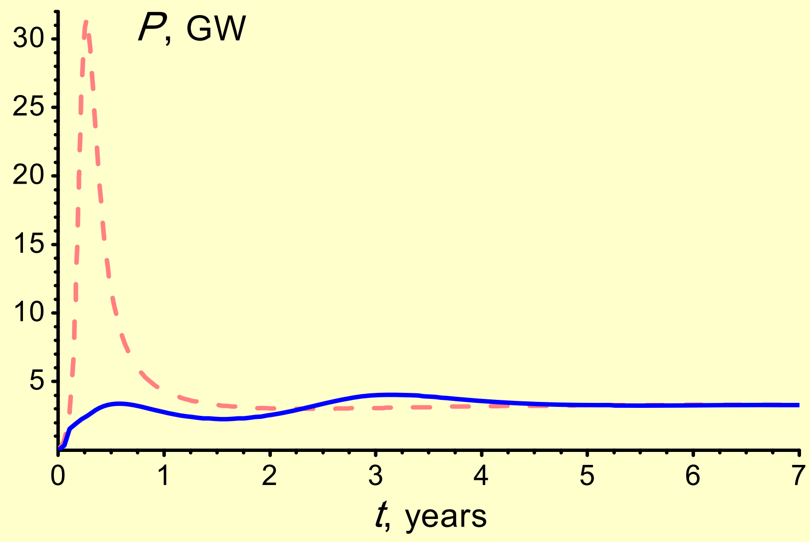
Smooth Startup of the NBW Reactor

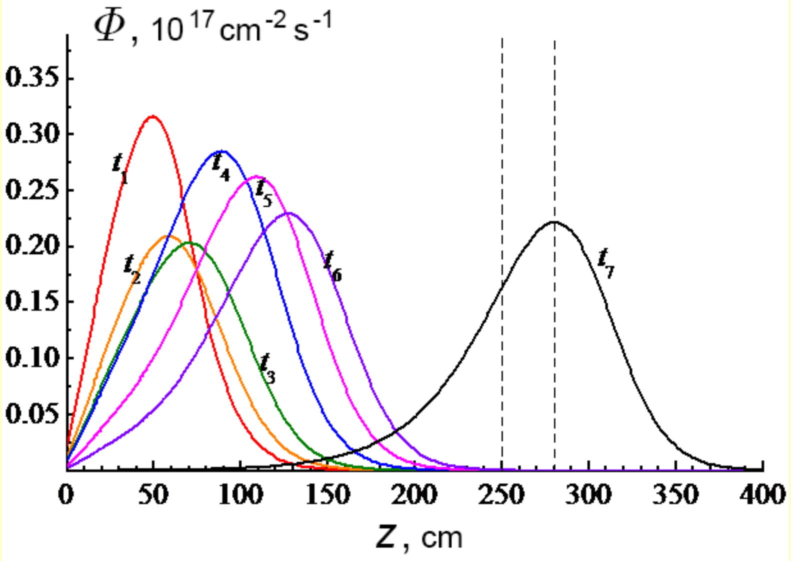


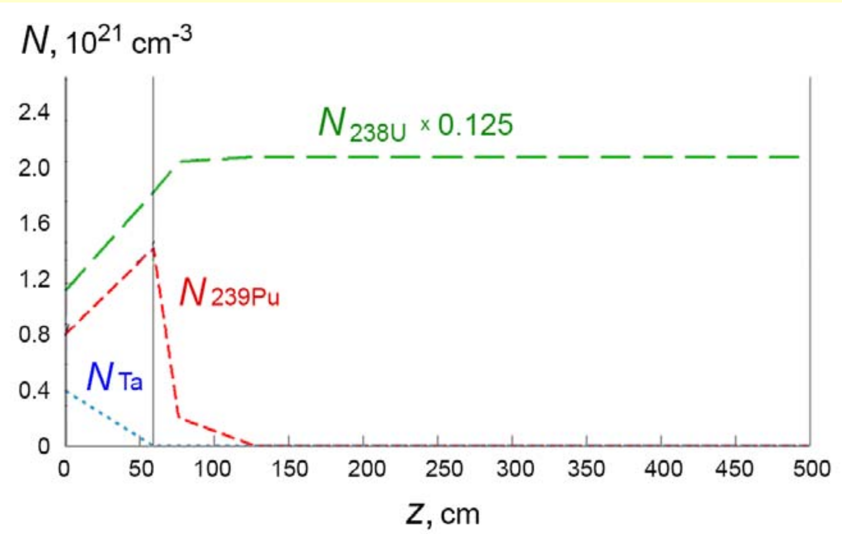
O. Fomin et al., *Journal of Kharkiv National University, #1041, physical series «Nuclei, Particles, Fields», 2 /58/* (2013) 49-56.

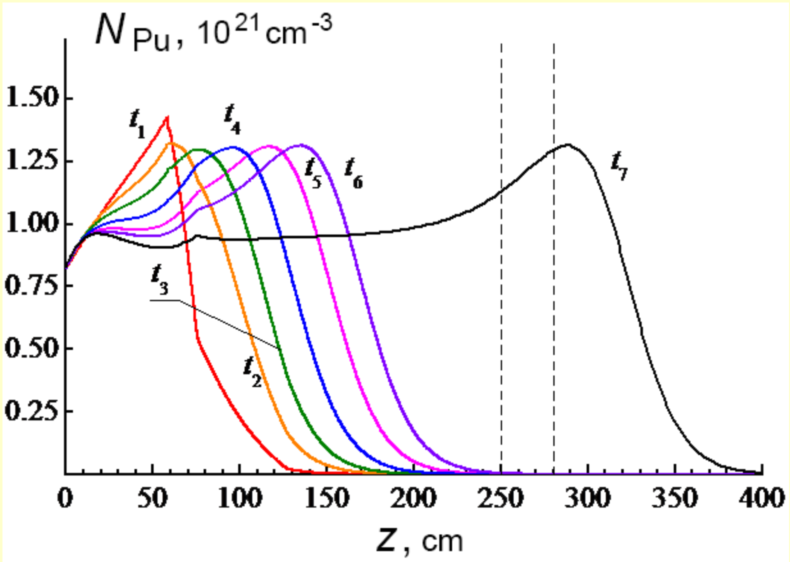


Smooth Startup of the NBW Reactor

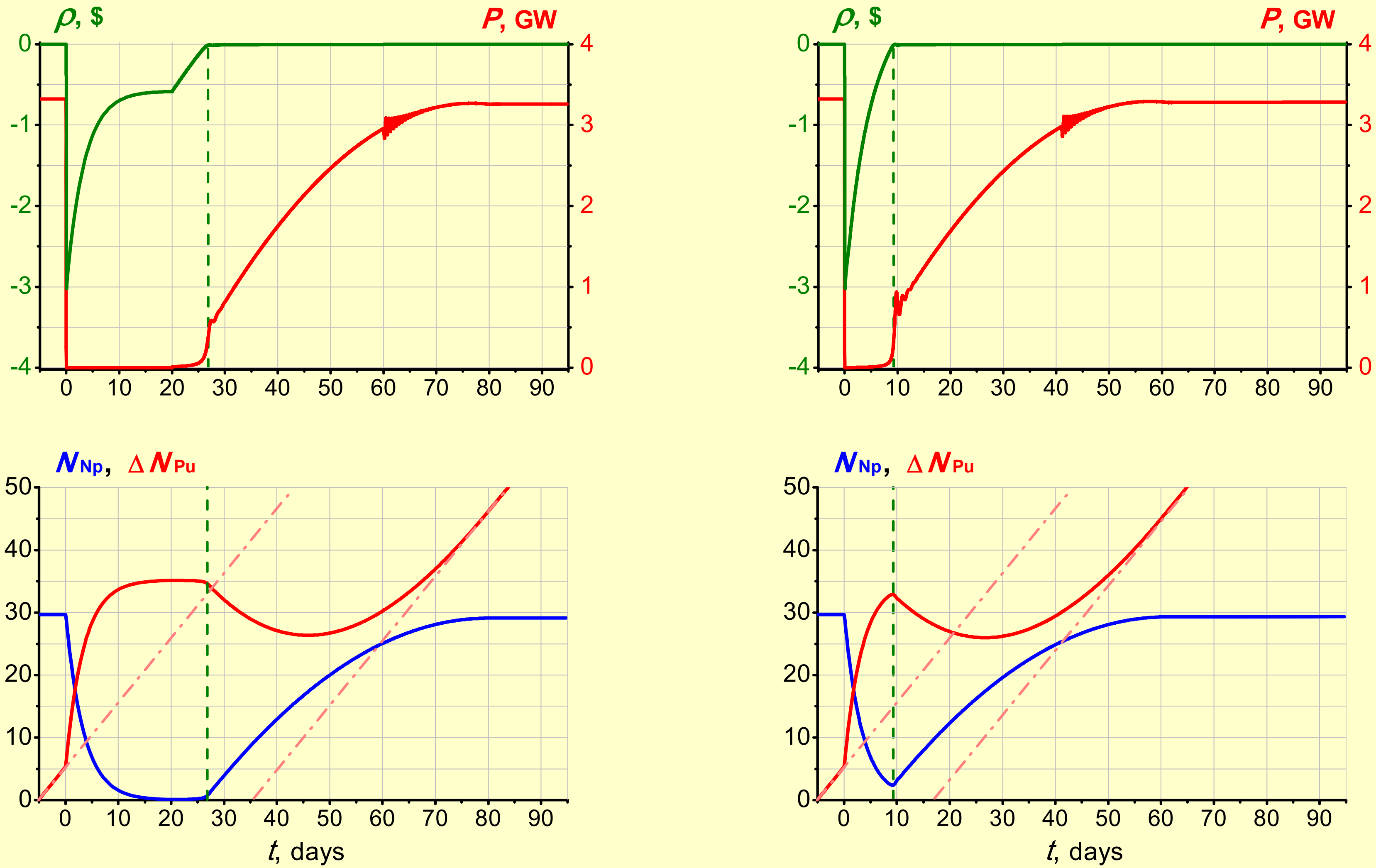






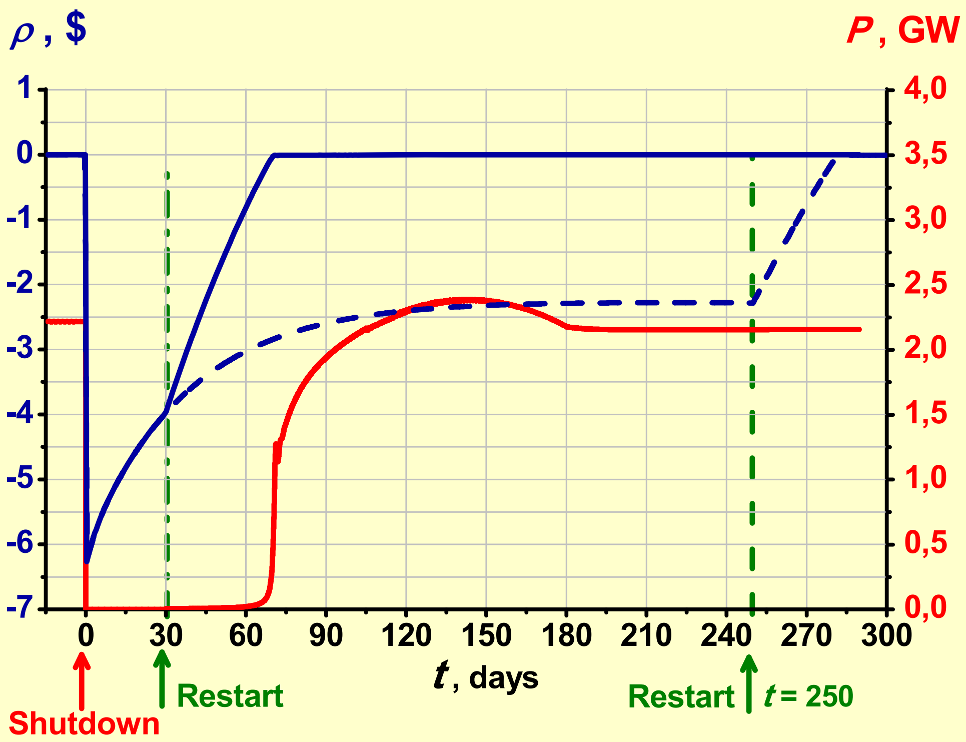


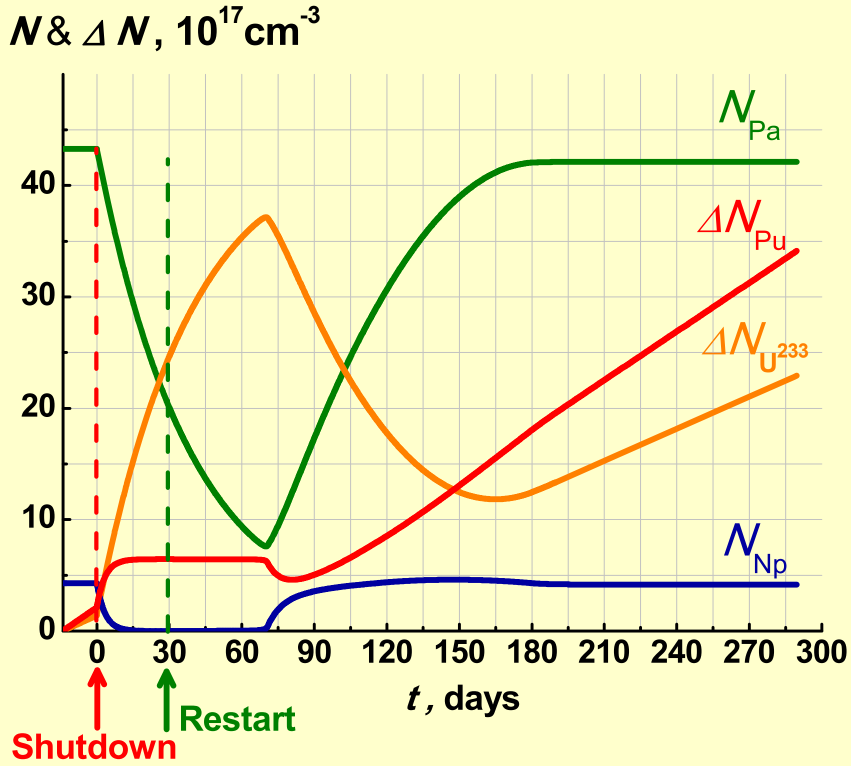
Shutdown and Restart of the NBW Reactor



Shutdown and Restart of the NBW Reactor

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





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**

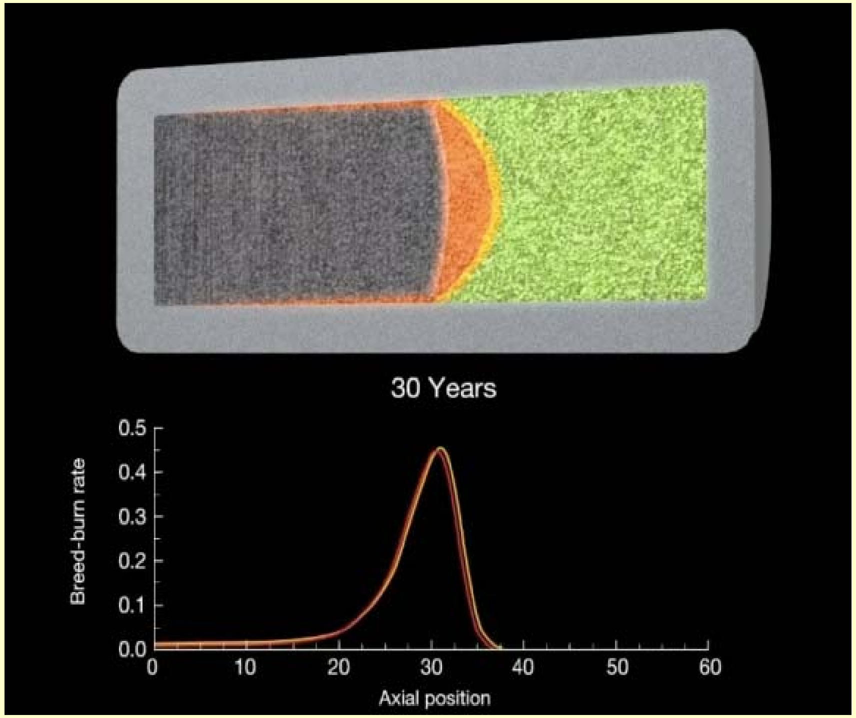
- **negative feedback on reactivity - intrinsic safety (!!!)**
- **long-term (decades!!) operation without refueling and external control**
- **possibility of ^{232}Th and ^{238}U utilization as a fuel**
- **fuel burn-up depth for both ^{238}U and ^{232}Th ≈ 50% (one through cycle !)**
- **neutron flux 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)**

Traveling-Wave Reactor

2010:

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

"TerraPower" + China = TWR (2020)



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

Minister Zhang of National Energy Administration Received Bill Gates

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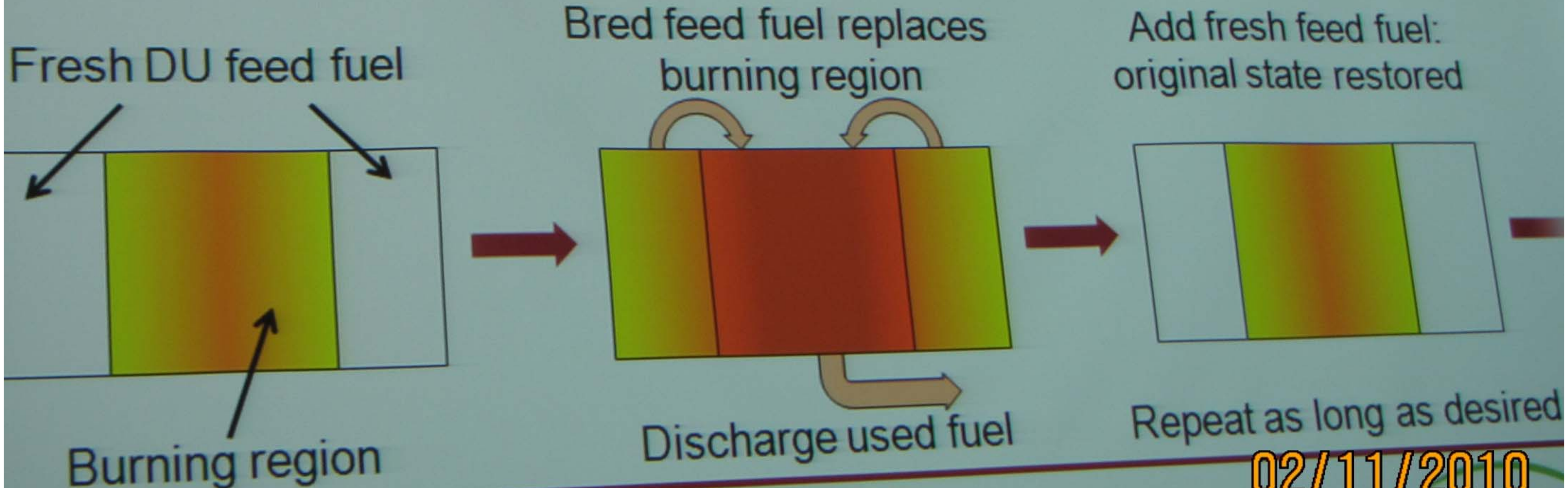
Traveling Wave Reactor Physics

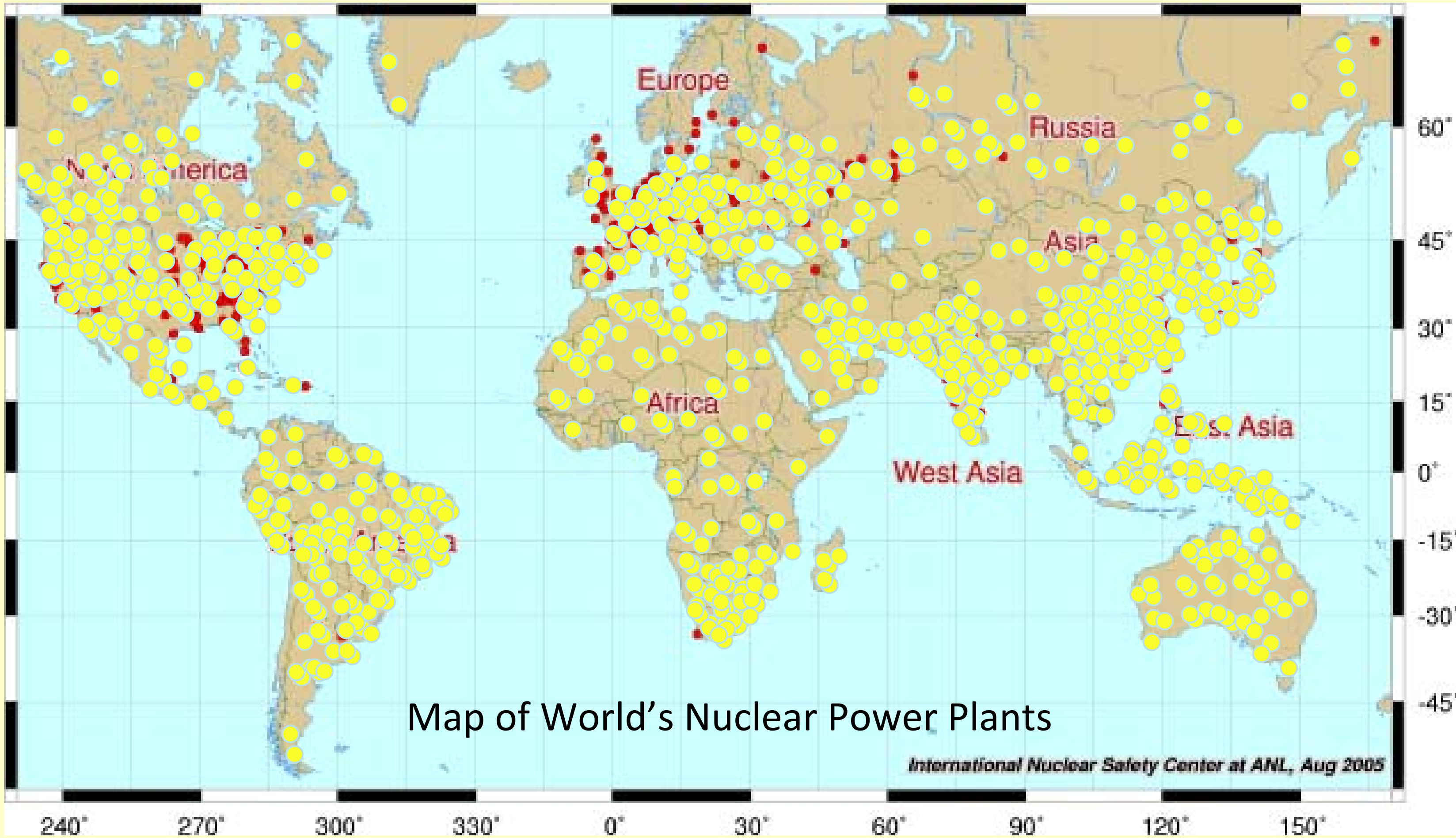
- A ***breed-and-burn*** reactor:
  - 1. First breed fissile Pu-239 in U-238 fuel, using leakage flux from burning region
  - 2. Newly created fuel can directly replace discharged fuel in burning region and sustain criticality
- **Schematic illustration of a two-zone TWR:**



02/11/2010

TerraPow

Reactors Start to Spread in Waves Around the World



Map of World's Nuclear Power Plants

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List of our publications on the NBW reactor :

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., 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.

O. Fomin et al., *Journal of KNU, #104, «Nuclei, Particles, Fields», issue 2 /58/* (2013) 49-56.

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.

1A-1-2: Sustainable Burning Reactors - Chairs: Kevan Weaver (TerraPower, USA)

Traveling-Wave Reactors: Challenges and Opportunities - Kevan Weaver et al. (TerraPower, USA)

Feasibility of LBE Cooled Breed and Burn Reactors - Ehud Greenspan (UC, Berkeley, USA)

Preliminary Engineering Design of Sodium-Cooled CANDLE Core - Hiroshi Sekimoto (TIT, Japan)

Nuclear Burning Wave in Fast Reactor with Mixed Th-U Fuel - Sergii Fomin et al (NSC KIPT, Ukraine)

Nuclear Traveling Wave in a Supercritical Water Cooled Fast Reactor – W. Maschek (KIT, Germany)

Development and Prospects of TWR Project in China - Zheng Mingguang (Shanghai NER&DI, China)

Special Presentation: Traveling-Wave Reactors - John Gilliland. (Director of TerraPower, USA)

1A-3: Thorium Fuel Reactors - Chair: Sergii Fomin (NSC KIPT, Ukraine)

(Th-U-Pu) - Mixed Fuel Cycle and Proliferation– E. Kryuchkov et al, (MEPhI, Russia)

Large Scale Utilization of Thorium in Gas Cooled Reactors - V. Jagannathan (Bhabha ARC, India)

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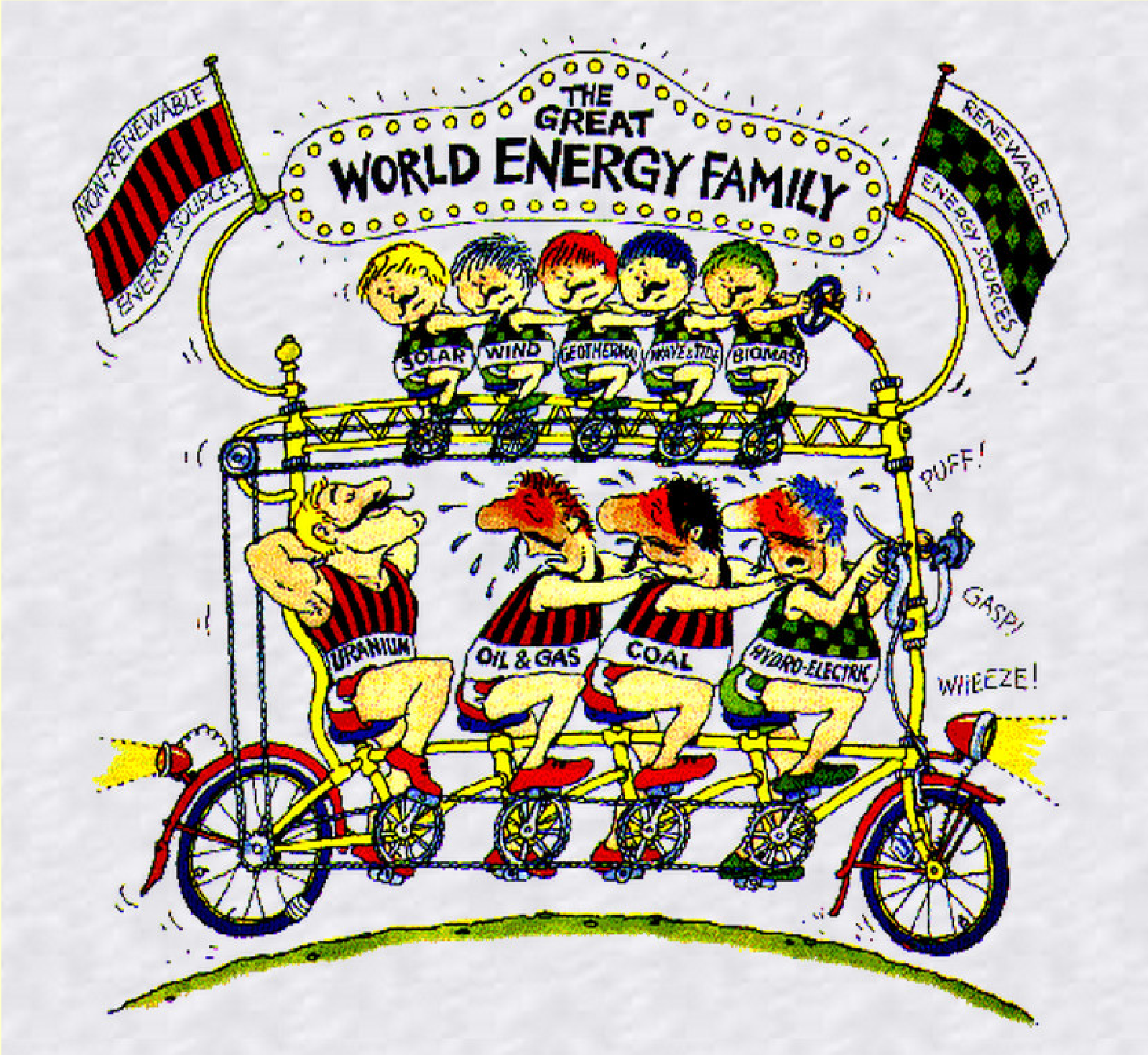

Thank you for attention !