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імені В.Н. Каразина
УНІ «Фізико-технічний факультет»
Кафедра фізики ядра і високих енергій
імені О.І. Ахієзера

## Спецкурс : Фізика ядерних реакторів

# *Тема 9*: Slow Nuclear Burning Phenomenon & Traveling Wave Reactor

*(лекція 10)*

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08.05.2023 Кіль-Харків КФЯВЕ - ФТФ - ХНУ

## Outline:

- Historical introduction
- Nuclear Burning Wave concept
- Mathematical approaches & calculation results
- U-Pu, Th-U & mixed Th-U-Pu fuel cycles
- Stability study of the NBW mode: specific mechanism of negative reactivity feedback (intrinsic safety)
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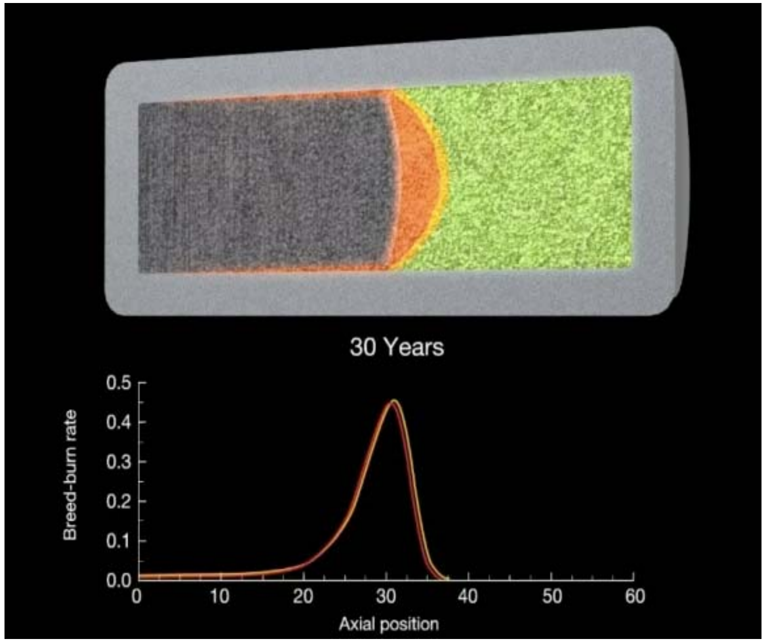
TerraPower

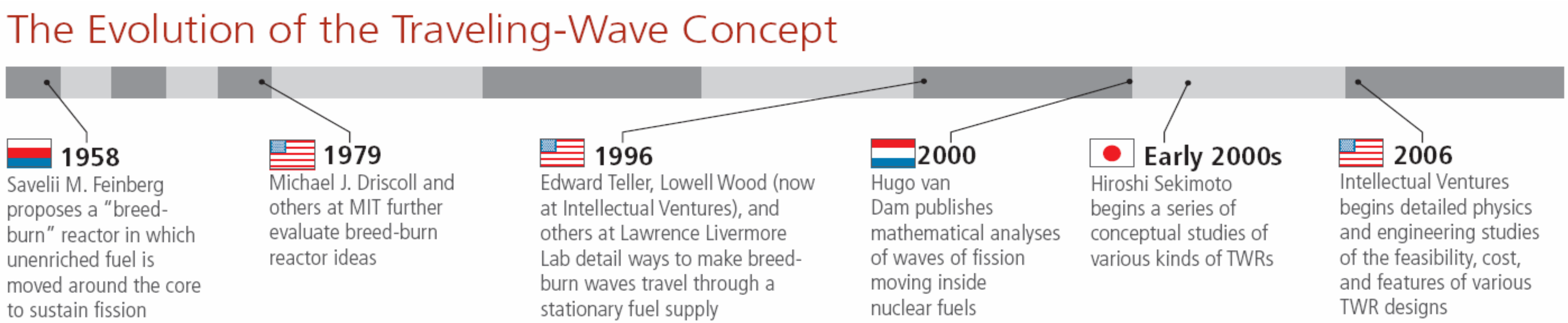
# Traveling-Wave Reactor


Technology, Entertainment and Design, 2010

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



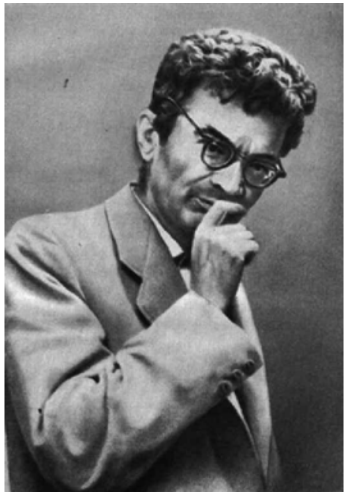

## TerraPower + China + Toshiba = TWR (2020)




http://www.intellectualventures.com/docs/terrappower/IV_Introducing%20TWR_3_6_09.pdf

# 1946 UPhTI (Kharkov) - Lab #1 at the Soveit Nuclear Project

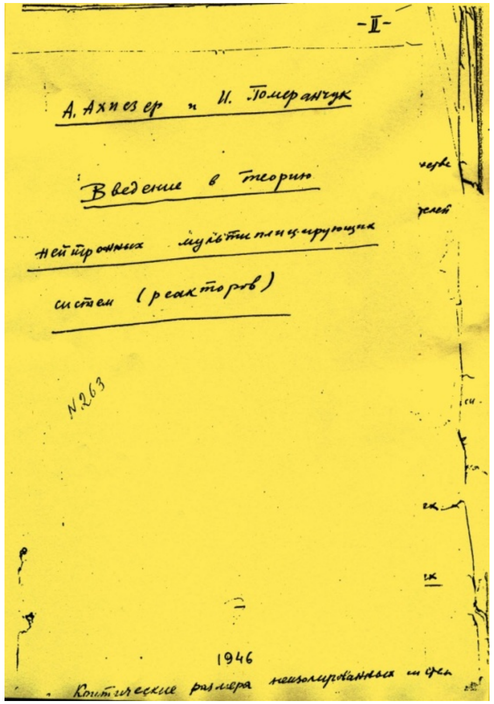
A.I. Akhiezer

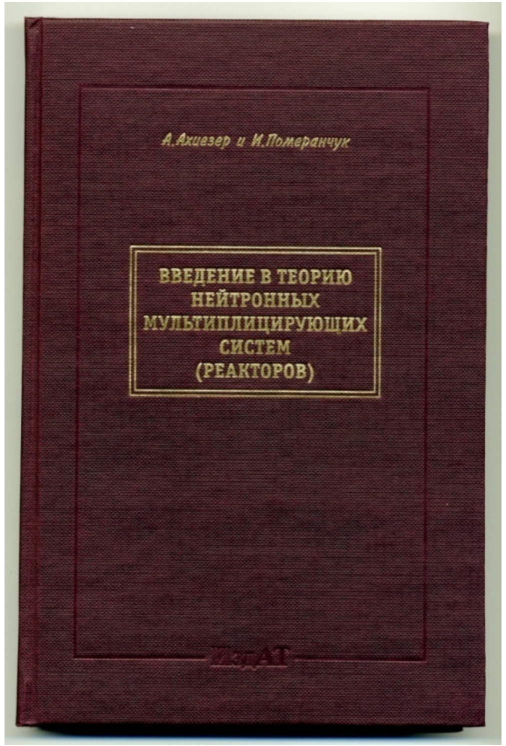


I.Ya. Pomeranchuk

**A.I. Akhiezer and I.Ya. Pomeranchuk "Introduction to the Theory of Neutron Multiplication Systems (Reactors)", 1946**

**It was the fist monograph on reactor theory in the world !**




**2001 - ITEP Moscow**

# History of the B'n'B and TWR Concepts

## Breed'n'Burn concept ≠ Traveling Wave concept

**S.M.Feinberg and E.P.Kunegin, 1958:** "Nuclear Power Plants, Part 2, Discussion", Proc. 2nd U.N. Int. Conf. Peaceful Uses of Atomic Energy,v.9, p.447, U.N., Geneva.

**K.Fuchs and H.Hessel, 1961:** "Uber die Moglichkeiten des Betriebs eines Natururanbrutreaktors ohne Brensttoffaufbereitung", Kernenergie, v.4, p.619.

**J.S.Slesarev, V.A.Stukalov, S.A.Subbotin, 1984:** "Problems of development of fast reactors self-provision without fuel reprocessing", Atomkernenenergie, Kerntechnik, v.45, p.58.

**V.Ya.Goldin, D.Yu. Anistratov, 1992:** "Mathematical modelling of neutron-nuclear processes in safe reactor", Preprint IMM RAS N. 43. … …

**L.P. Feoktistov, 1988:** An analysis of a concept of a physically safe reactor. Preprint IAE-4605/4; & **1989**: "Neutron-fission wave", Sov. Phys. Doklady, v.34, p.1071. "Variant of safe reactor", *Nature*, v.1, p. (in Russian)

**A.I.Akhiezer et al.,1999:** "Propagation of a Nuclear Chain Reaction in the Diffusion Approximation", *Physics of Atomic Nuclei, v.62, p.1474.* **2001:** "Slow Nuclear Burning", *Problem of Atomic Science & Technology*, v.6, p.272.

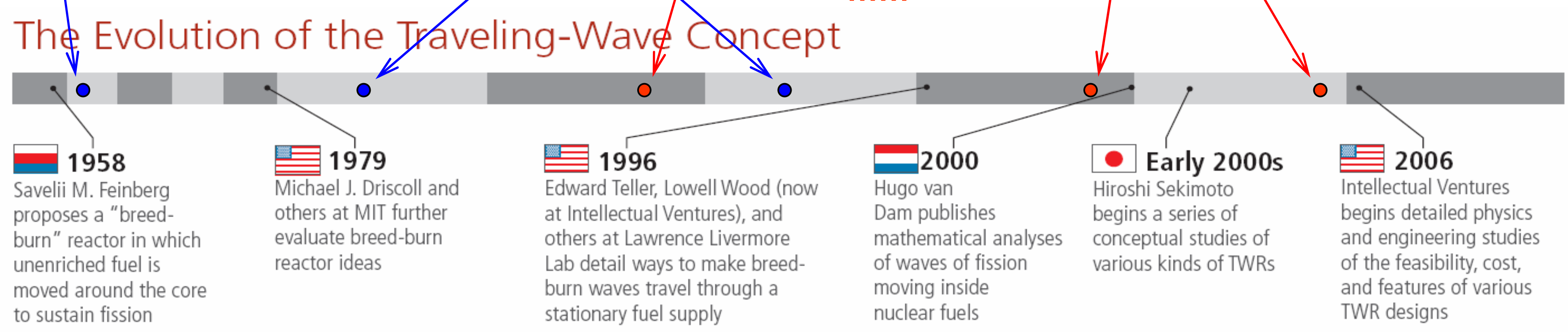
**V.Pilipenko et al. 2003** ICAPP'03, Paper 3169, Spain.

**S.Fomin, Yu.Mel'nik, V.Pilipenko, N.Shul'ga, 2005** Annals of Nuclear Energy (ANE), v.32, p.1435. … …

**X.-N.Chen, W.Maschek, 2005:** ANE, v.32, p.1377.

**B.Gaveau et al., 2005:** Nucl.Eng.Design, v.235, p.1665.

……




http://www.intellectualventures.com/docs/terrappower/IV_Introducing%20TWR_3_6_09.pdf

# TerraPower :

## The Evolution of the Traveling-Wave Concept

**1958**
Savelii 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

**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

**Early 2000s**
Hiroshi Sekimoto begins a series of conceptual studies of various kinds of TWRs

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

**2010**

## 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

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

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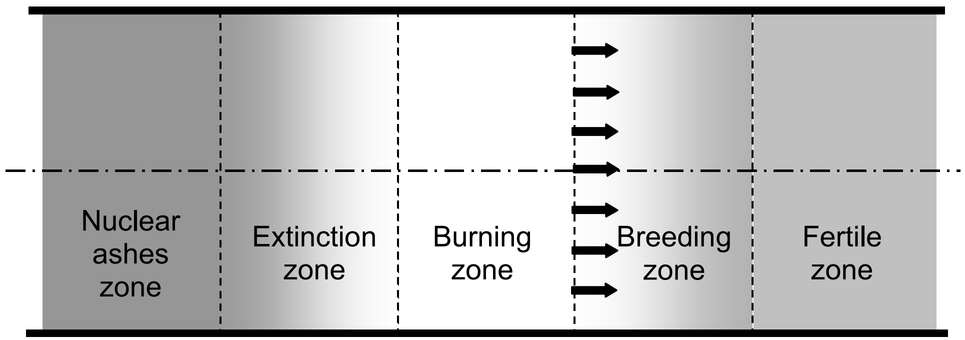
## Lev Feoktistov (USSR, 1988):

# 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**

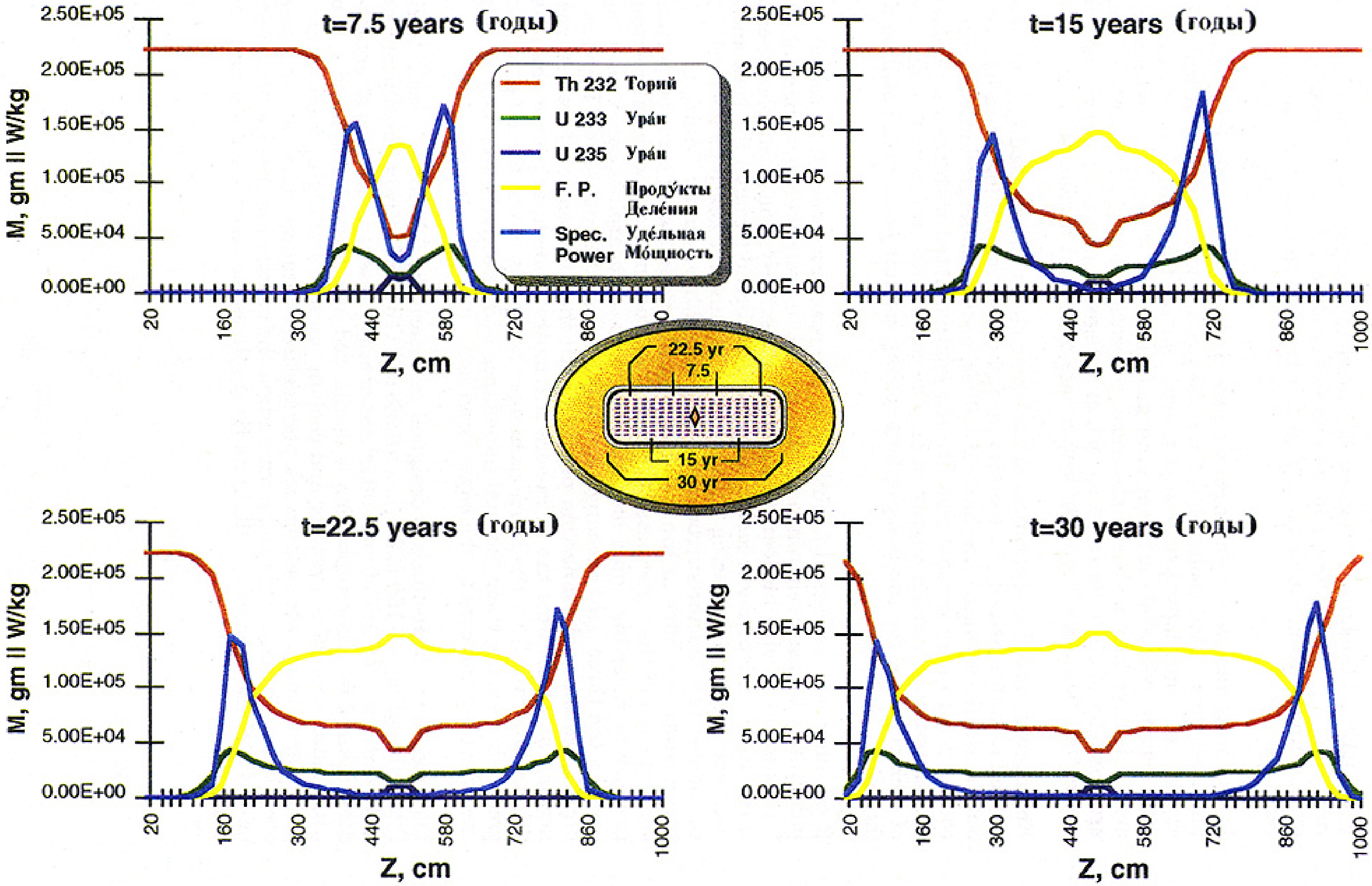
**Hiroshi Sekimoto (Japan, 2001): CANDLE Deterministic approach**

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

**Edward Teller: Nuclear Energy for the Third Millennium**

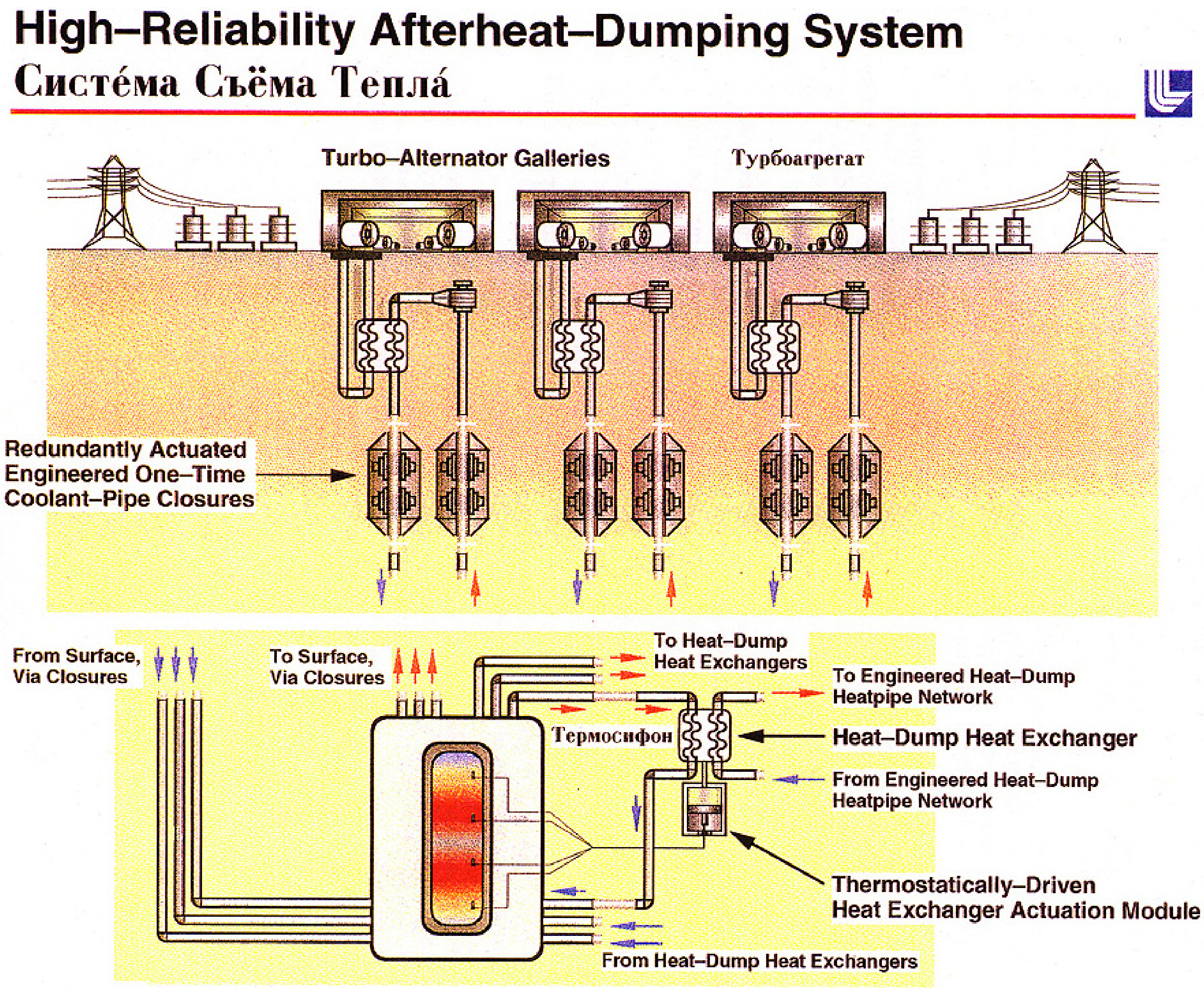
Preprint UCRL-JC-129547, LLNL, 1997. **Th-U fuel cycle**

## Salient Features Of Nuclear Deflagration Wave Propagation (Full–Power Case)



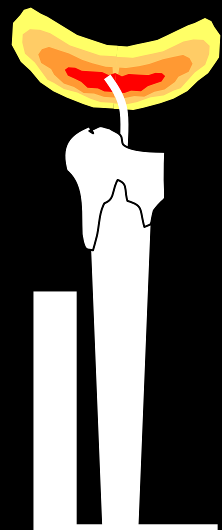
# Edward Teller (LLNL, USA) 1997: Traveling Wave Reactor

**E.Teller, 1997**. *Nuclear Energy for the Third Millennium*. Preprint UCRL-JC-129547, LLNL.



與其詛咒黑暗
不如點亮蠟燭

中國諺語



# CANDLE

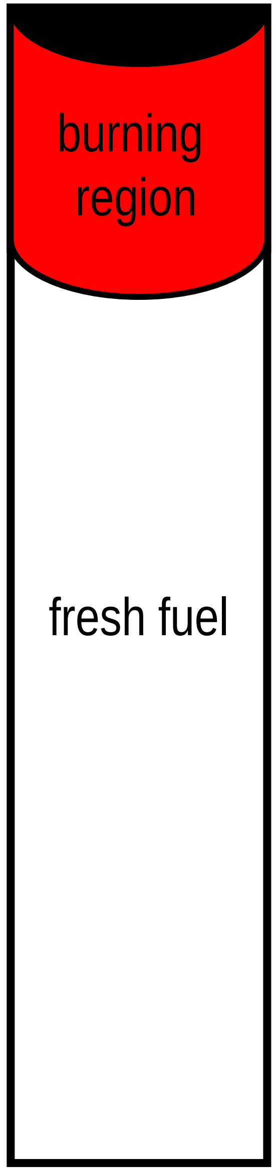
Better to light a candle than curse the darkness

# CANDLE

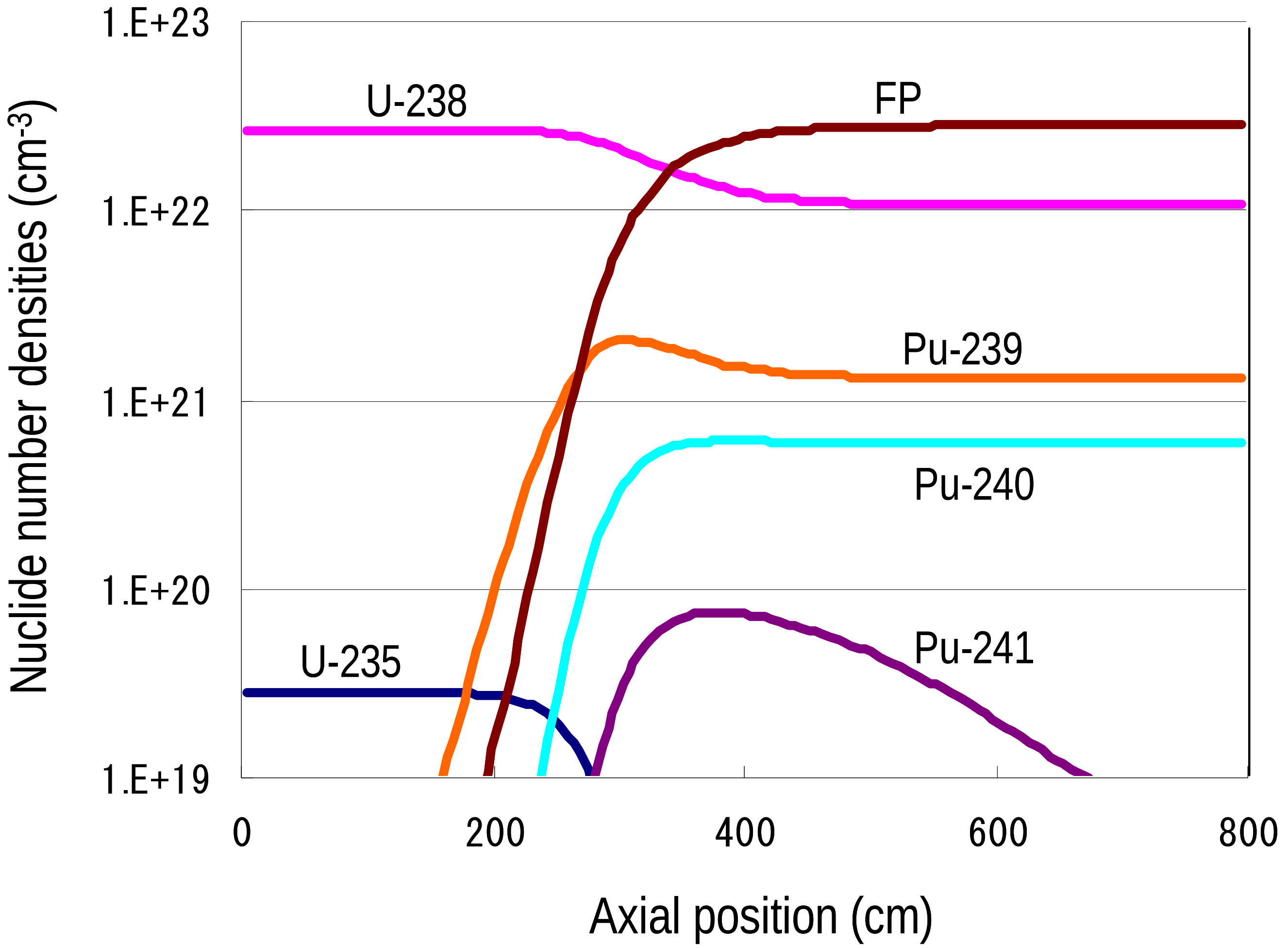
Constant Axial Shape of Neutron Flux,
Nuclide Densities and Power Shape
During Life of Energy Production

where

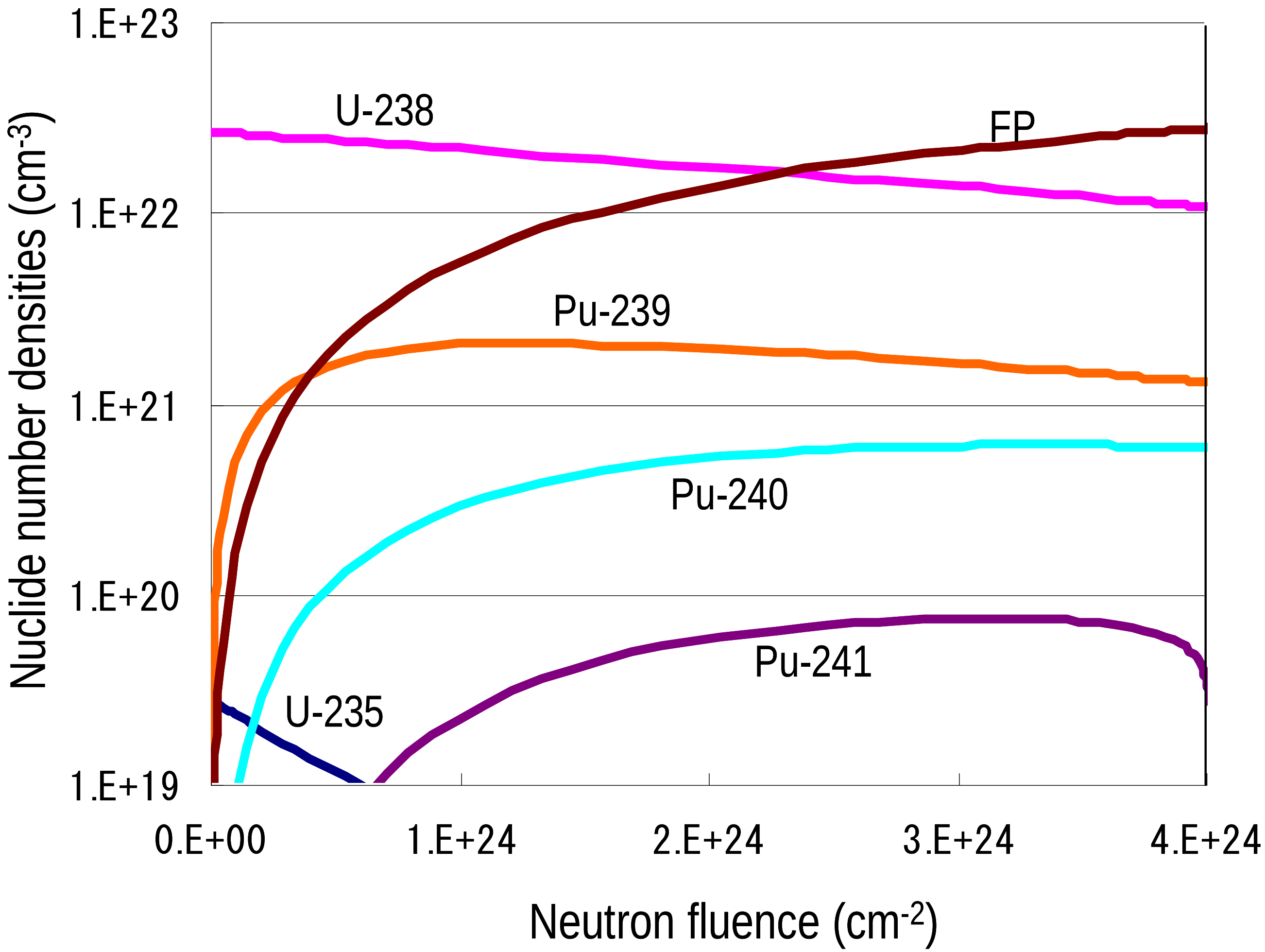
- Solid fuels are fixed in the reactor core.
  (same as the conventional reactors)
- No burnup control mechanism
  (such as control rod, movable reflector)



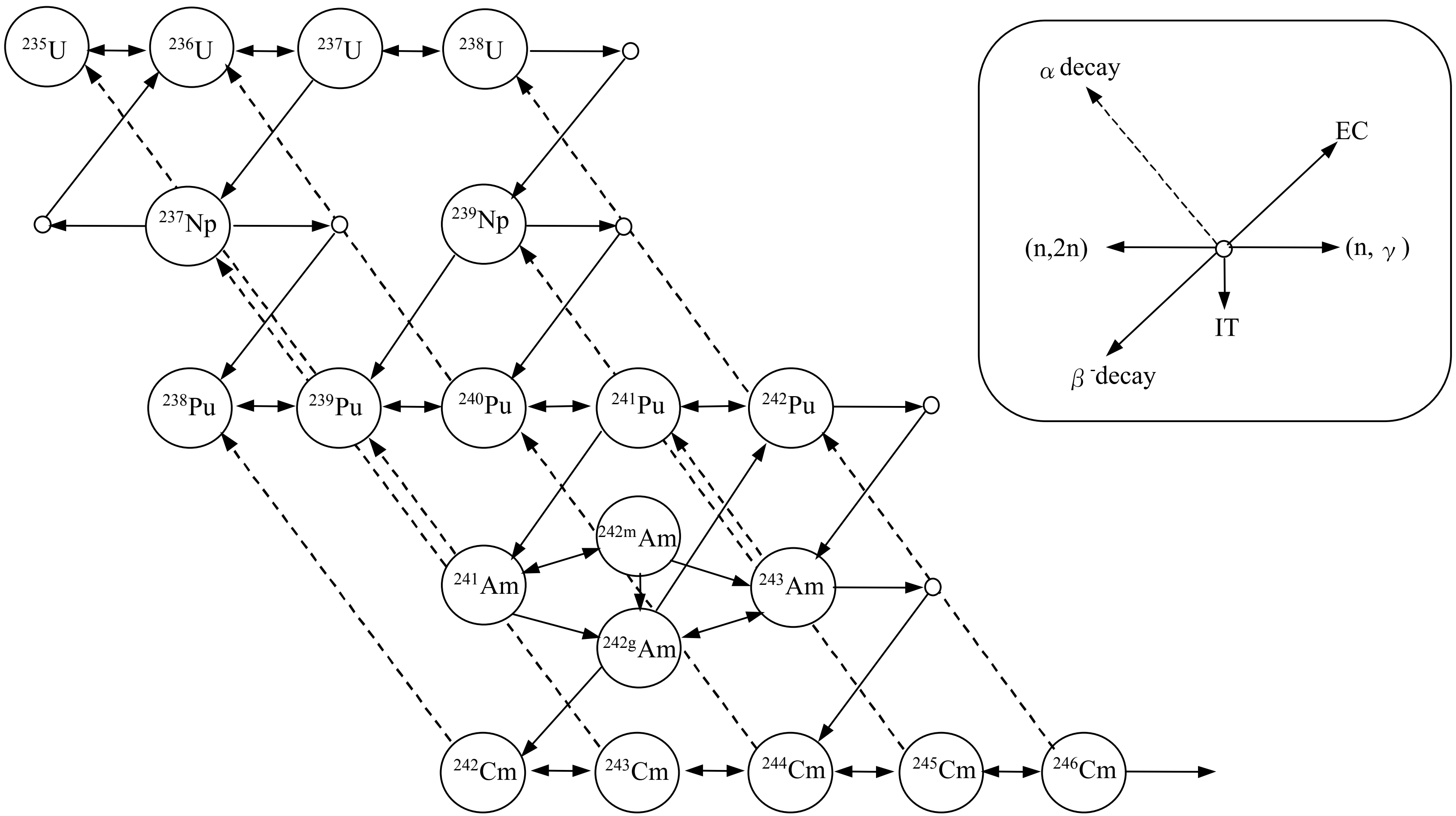
# Nuclide Number Densities along Core Axial Position



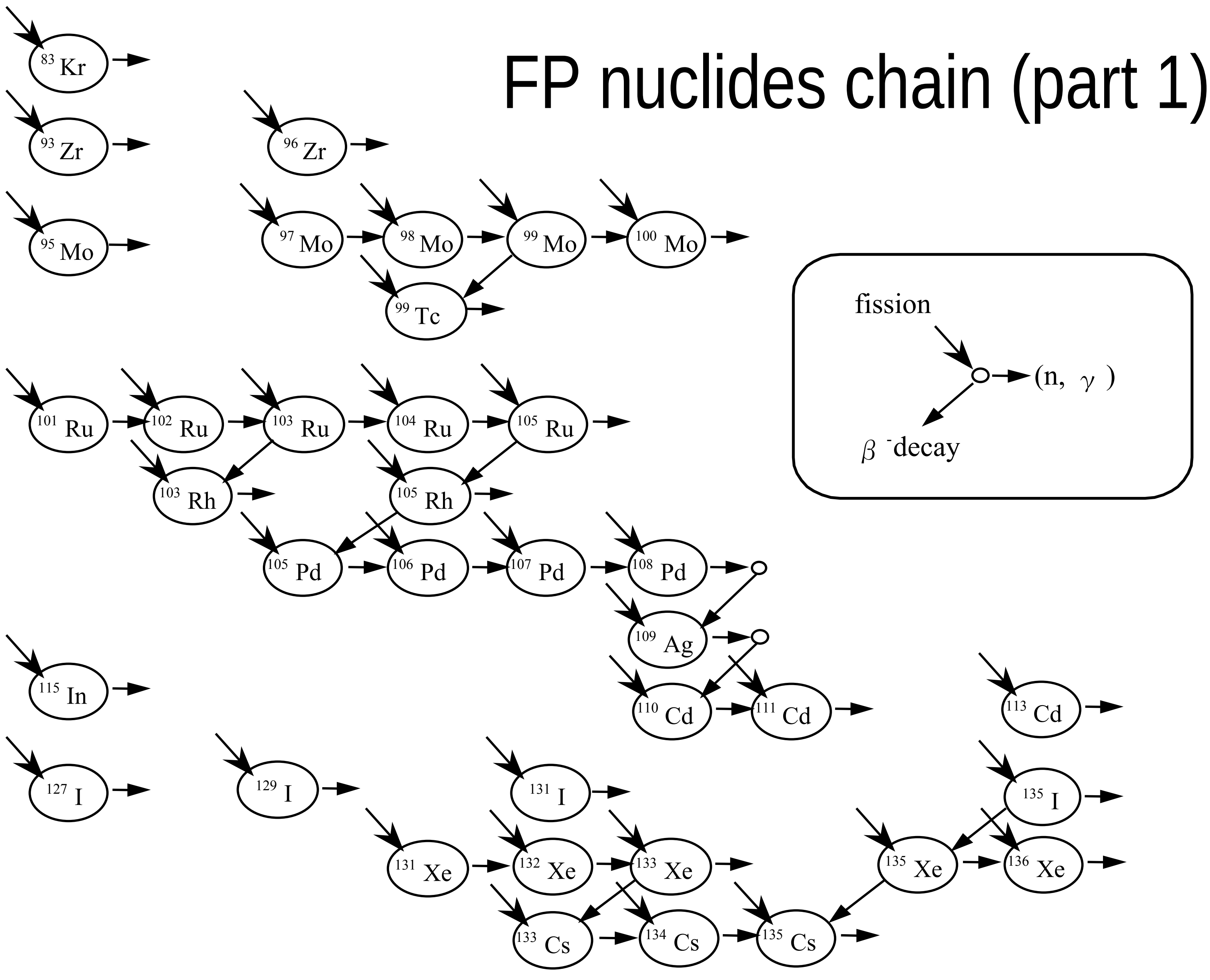
# Nuclide Number Densities along Burnup



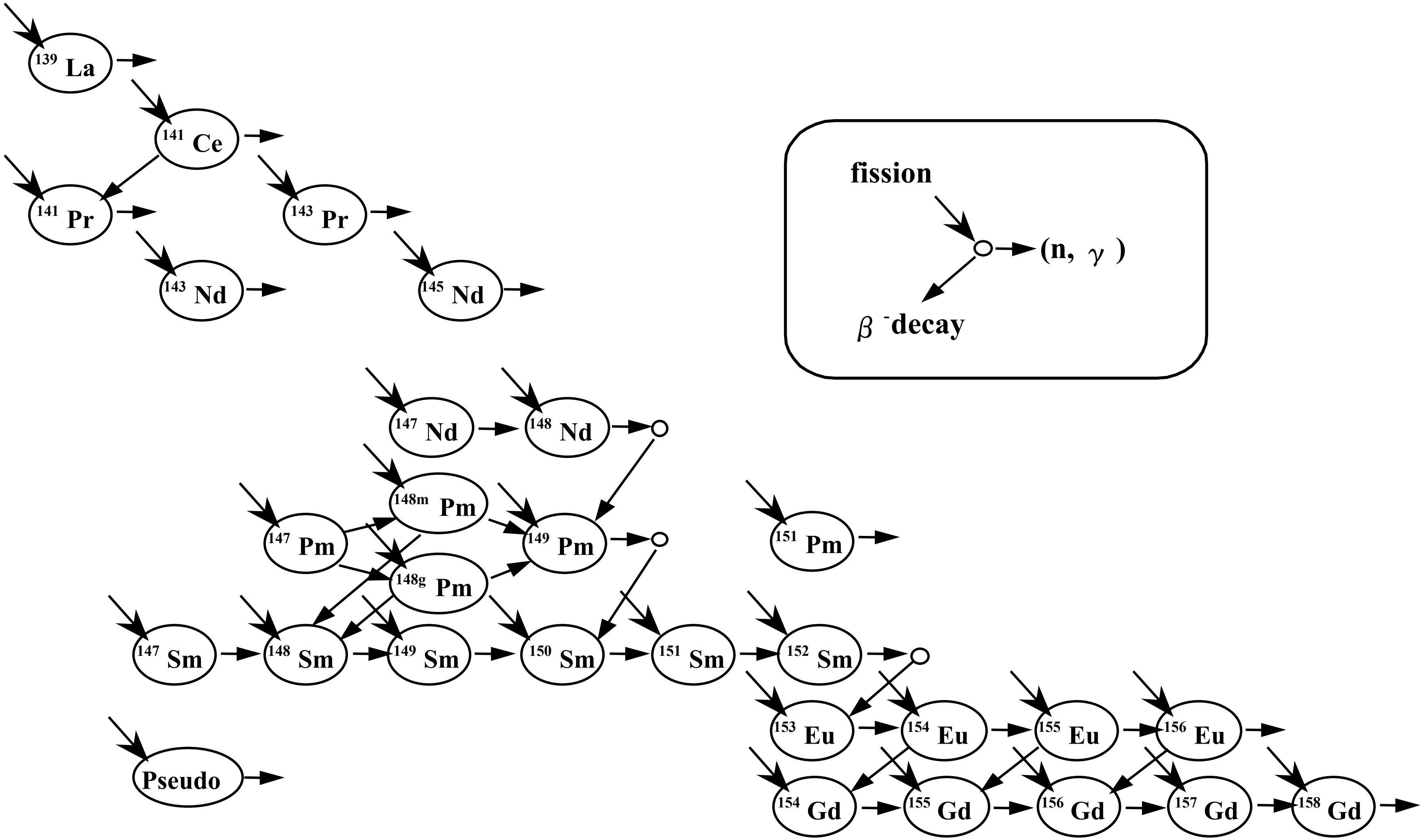
# Actinides nuclides chain



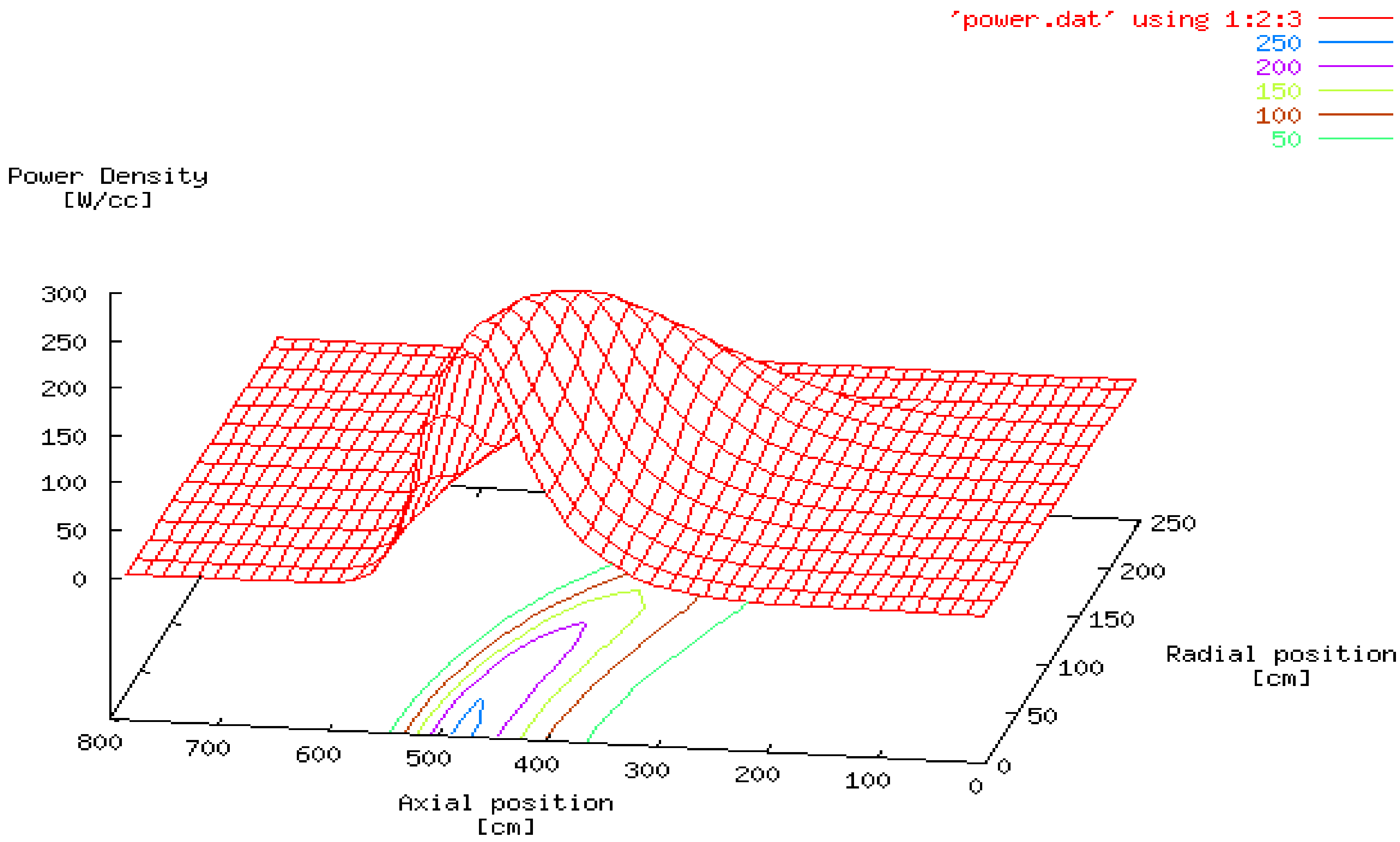
# FP nuclides chain (part 1)



# FP nuclides chain (part 2)



# Power density distributions in natural uranium fueled reactor



# Reactor characteristics change for different fuel volume fractions

| Fuel volume fraction | 40% | 50% | 60% |
|---|---|---|---|
| Effective neutron multiplication factor | 0.989 | 1.015 | 1.035 |
| Speed of burning region shift (cm/year) | 4.8 | 3.8 | 3.2 |
| Average burnup of spent fuel (GWd/t) | 427 | 426 | 427 |

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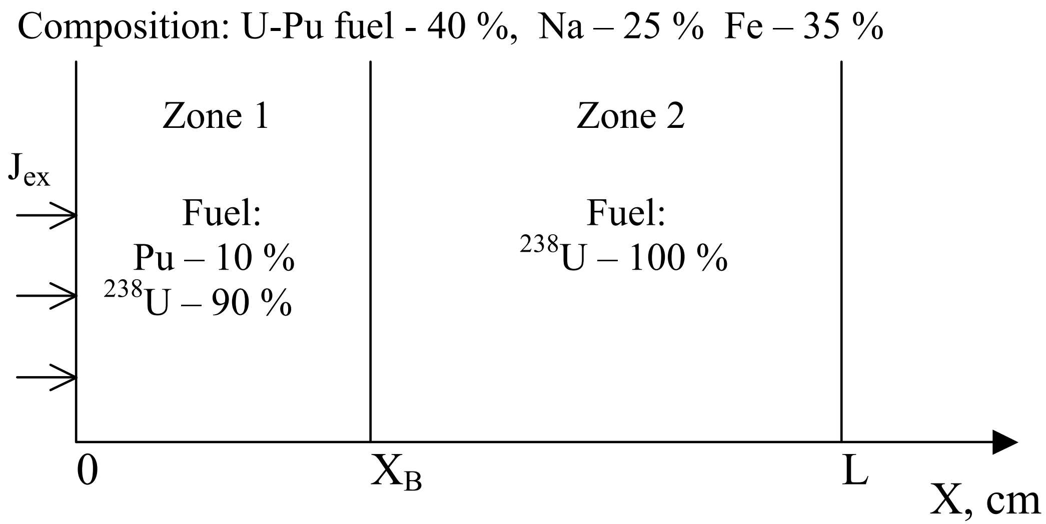
**1992 V.Goldin, D. Anistratov (Moscow Institute of Applied Mathemetics)**

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




**Non-stationary problem !**

**1d one-group approoaximation**

**(U-Pu fuel cycle)**

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

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

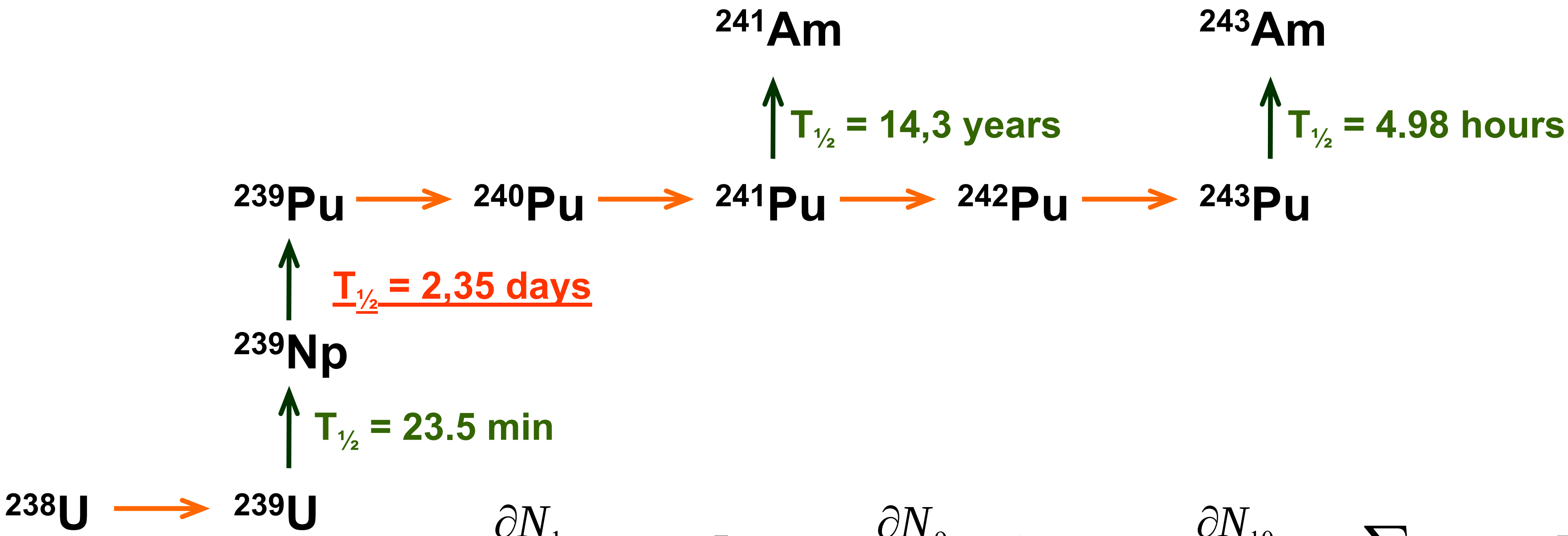
$$\frac{1}{v}\frac{\partial \Phi}{\partial t} - \frac{\partial}{\partial x}\left(D\frac{\partial \Phi}{\partial x}\right) + \Sigma_a \Phi - (1-\overline{\beta})(\nu_f \Sigma_f)\Phi = \sum_l \sum_i \lambda_l^i C_l^i \qquad \overline{\beta} = \sum_l \beta_l (\nu_f \Sigma_f)_l / \nu_f \Sigma_f$$

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

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

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

# Dynamics of the FR nuclear composition




$$\frac{\partial N_1}{\partial t} = -\sigma_{a1}\Phi N_1\,, \qquad \frac{\partial N_9}{\partial t} = \Lambda_6 N_6\,, \qquad \frac{\partial N_{10}}{\partial t} = \sum_{l=1,4,5,6,7} \sigma_{fl} N_l \Phi$$

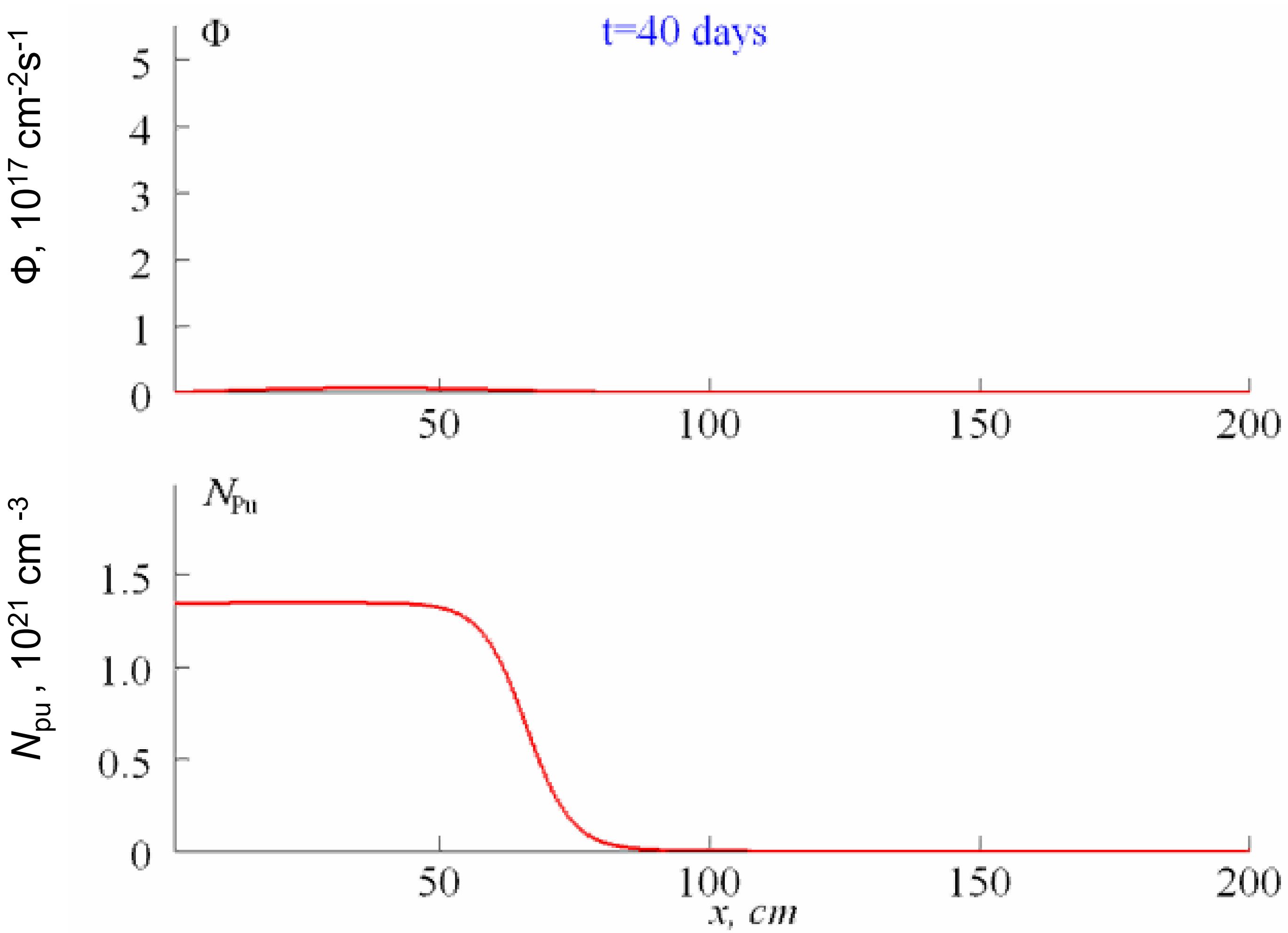
$$\frac{\partial N_l}{\partial t} = -\left(\sigma_{al}\Phi + \Lambda_l\right) N_l + \left(\sigma_{c(l-1)}\Phi + \Lambda_{(l-1)}\right) N_{(l-1)}\,, \quad (l = 2 \div 8)\,,$$

$$\sigma_{al} = \sigma_{cl} + \sigma_{fl}\,, \qquad \Lambda_l = \ln 2 / T^l_{1/2}\,, \qquad N_l(x, t=0) = N_{0l}(x)$$

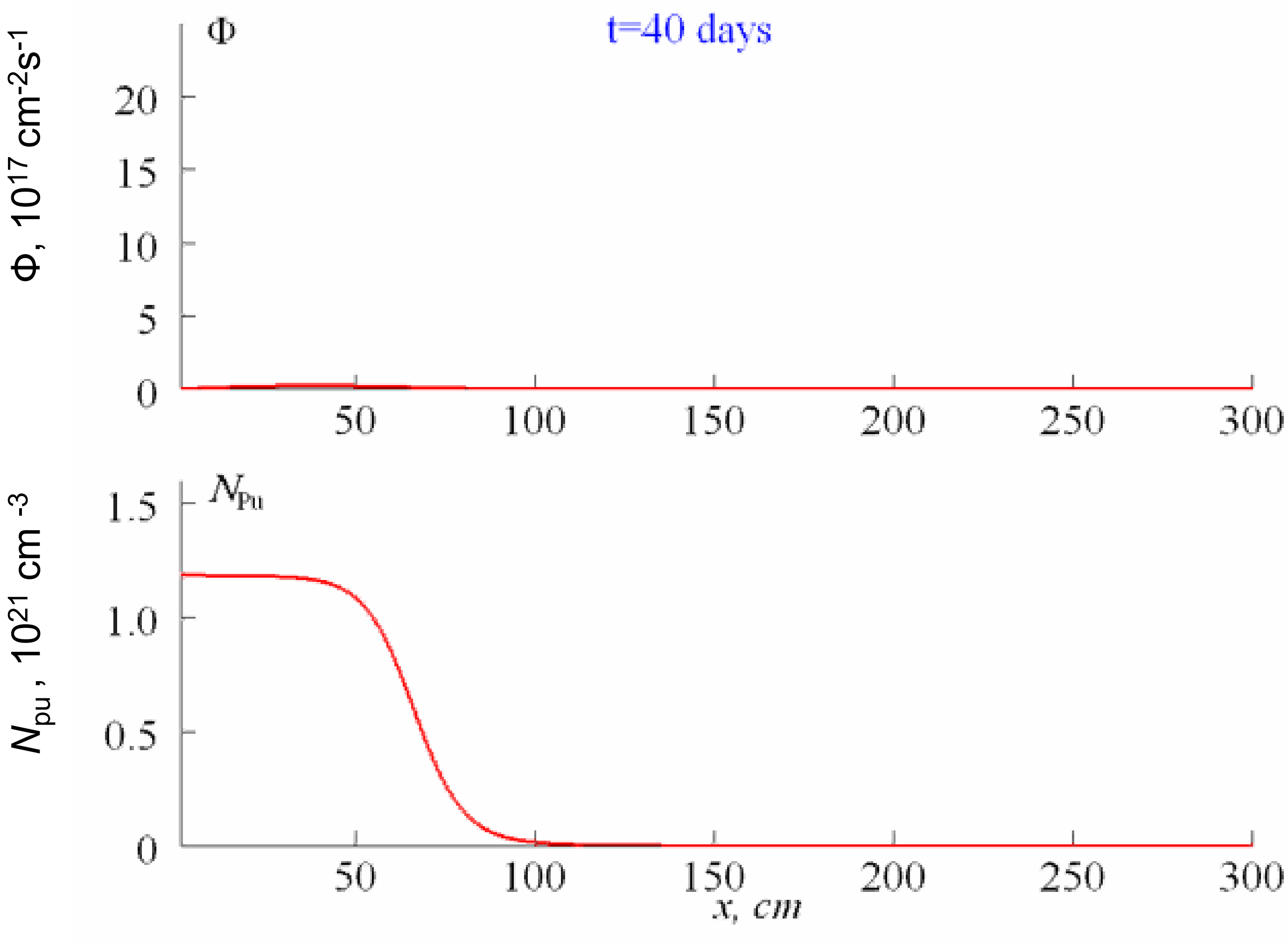
*The numeration of the nuclei in the U–Pu transformation chain*

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Nucleus | $^{238}$U | $^{239}$U | $^{239}$Np | $^{239}$Pu | $^{240}$Pu | $^{241}$Pu | $^{242}$Pu | $^{243}$Am | $^{241}$Am | FP |

# Goldin's Solution for NBW in Fast Reactor

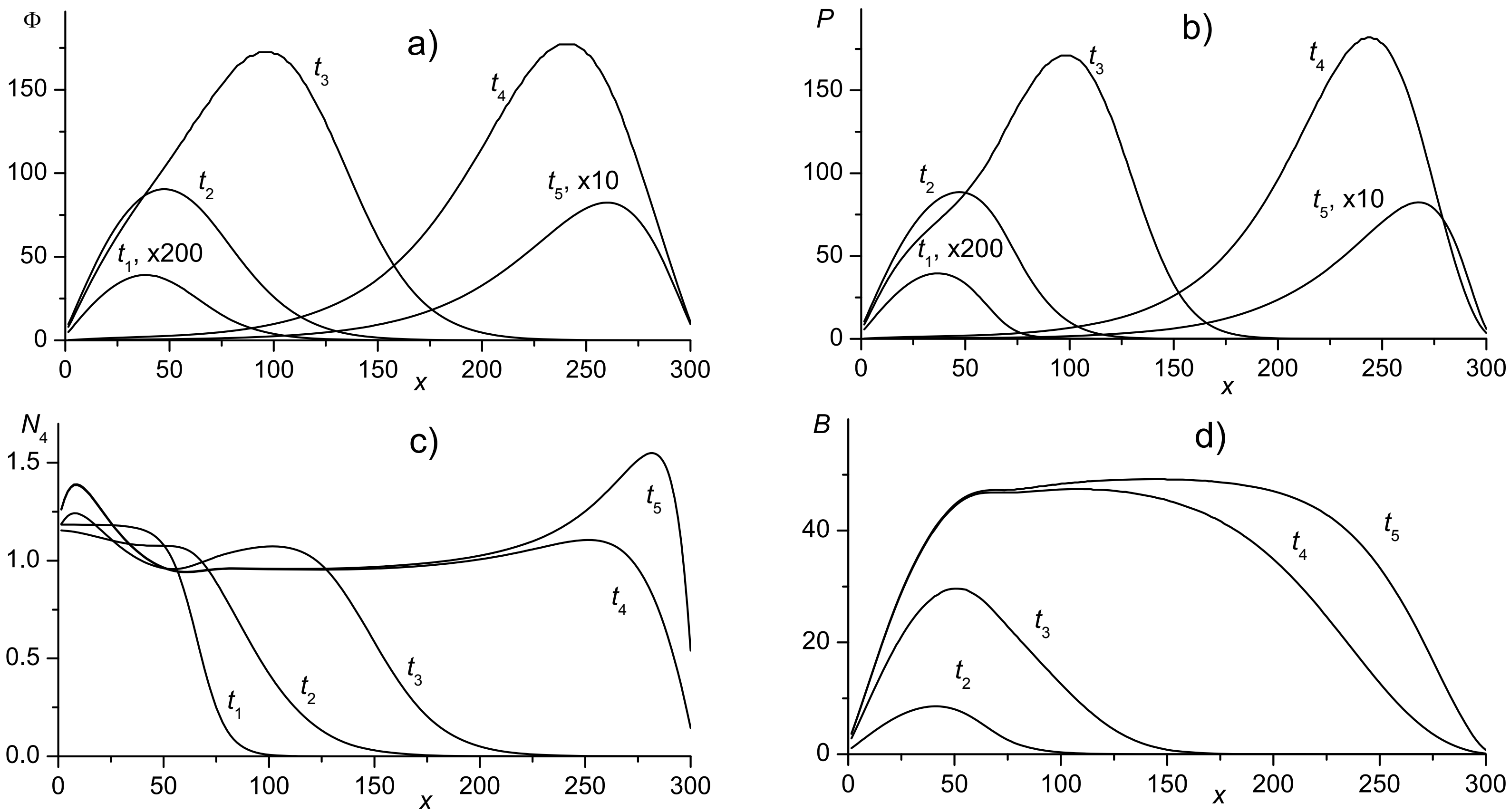


# Corrected Goldin's Solution for NBW in Fast Reactor



# Nuclear burning wave in FR

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



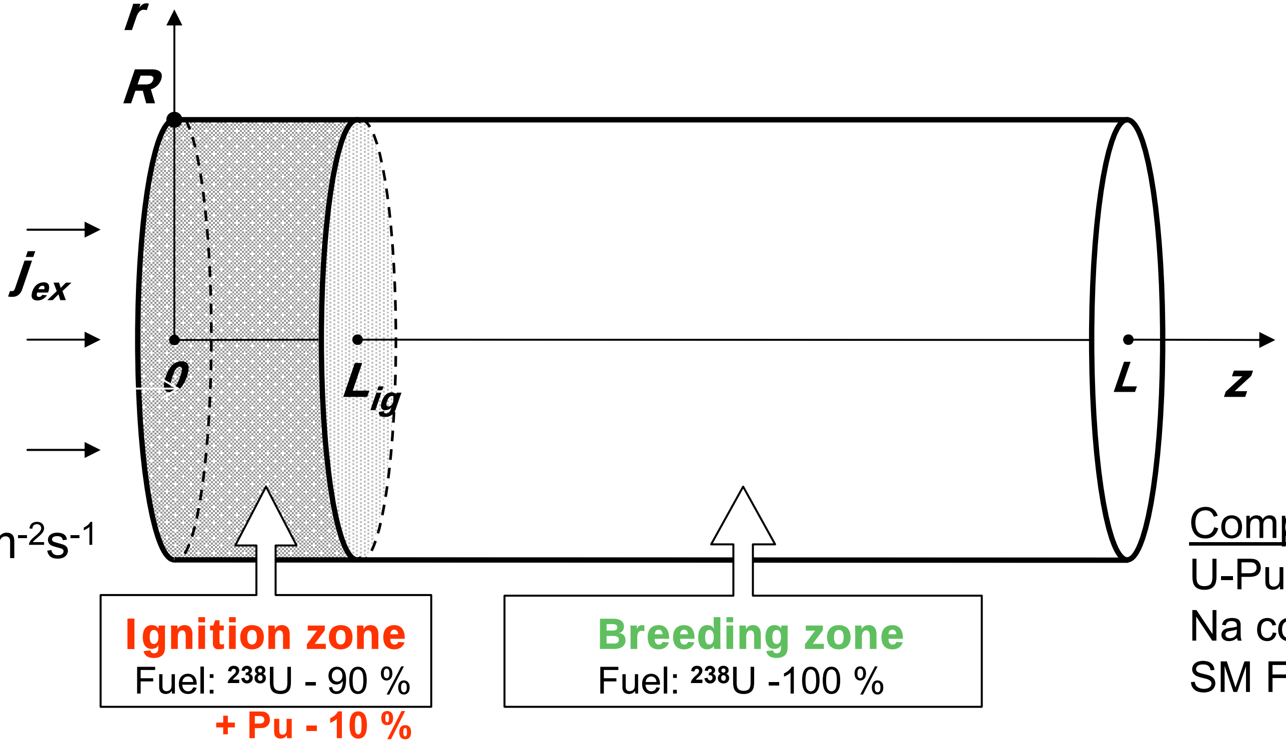

(a) scalar neutron flux ($\times 10^{16}$ $cm^{-2}$ $s^{-1}$); (b) power density ($kW$ $cm^{-3}$);

(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):

# Nuclear burning wave in cylindrical FR (buckling concept)

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




$j_{ex}$= 6·1011 $cm^{-2}s^{-1}$

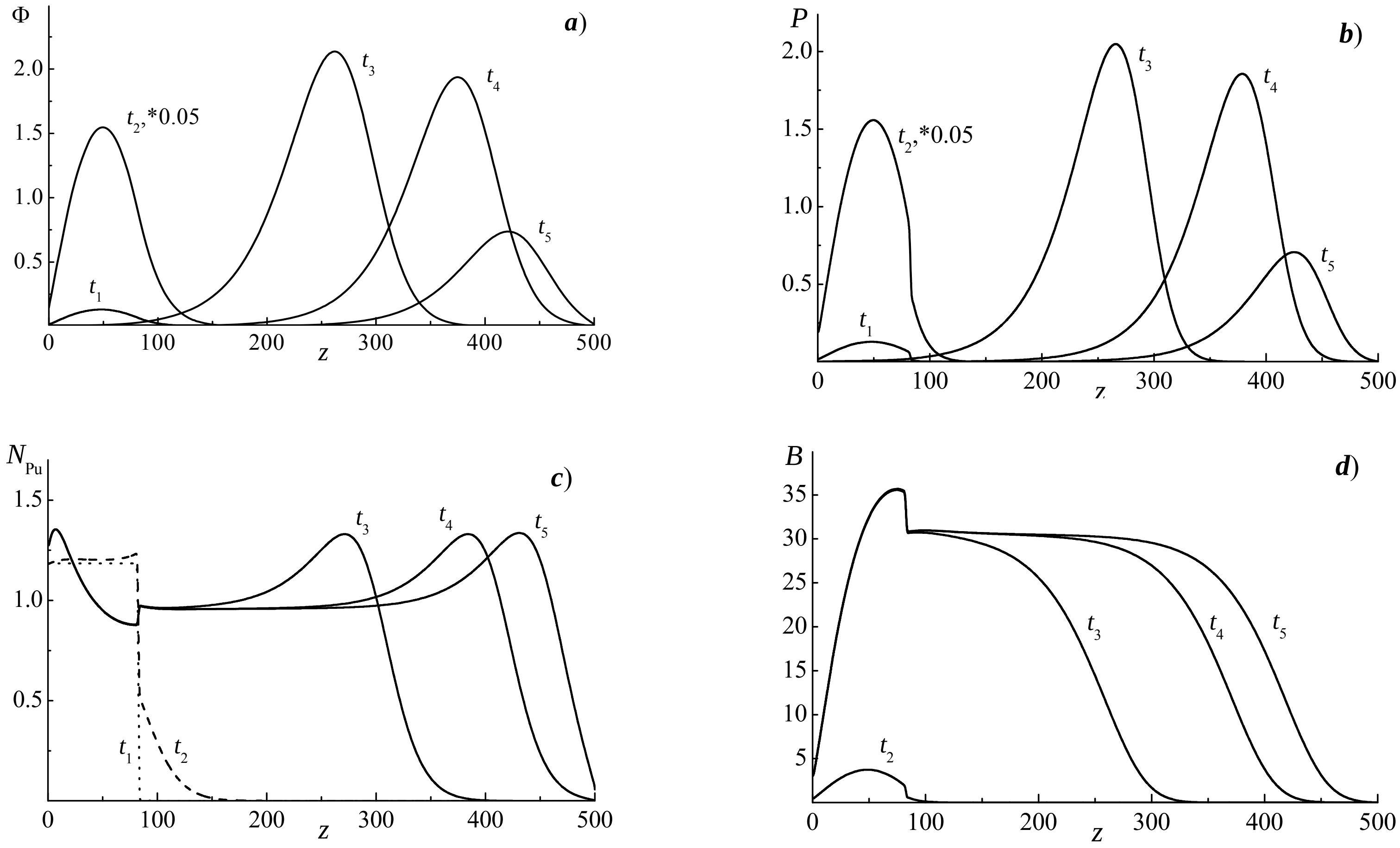
Composition:
U-Pu fuel - 44 %,
Na coolant - 36%
SM Fe - 20 %

Buckling concept: $\Phi(r,z) = \Phi_r(r) \cdot \Phi_z(z) \quad \Rightarrow \quad \Phi_r \sim J_0(B_r r)$

$$\frac{1}{v}\frac{\partial \Phi_z}{\partial t} - \frac{\partial}{\partial z} D \frac{\partial \Phi_z}{\partial z} + DB_r^2 \Phi_z + \Sigma_a \Phi_z - (1-\overline{\beta})(\nu_f \Sigma_f)\Phi_z = \sum_l \sum_i \lambda_l^i C_l^i + Q(z,t)$$

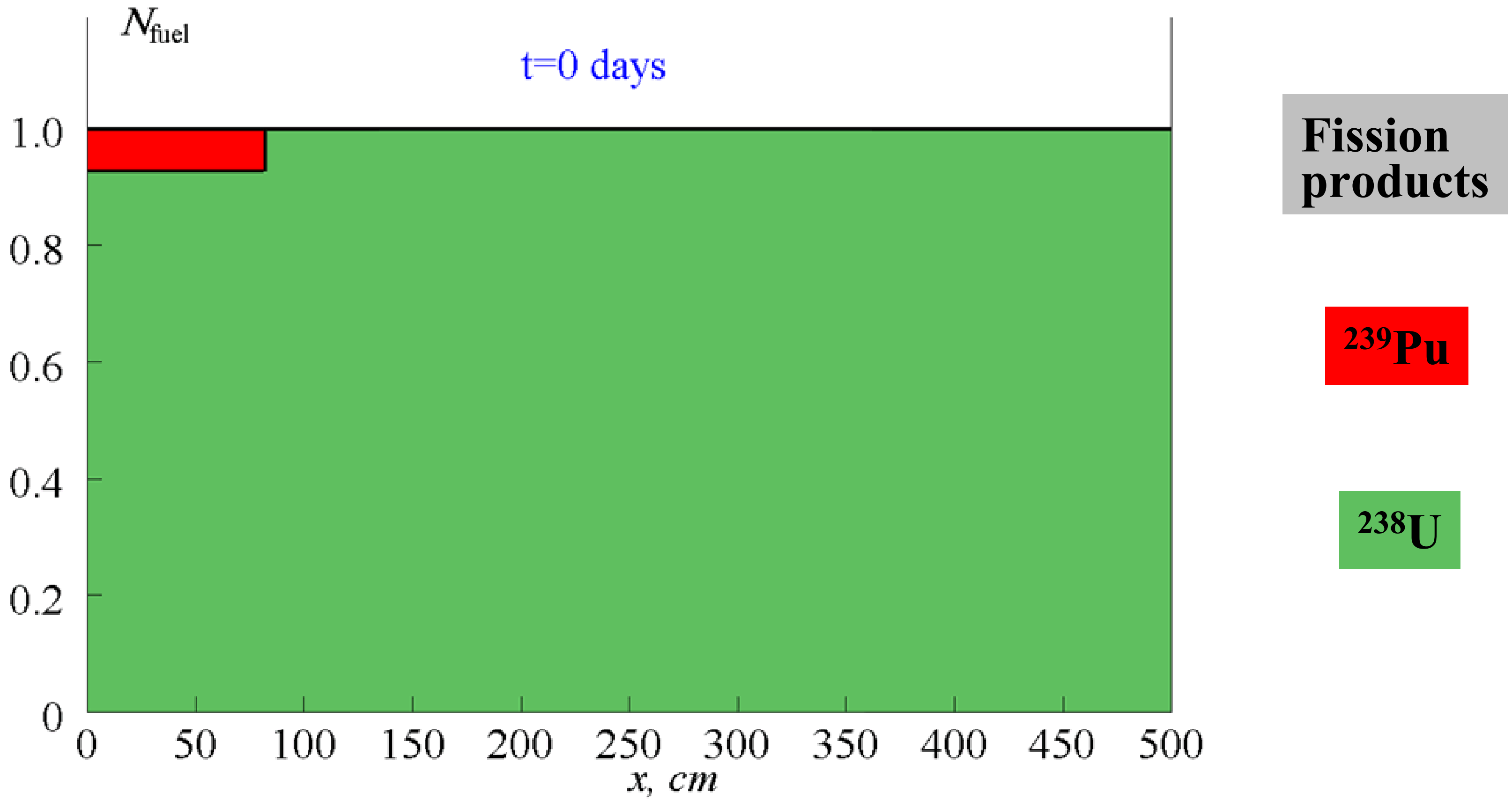
- variable separation approximation

# Results for the 5m length and 110 cm radius cylindrical FR




(a) scalar neutron flux ($\times 10^{16}$ $cm^{-2}$ $s^{-1}$); (b) power density ($kW$ $cm^{-3}$); (c) concentration of $^{239}$Pu ($\times 10^{21}$ $cm^{-3}$); (d) depth of fuel burn-up (%) for for $t_1 = 5$, $t_2 = 100$, $t_3 = 2000$, $t_4 = 4000$ and $t_5 = 5000$ days.

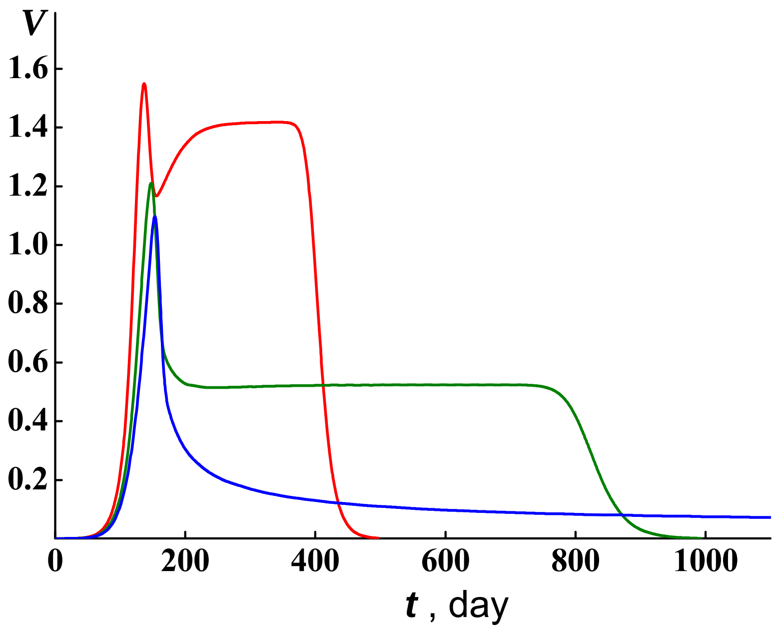
# Fuel burn-up  (U-Pu fuel cycle)



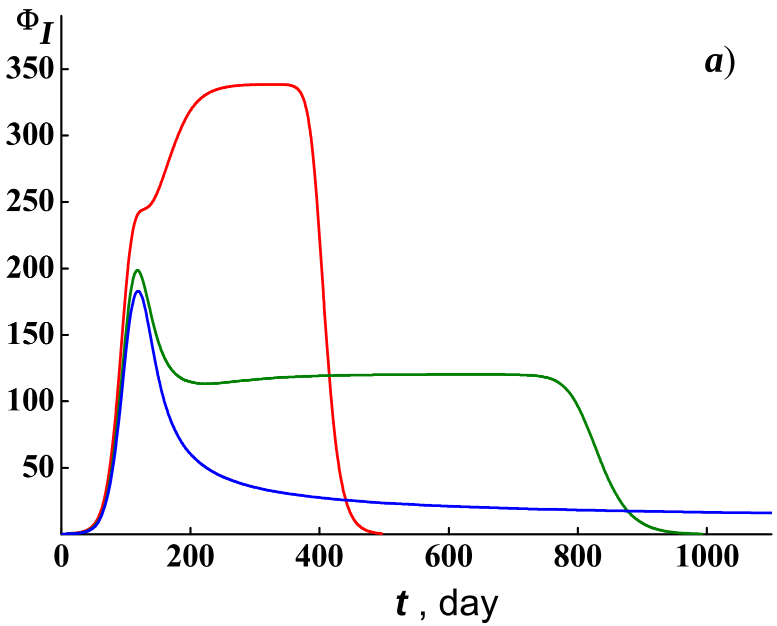
# Nuclear burning wave in 5m length cylindrical FR for different reactor radius *R*

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

NBW velocity $V$, cm/day




Integral neutron flux $\Phi_I$, $\times 10^{17} cm^{-1}s^{-1}$




**R = 150 cm (red line) ; 120 cm (green line) ; R = 110 cm (blue line)**

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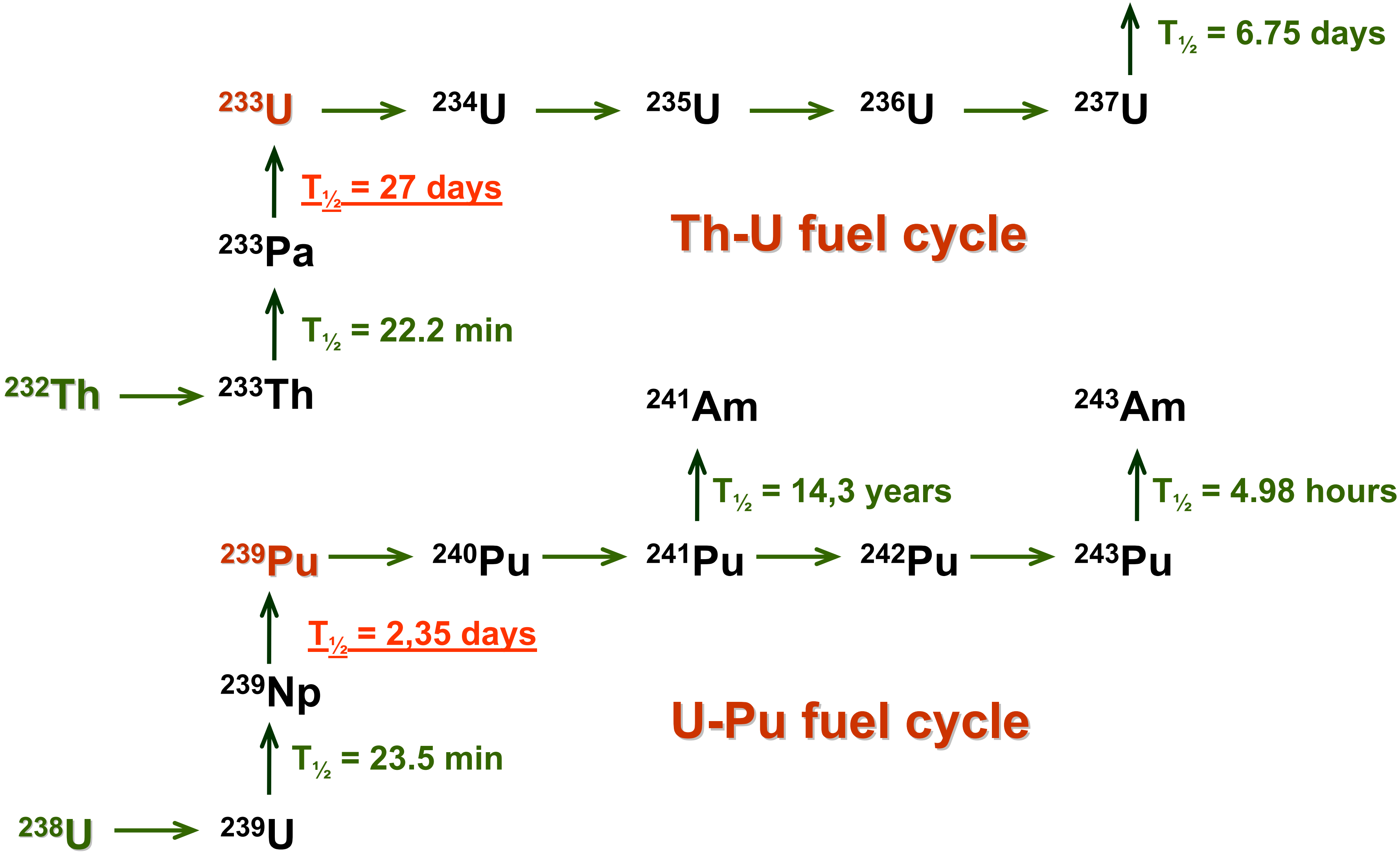
# Nuclear fuel reproduction



# Dynamics of the FR nuclear composition

*The numeration of the nuclei in the Th – U transformation chain*

| $l$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Nucleus | $^{232}$Th | $^{233}$Th | $^{233}$Pa | $^{233}$U | $^{234}$U | $^{235}$U | $^{236}$U | $^{237}$U | $^{237}$Np | FP |

$$\frac{\partial N_1}{\partial t} = -\sigma_{a1}\Phi N_1 \qquad \frac{\partial N_{10}}{\partial t} = \sum_{l=1,3\div 7,9} \sigma_{fl}\Phi N_l$$

$$\frac{\partial N_l}{\partial t} = -\left(\sigma_{al}\Phi + \Lambda_l\right)N_l + \left(\sigma_{c(l-1)}\Phi + \Lambda_{(l-1)}\right)N_{(l-1)}, \qquad (l = 2\div 9)$$

$$\sigma_{al} = \sigma_{cl} + \sigma_{fl}, \qquad \Lambda_l = \ln 2 / T^l_{1/2}, \qquad N_l(z,t=0) = N_{0l}(z)$$

**Equations of nuclear kinetics for the precursor nuclei of delayed neutrons**

(approximation of one equivalent group of delayed neutrons)

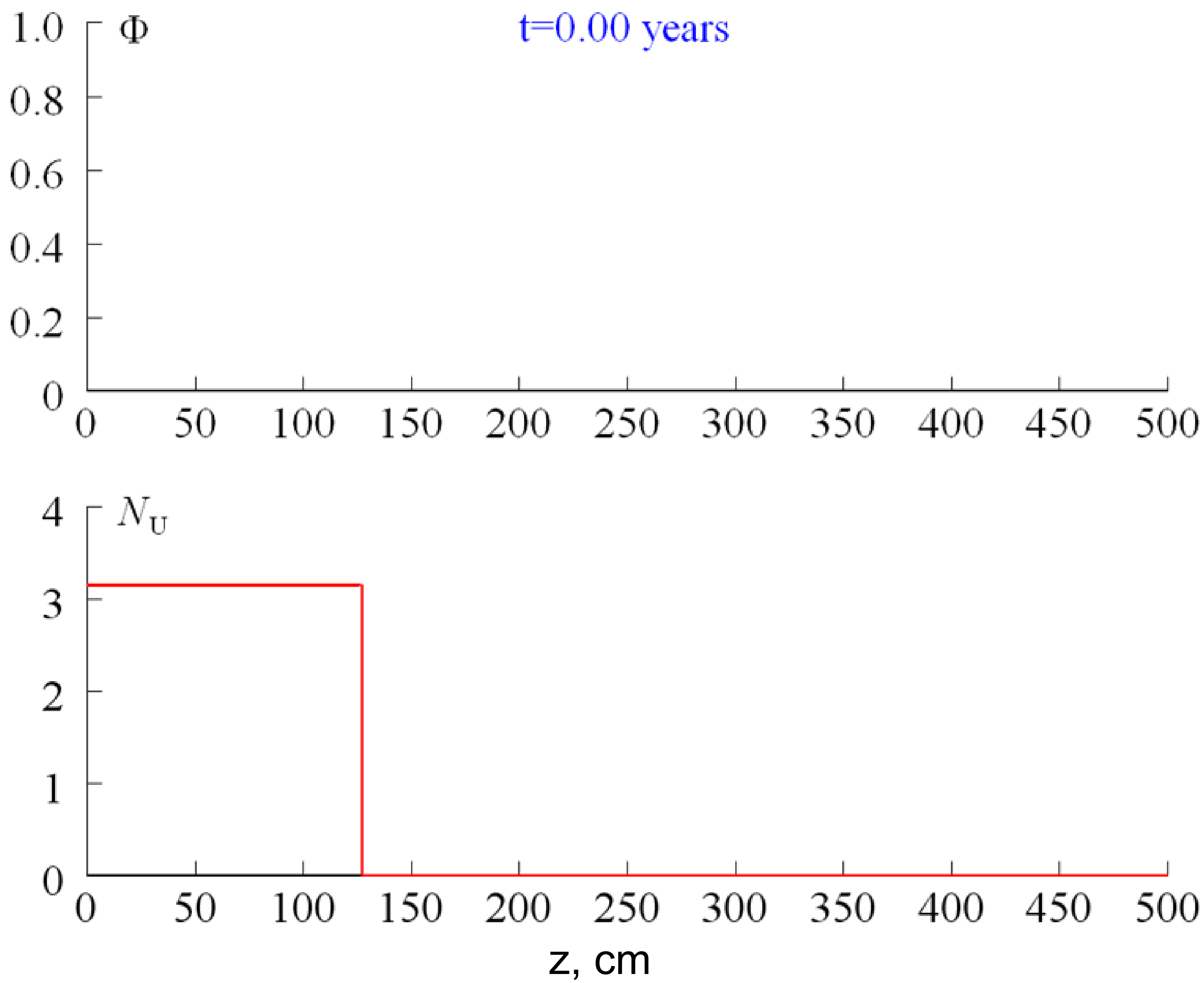
$$\frac{\partial C_l}{\partial t} = -\lambda_l C_l + \beta_l(\nu_f\Sigma_f)_l\Phi, \qquad C_l(z,t=0) = C_{0l}(z).$$

$l = 1,\ 3\div 7,\ 9$ – the fissile nucleus number.

# Nuclear Burning Wave in Pure Th-U medium

## Cylindrical reactor: R=350 cm, L= 500 cm ($L_{ig}$= 127 cm)

Scalar neutron flux Φ, $10^{17}$ $cm^{-2}s^{-1}$ ; Uranium concentration $N_U$ , $10^{21}$ $cm^{-3}$




$j_{ex}$~$10^{12}$ $cm^{-2}$ $s^{-1}$

$t_{off}$=365 days

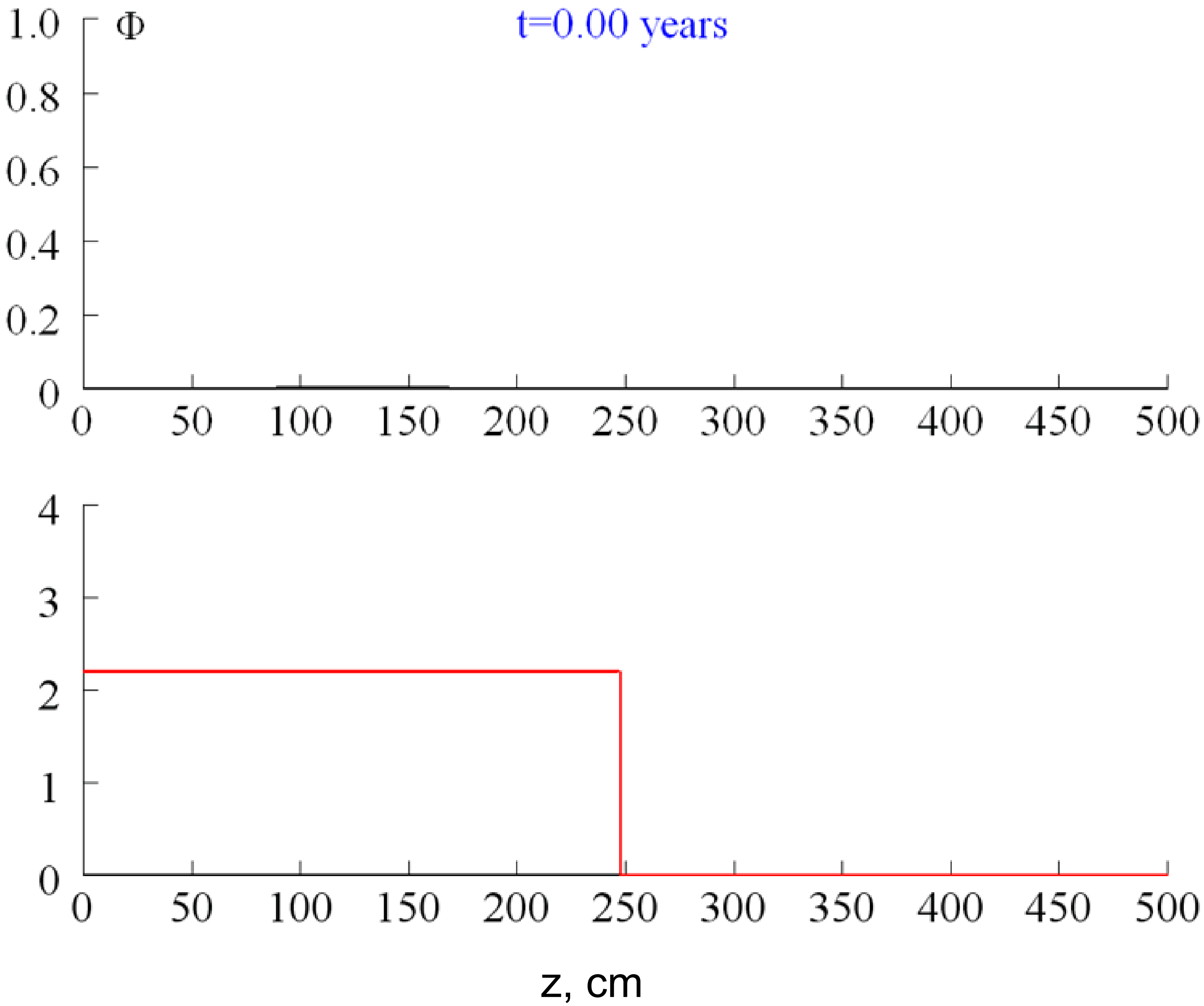
Black – $^{233}U$

Red – total U

## No Wave in Th-U medium with 10% CM (Fe), 20% Coolant (He)

**Cylindrical reactor R = 400 cm, L = 500 cm ($L_{ig}$= 247 cm).**

Scalar neutron flux Φ, $10^{17}$ $cm^{-2}s^{-1}$ ; uranium concentration $N_U$ , $10^{21}$ $cm^{-3}$.




**$j_{ex}$~$10^{12}$ $cm^{-2}$ $s^{-1}$**

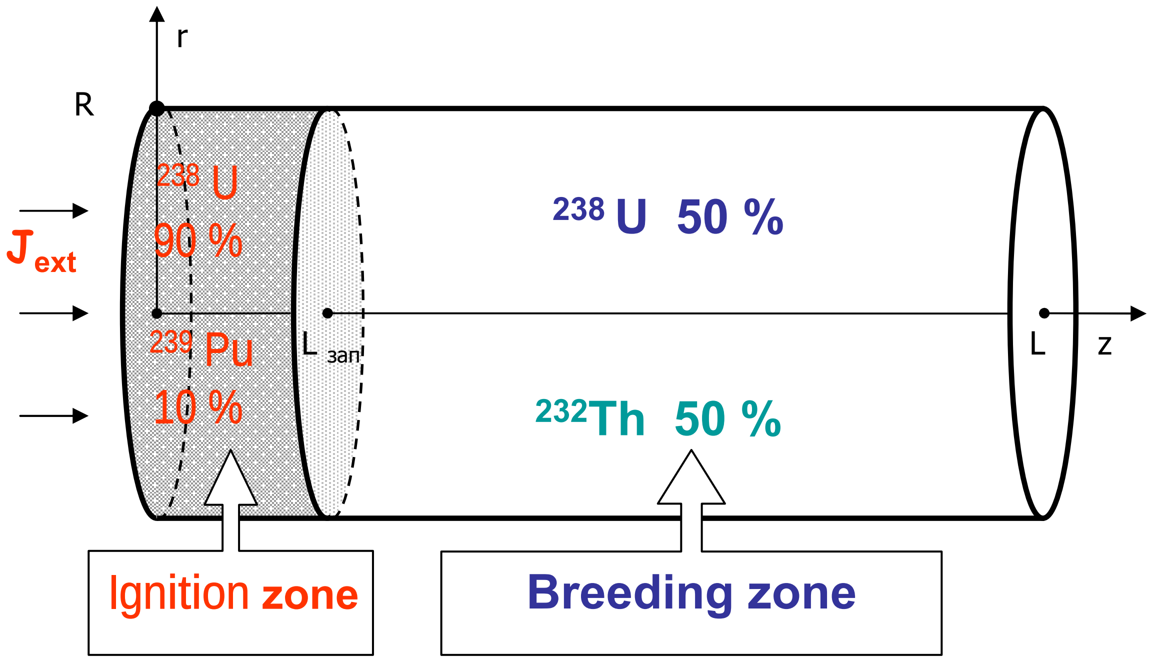
**$t_{off}$=365 days.**

Black – $^{233}U$

Red – total U

# NBW reactor with mixed Th-U-Pu fuel

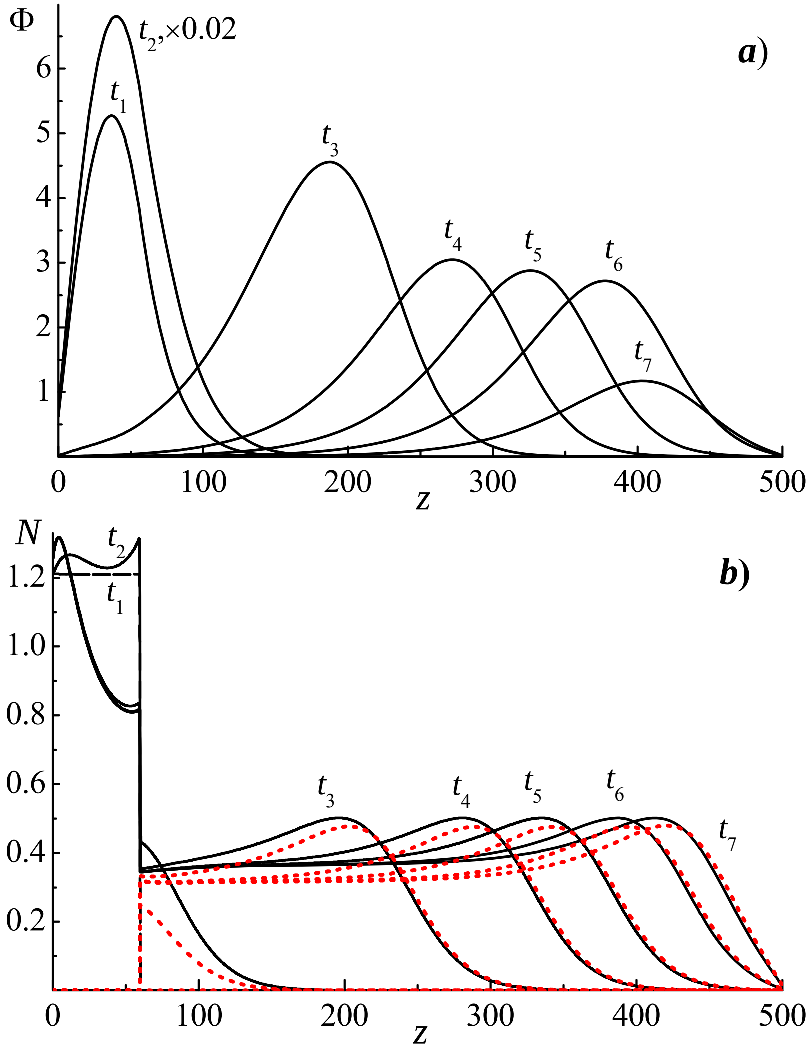
S. Fomin et al., ICAPP 2010 (San Diego, USA) paper 10302.
S. Fomin et al., Progress in Nuclear Energy, 52 (2011) 800-805.




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

# NBW reactor with mixed Th-U-Pu fuel

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



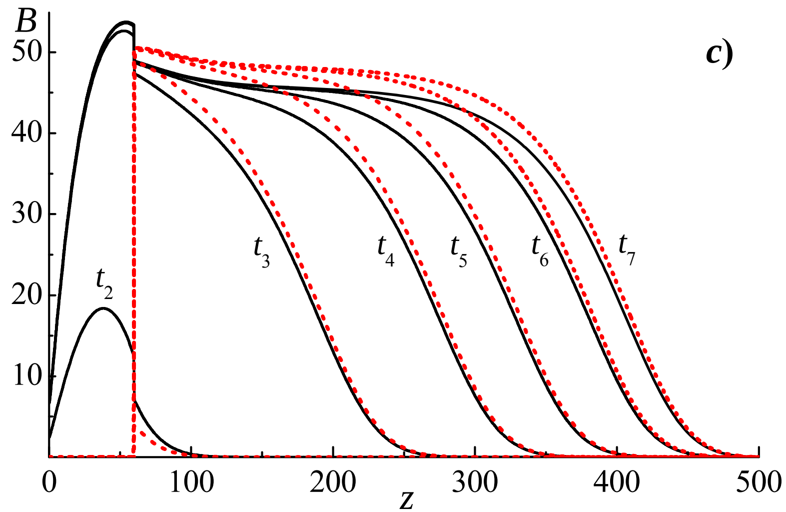
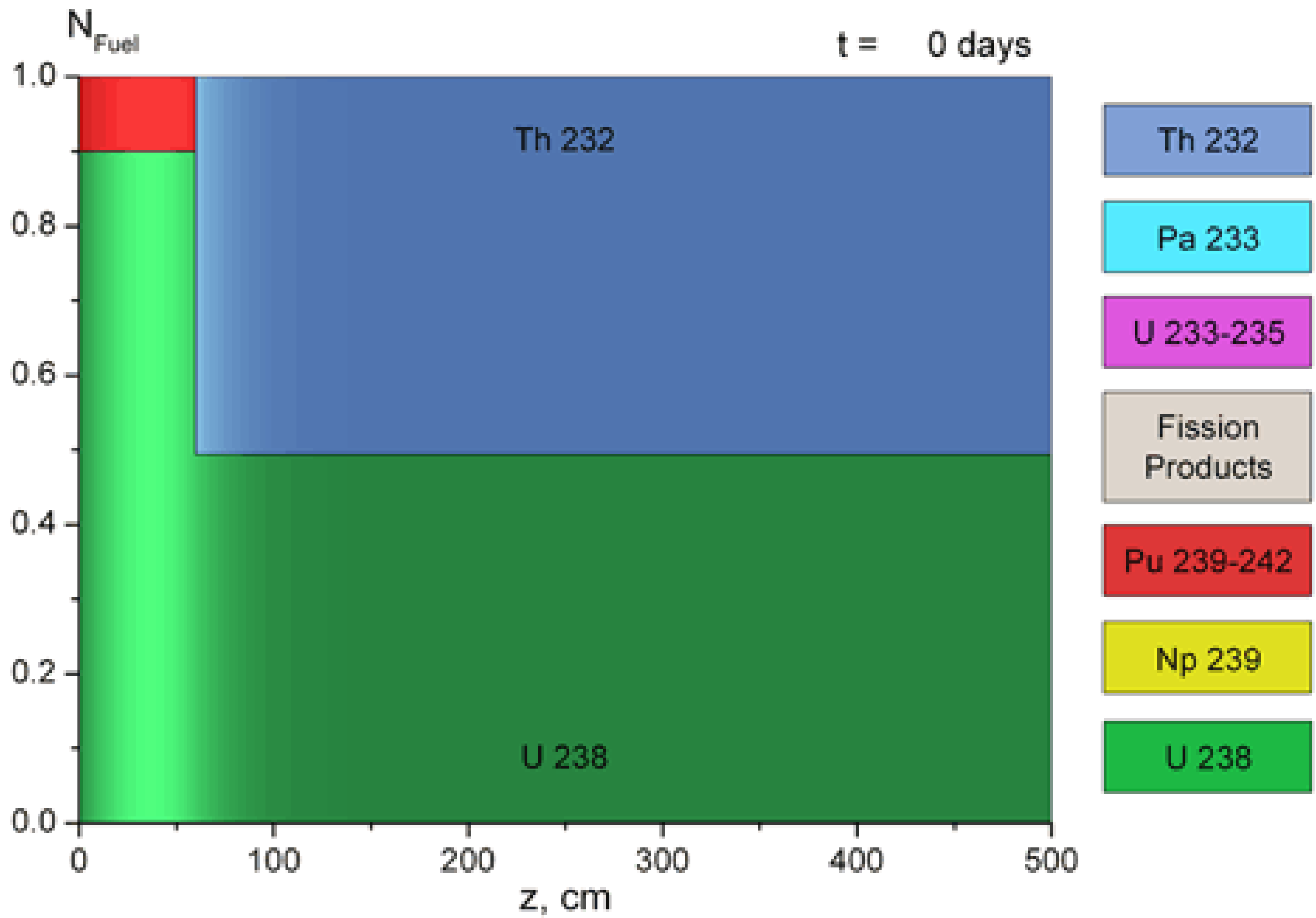




FIG. 3. the axial distributions ($z$, cm) of the nbw characteristics: (a) scalar neutron flux Φ (×$10^{15}$ cm$^{-2}$ s$^{-1}$); (b) concentration $n$ (×$10^{21}$ cm$^{-3}$) for $^{239}$Pu (solid curves) and $^{233}$U (dots); (c) fuel burn-up depth $b$ (%) for the fuel components $^{238}$U–Pu (solid curves) and $^{232}$Th (dots) for calculation variant 1 for time moments $t_1$ = 4, $t_2$ = 100 days, $t_3$ = 10, $t_4$ = 30, $t_5$ = 45, $t_6$ = 60 and $t_7$ = 70 years.

# Fuel burn-up for Th-U-Pu cycle



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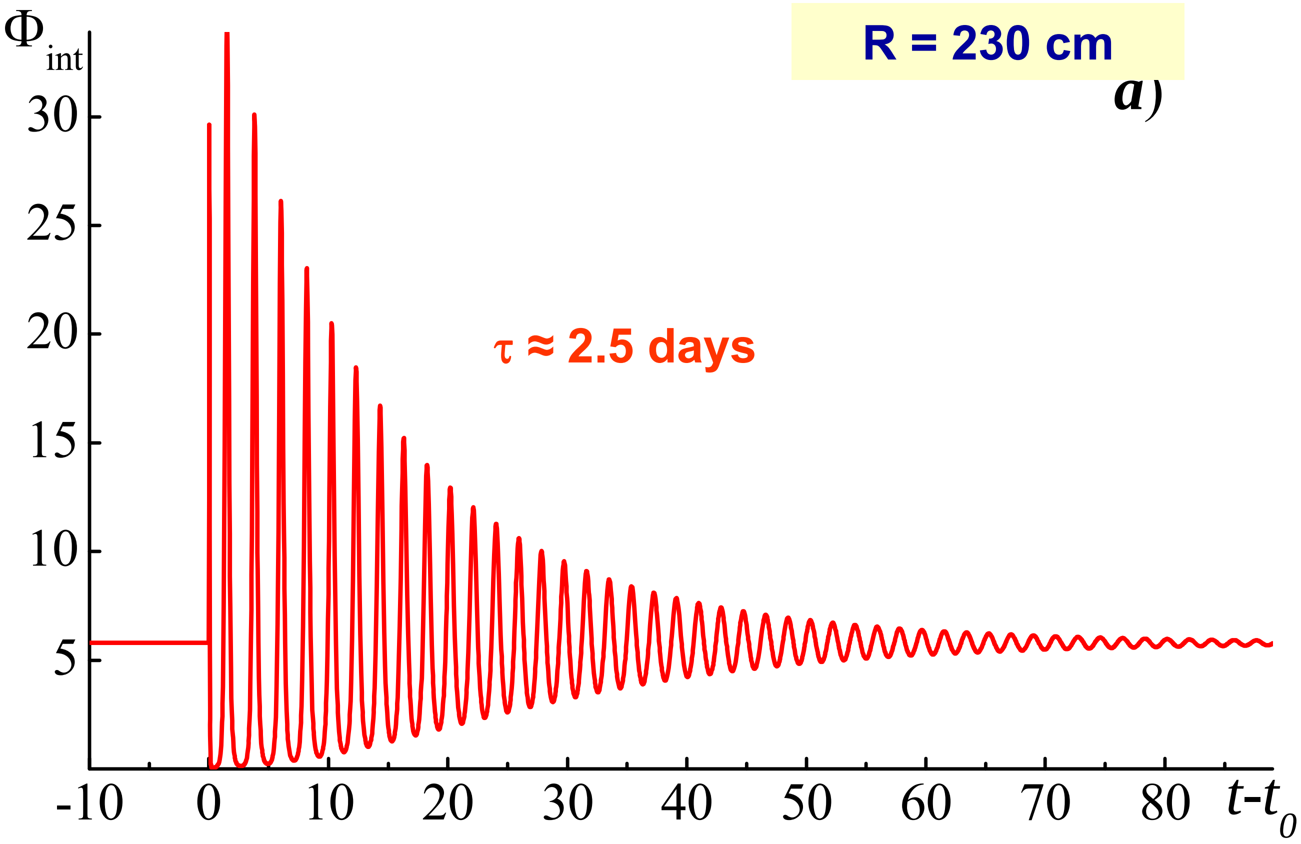
# Stability of the NBW Regime

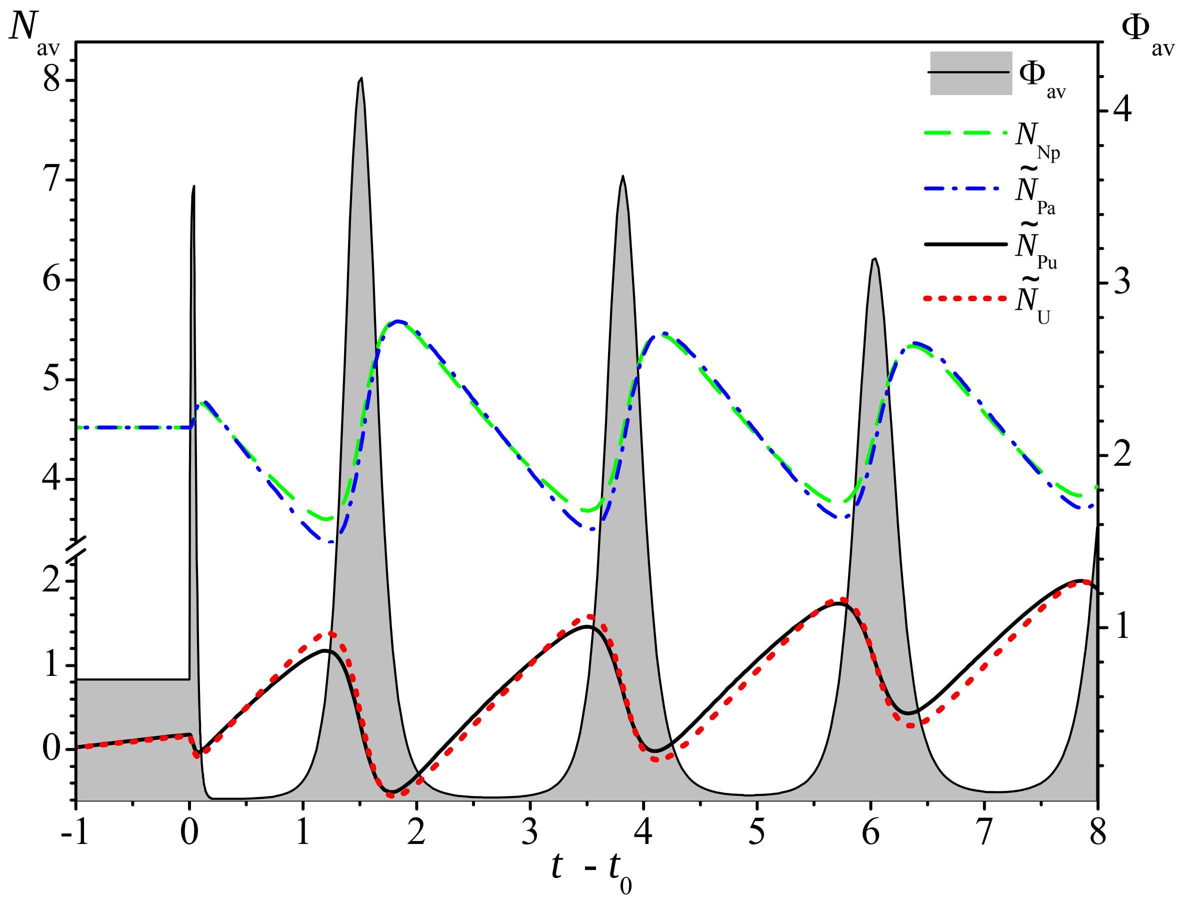
S. Fomin et al., *IC "Fast Reactors 2013" (Paris, France)* paper CN-199-457.




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

# Stability of the NBW Regime: Negative Reactivity Feedback

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

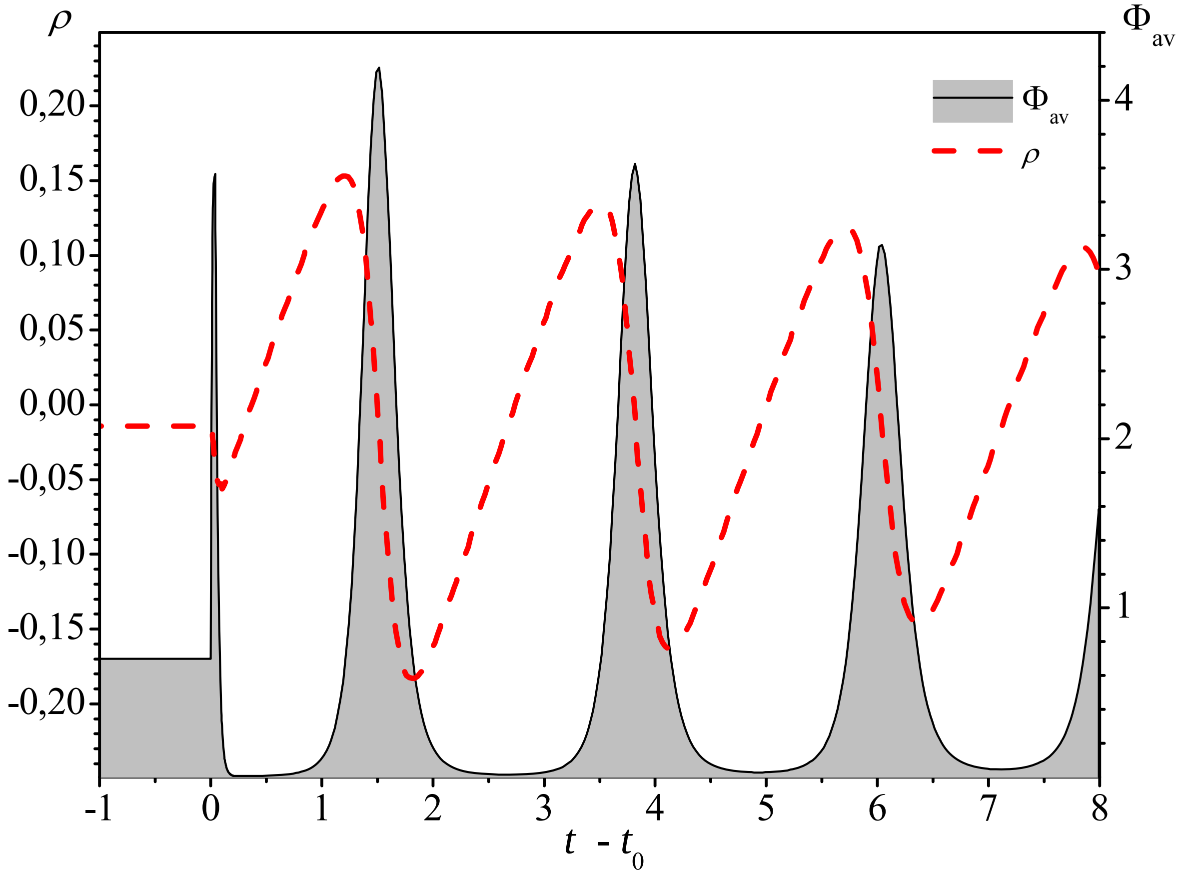



**τ ≈ 2.5 days**

Evolution of the volume-averaged neutron flux $F_{av}$ ($\times 10^{15}$ см$^{-2}$ c$^{-1}$) and concentrations $N_{av}$ ($\times 10^{17}$ 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.

## 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$^{-1}$)

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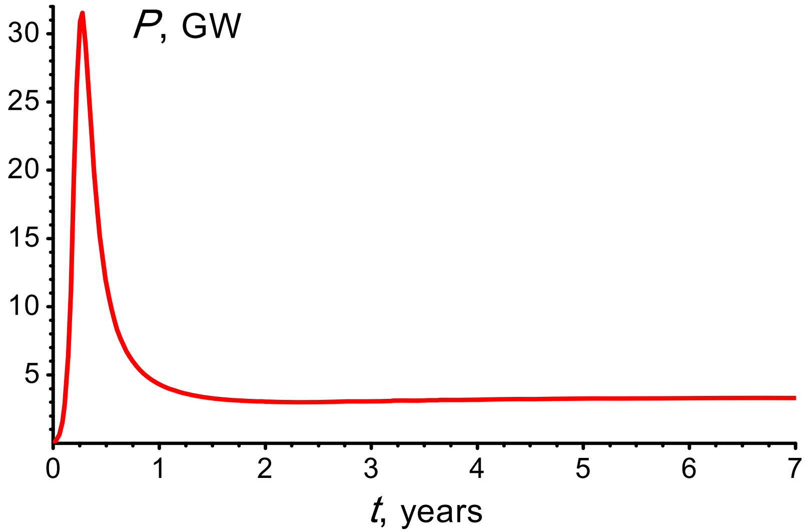
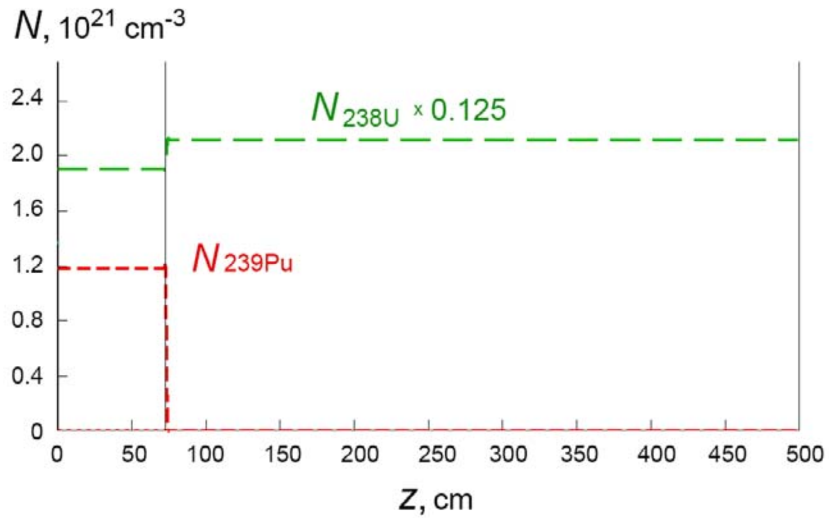
# Smooth Startup of the NBW Reactor

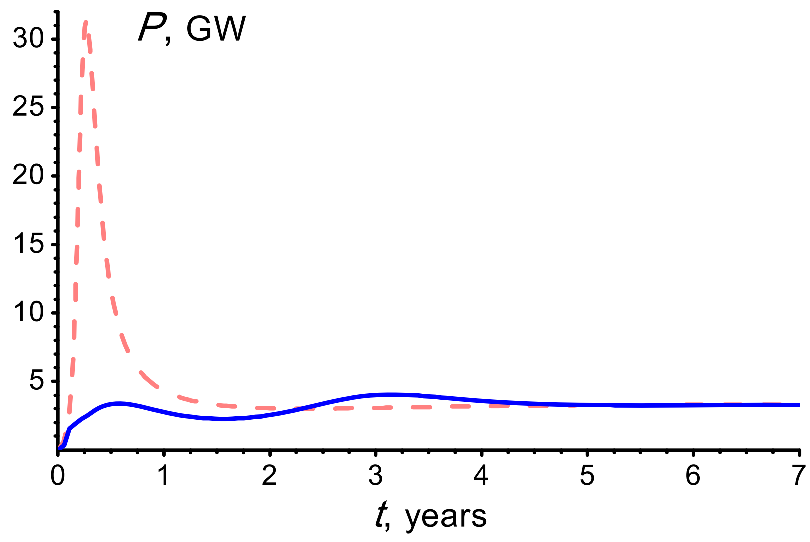
O. Fomin et al., *Journal of KNU, #104, «Nuclei, Particles, Fields», issue 2 /58/* (**2013**) 49-56.

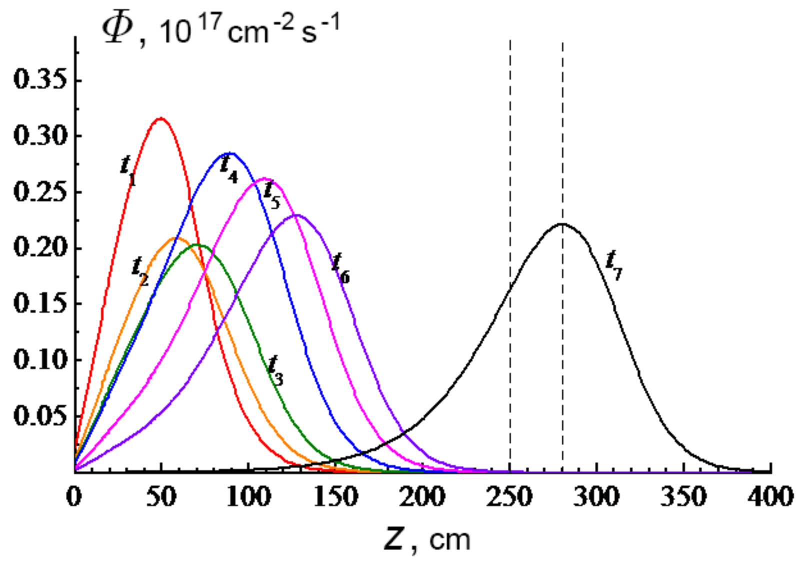


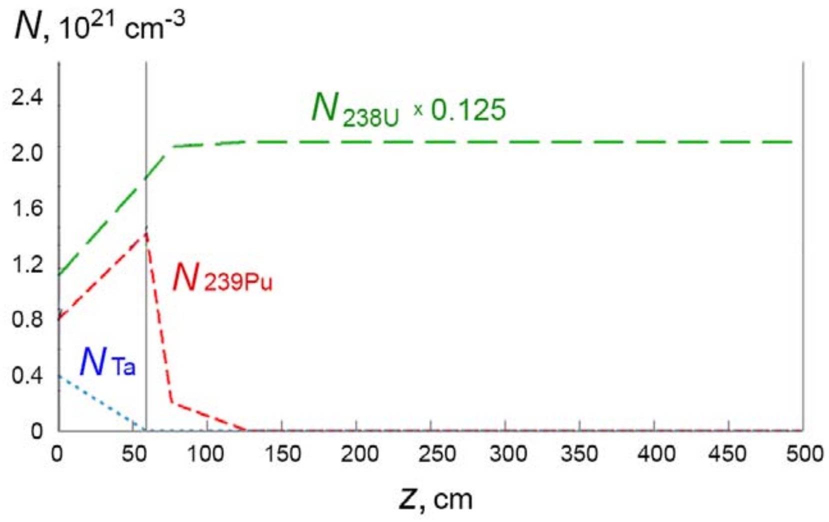



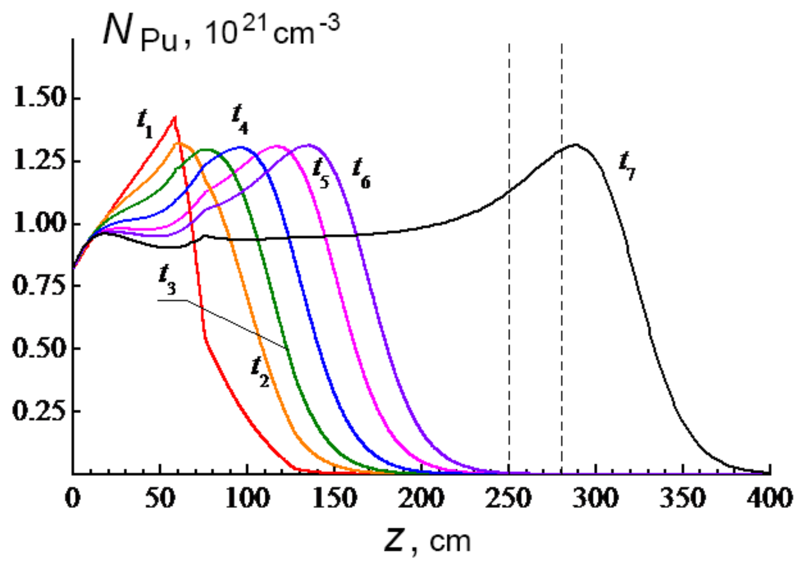
# Smooth Startup of the NBW Reactor

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



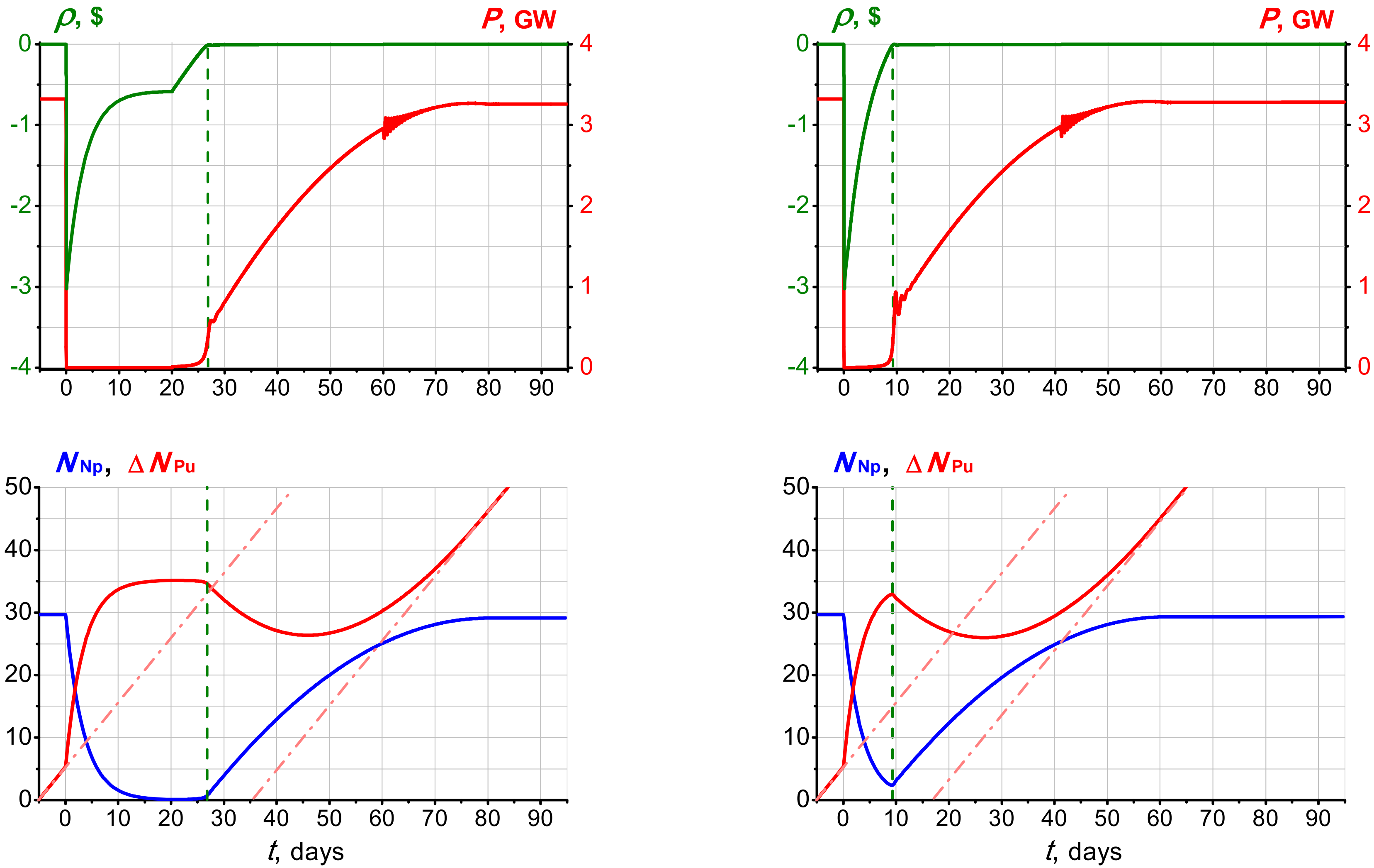



# Shutdown and Restart of the NBW Reactor

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



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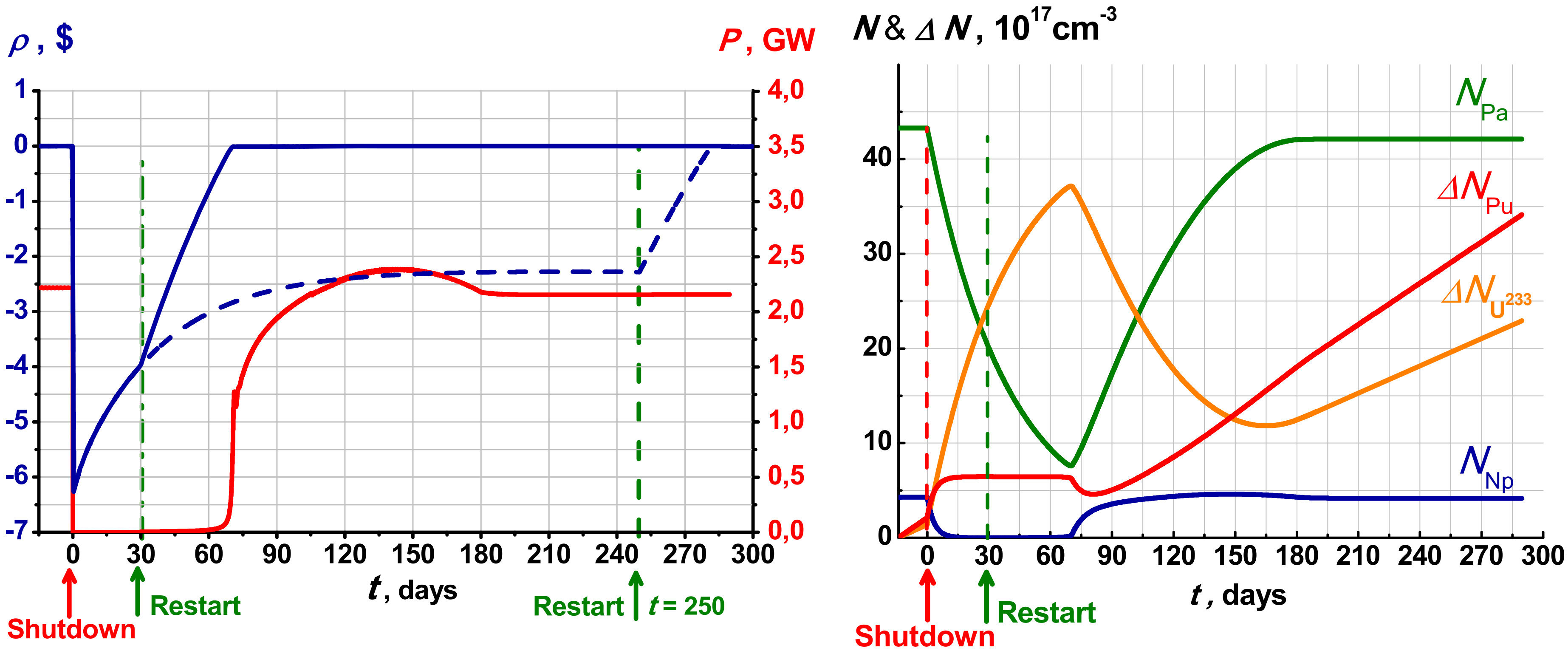
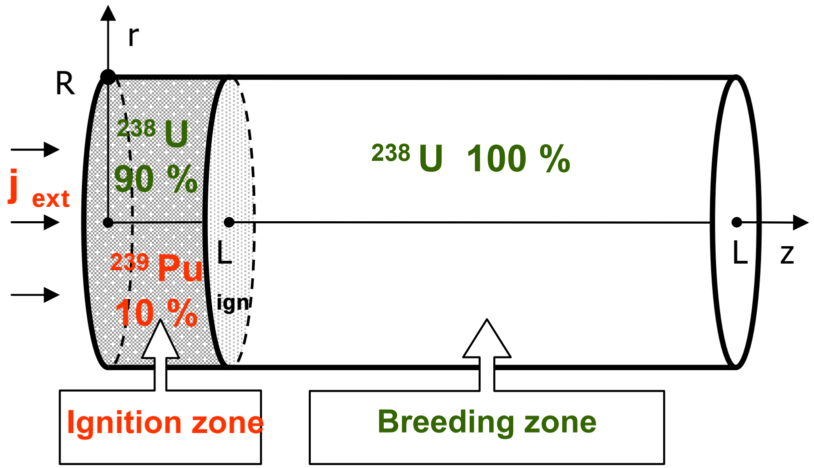
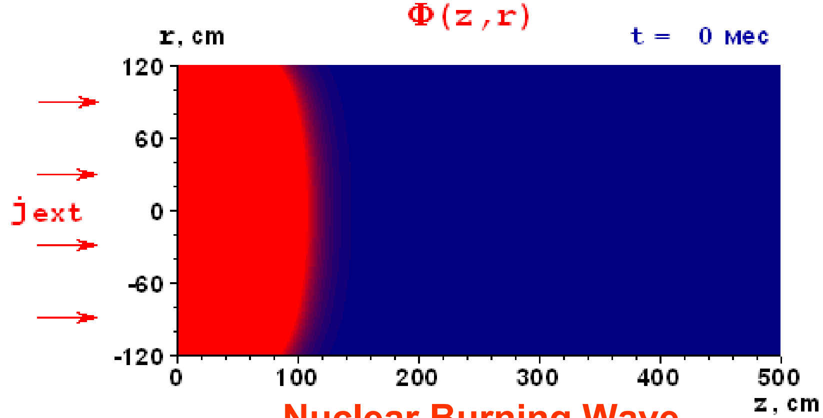


# 2D Non-Stationary Theory of Nuclear Burning Wave

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




Nuclear Burning Wave

## 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%)

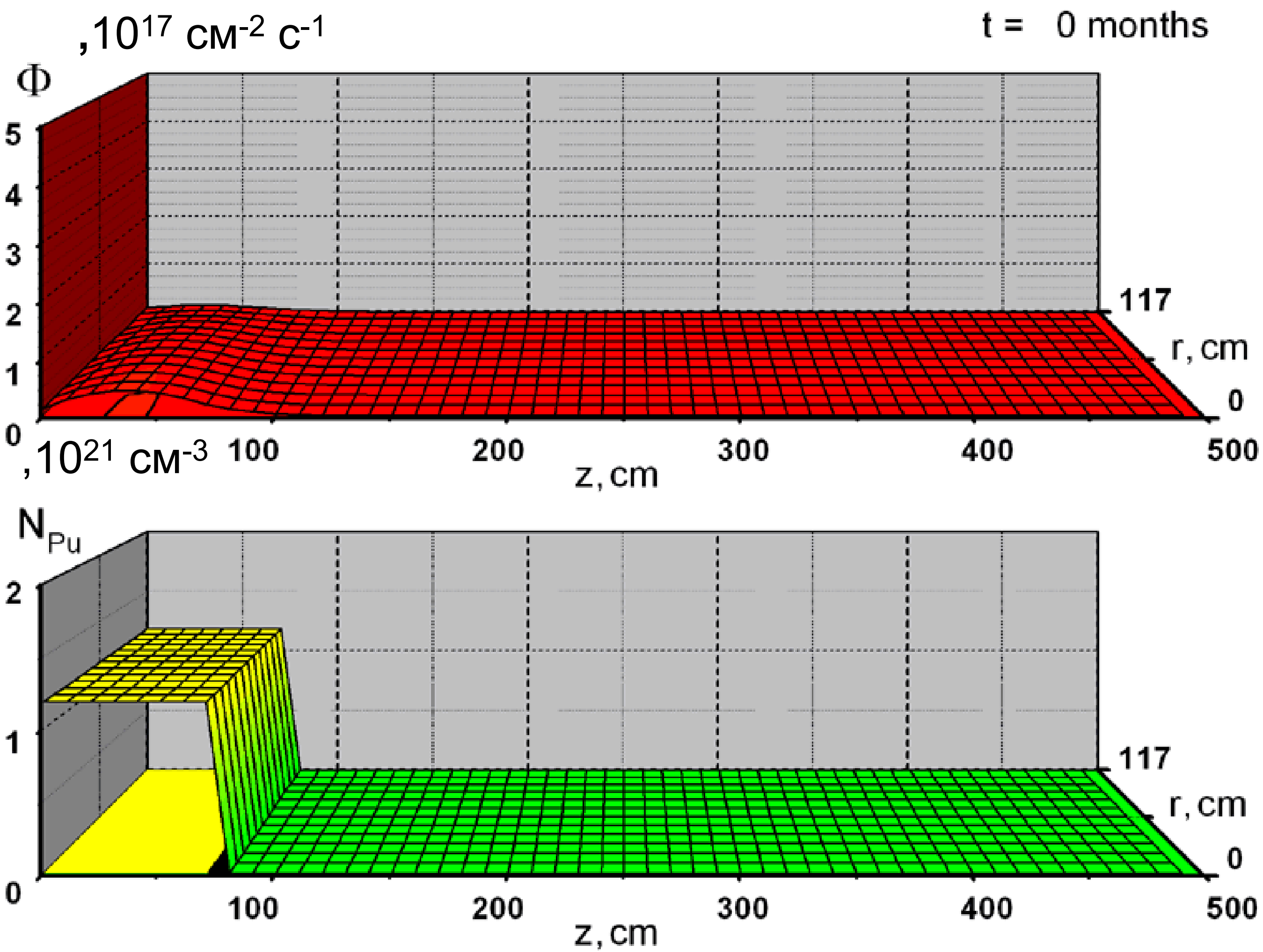
CM - Fe (20%)

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

$t_{off}$ = 400 days

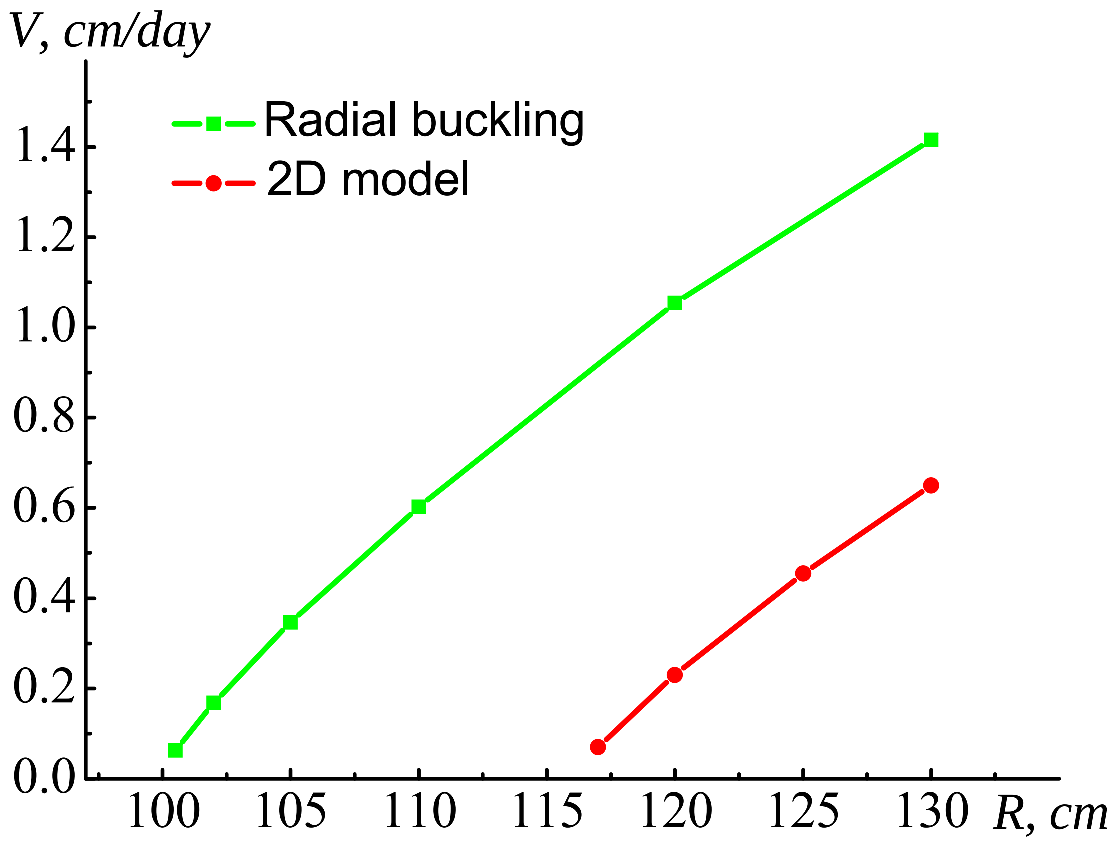
# NBW Reactor : R=117 cm, L = 500 cm , $t_{off}$ = 950 days

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



# Dependence of the NBW velocity *V* on the reactor radius *R*

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



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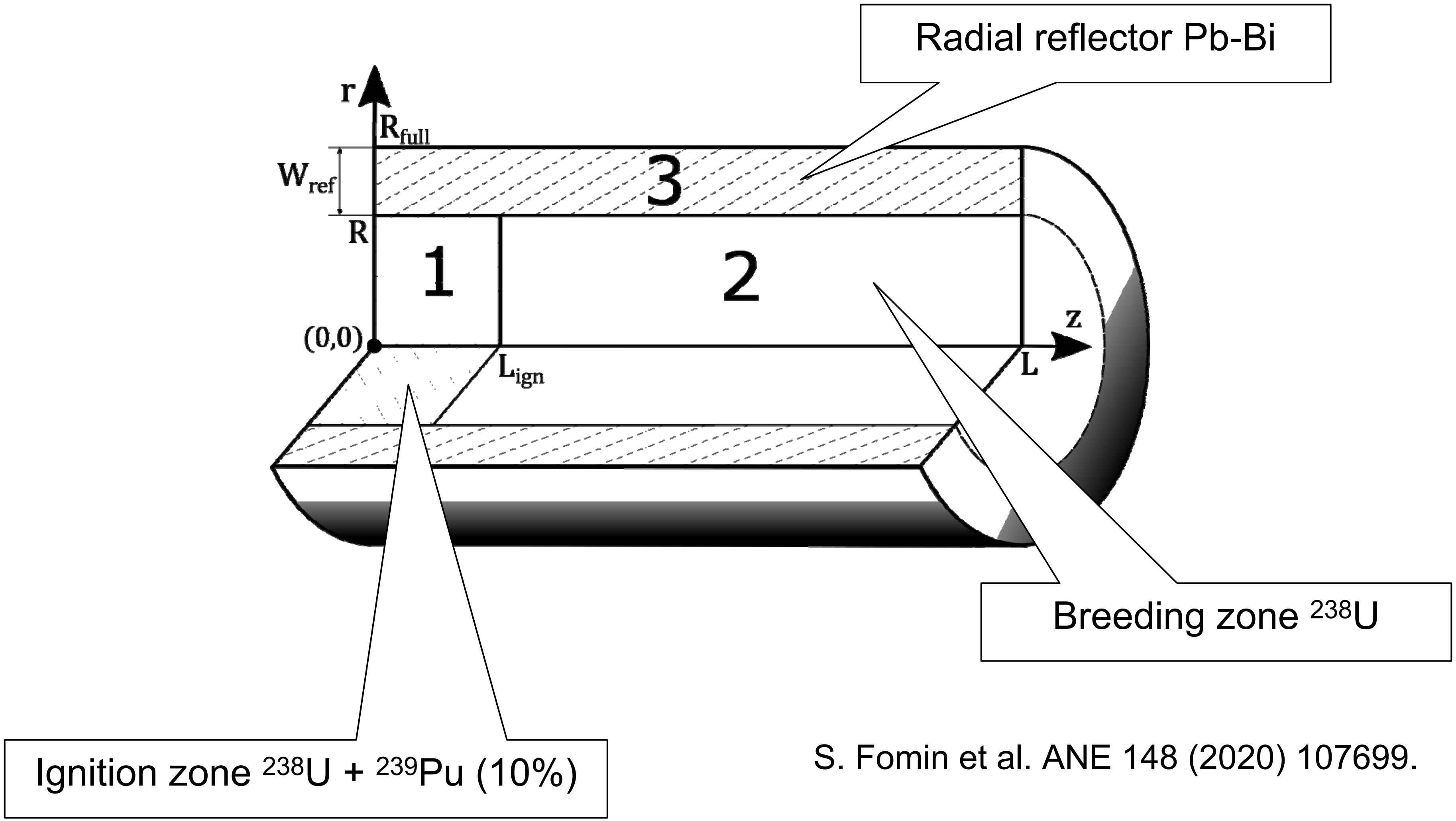
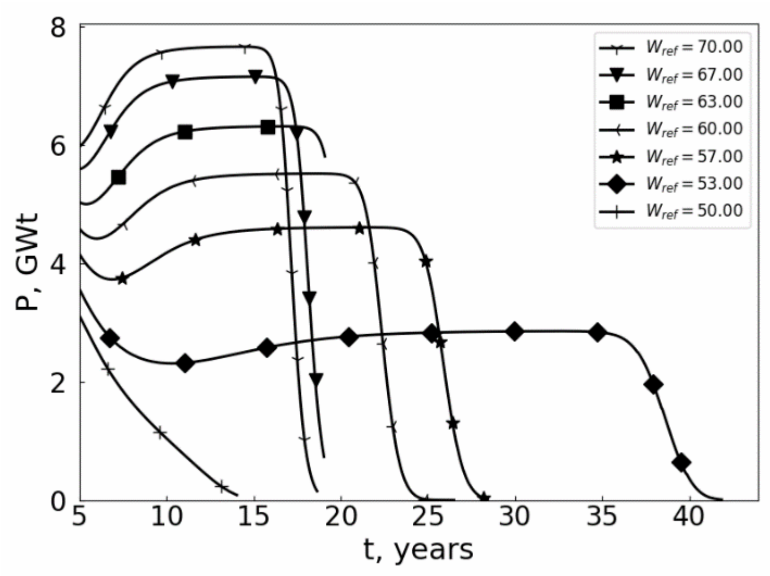
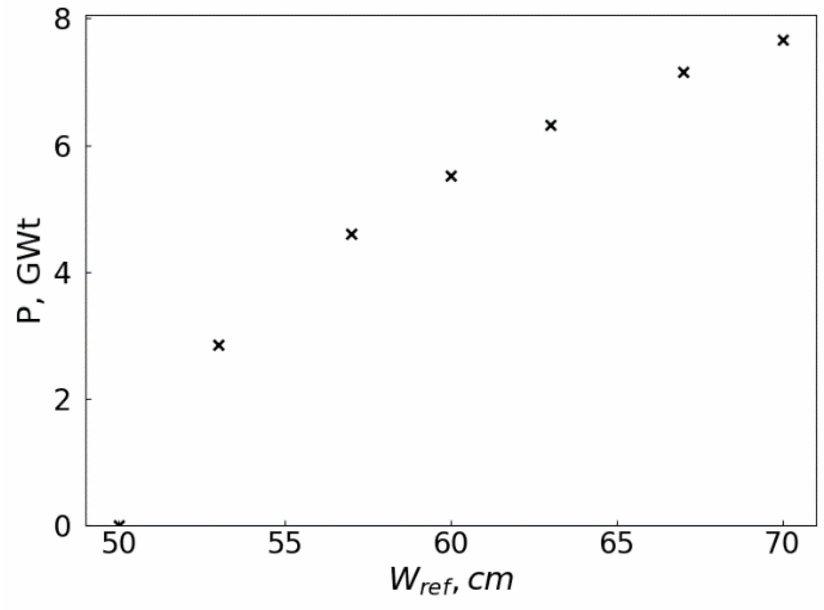
# 2D Non-Stationary Theory of Nuclear Burning Wave:
# The reflector effects study

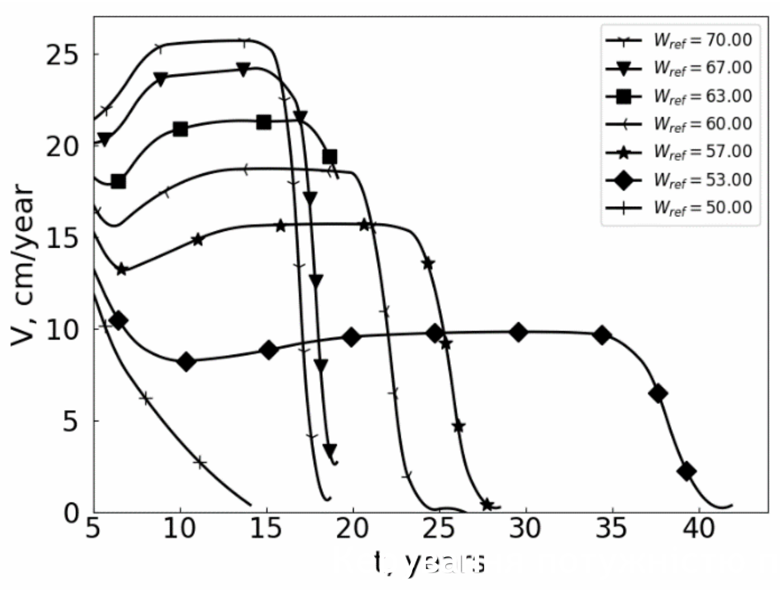



S. Fomin et al. ANE 148 (2020) 107699.

# NBW reactor power vs radial reflector thickness



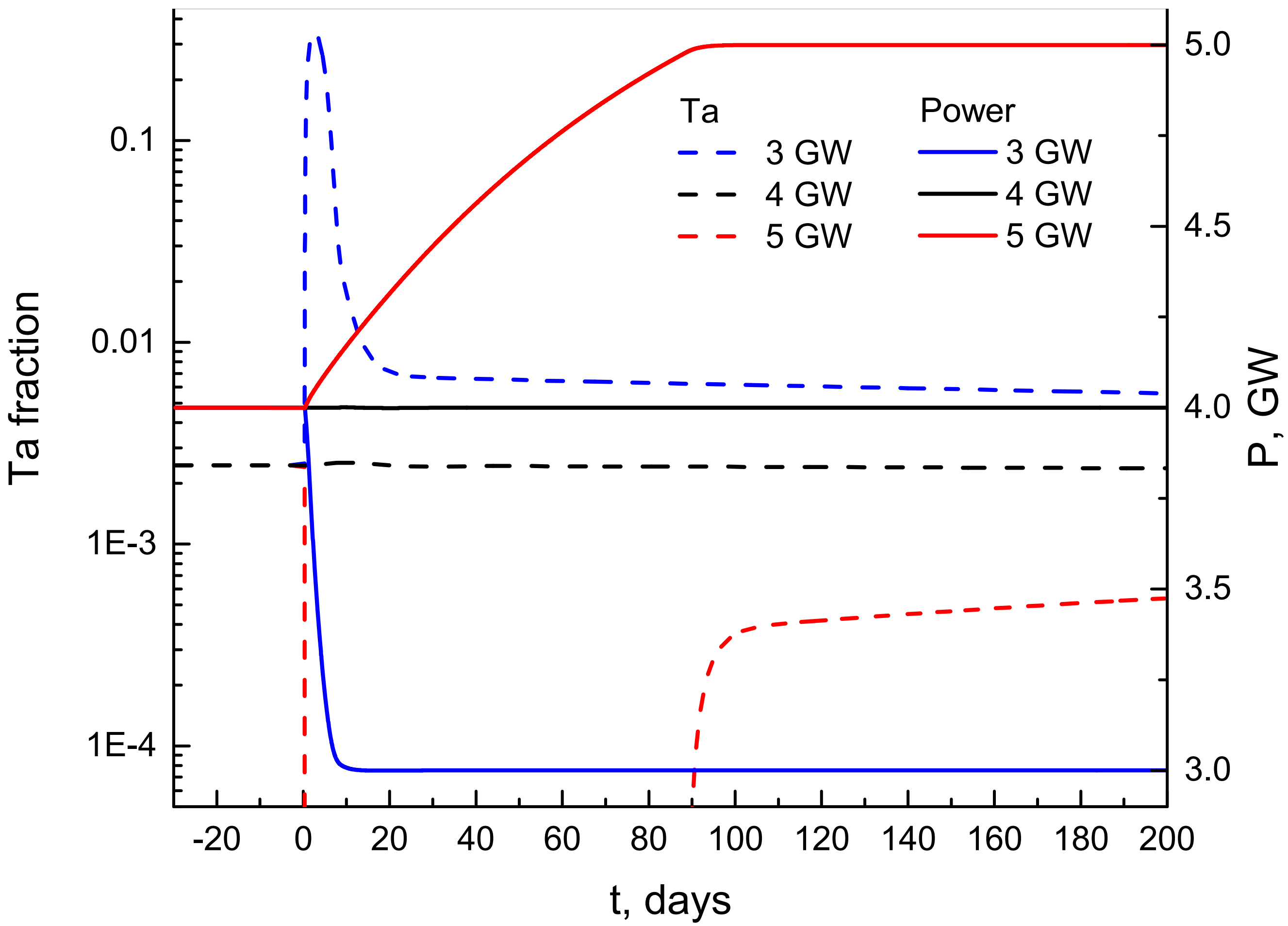




Malovytsia M.S., “Power control of an advanced fast reactor operating in a self-sustained Nuclear Burning Wave mode”, PhD thesis, 30 June 2021, Karazin Kharkiv National University, Kharkiv, Ukraine.

# The reflector effects study

Fomin S.P., et al. Annals of Nuclear Energy. 2020. Vol.148, p.107699.




Malovytsia M.S., PhD thesis, defense 30 June 2021, Kharkiv, Ukraine.

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# 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 :

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.

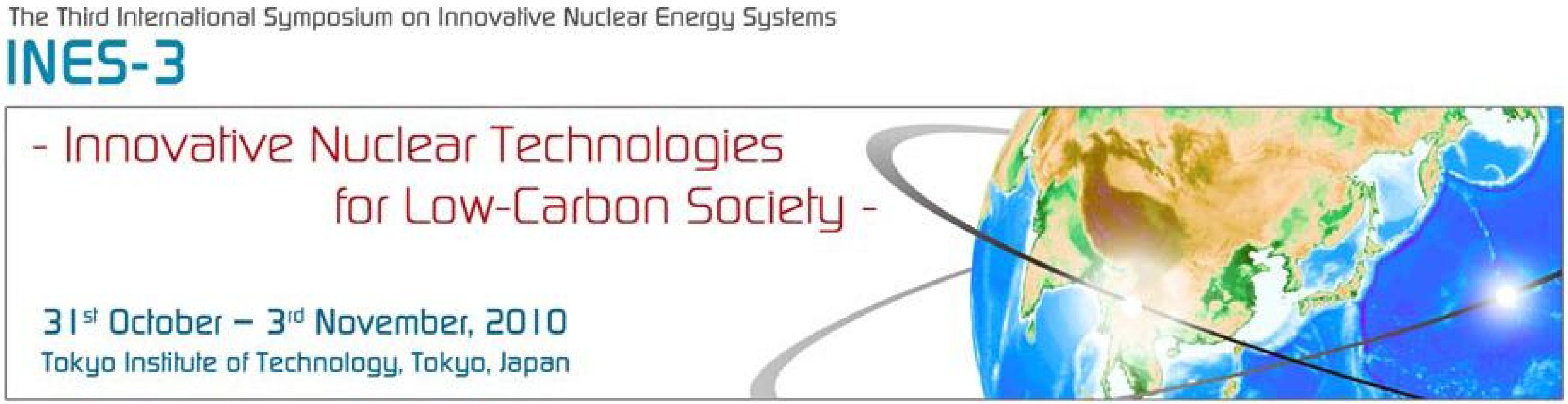
O. Fomin et al., *Journal of KNU, #104, «Nuclei, Particles, Fields», issue 2 /58/* (2013) 49-56.

*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.*

*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*




**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)**

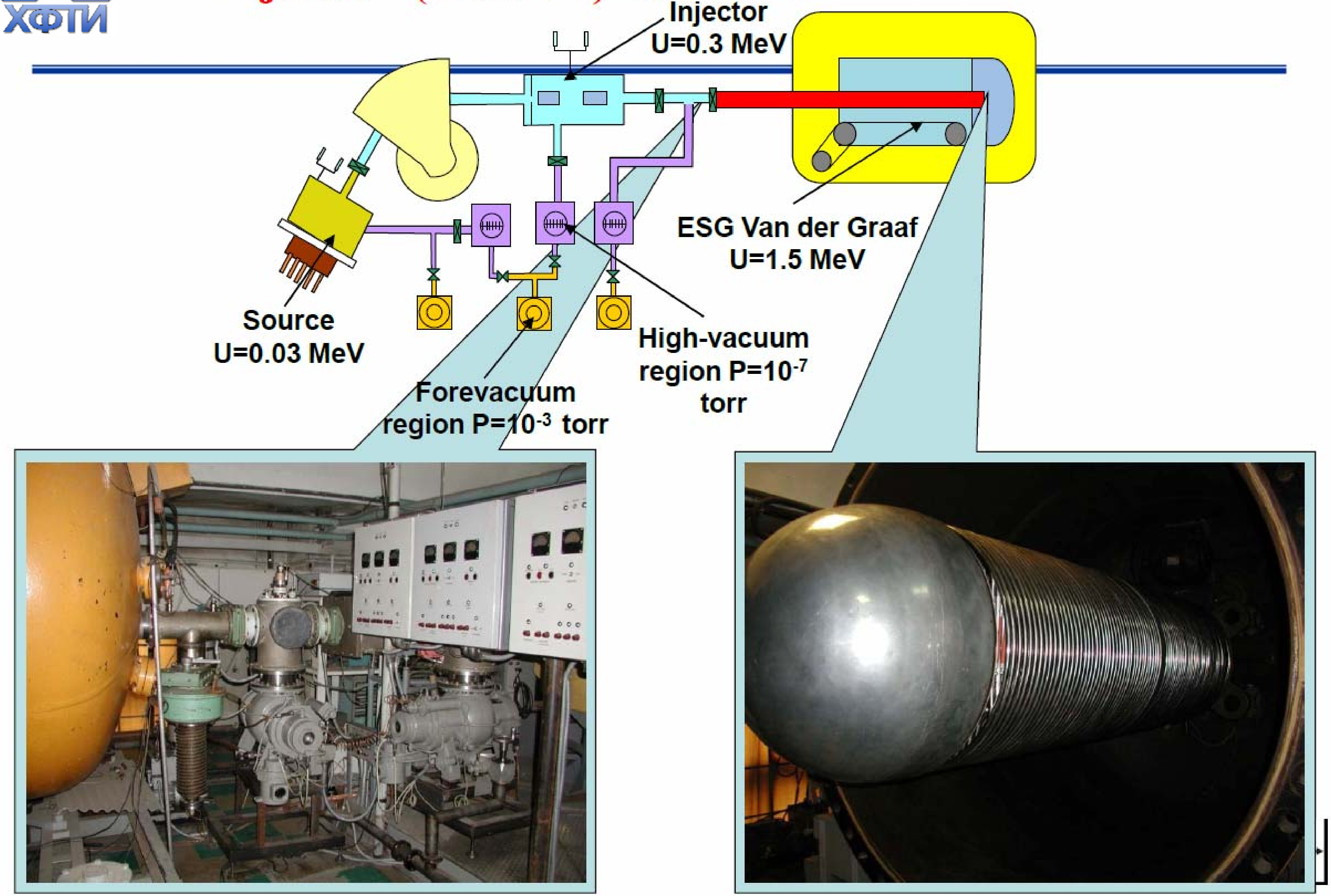
**1A-3: Thorium Fuel Reactors - Chair: Sergii Fomin (NSC KIPT, Ukraine)**

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

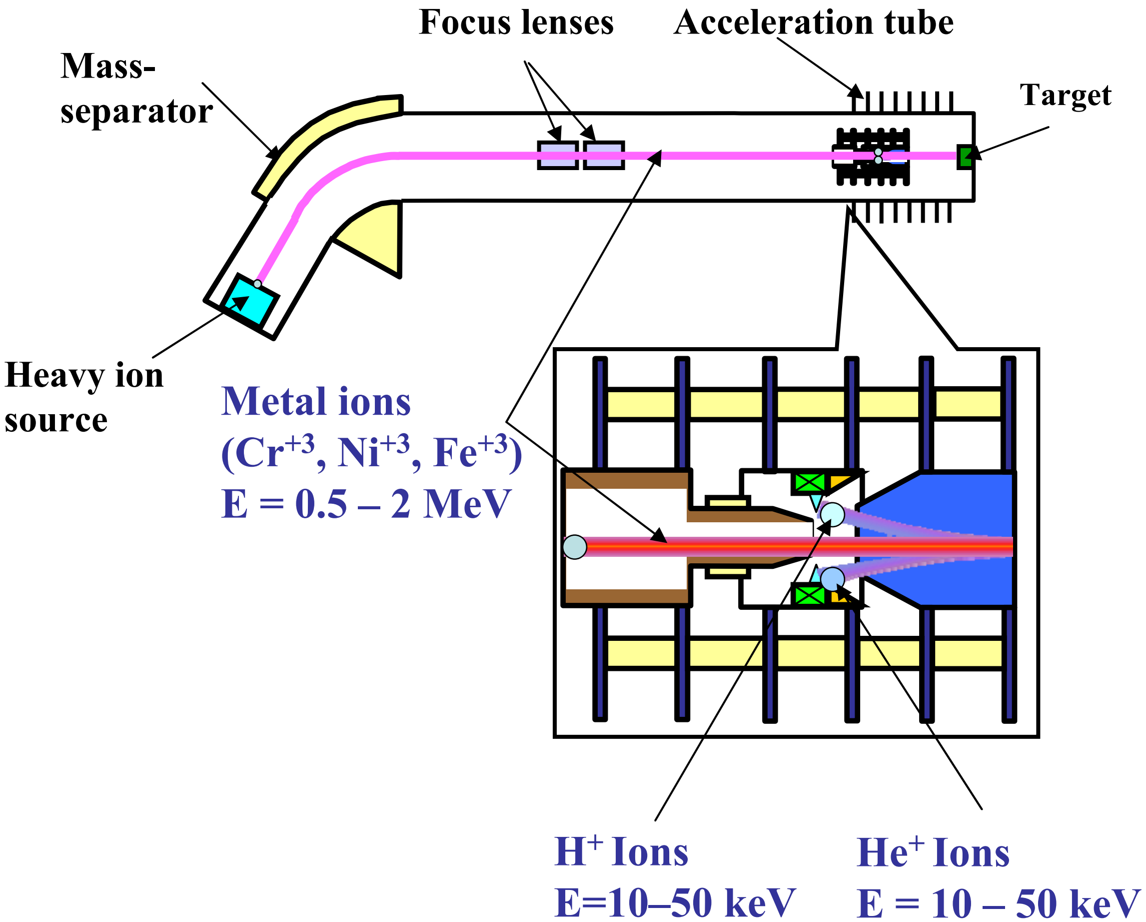
**Large Scale Utilization of Thorium in Gas Cooled Reactors - V. Jagannathan (Bhabha ARC, India)**

**. . .**

# Electrostatic Accelerator with External Injector (ESUVI) at KIPT



# ESUVI Accelerator: ion guide with hollow source of gas ions



# What was done in KIPT on swelling of steels

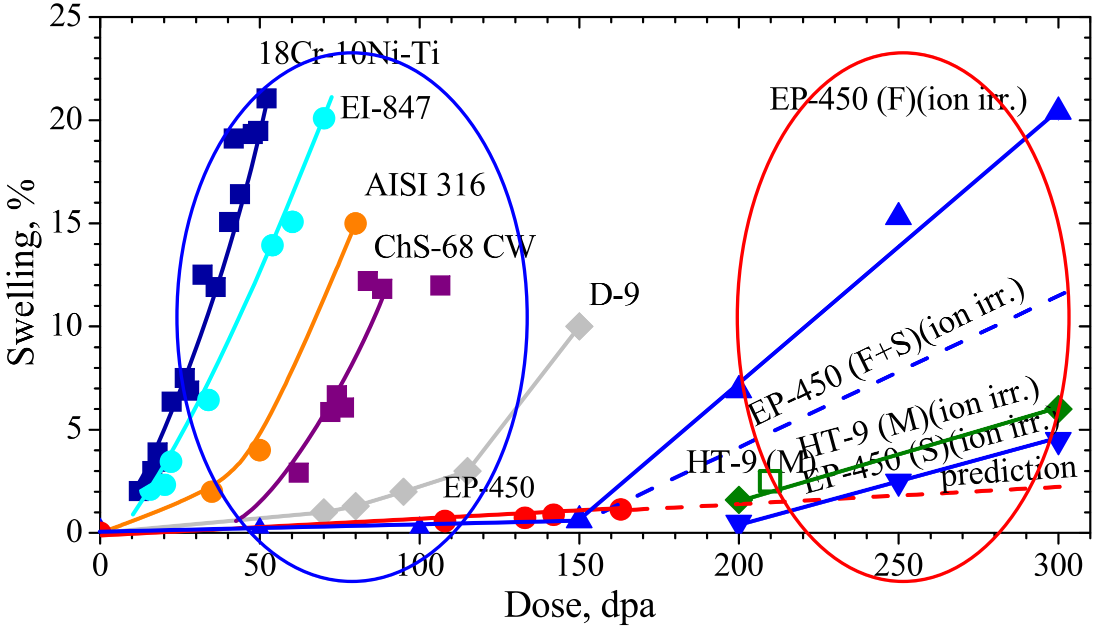
- Various nuclear concepts require low void swelling of structural materials at very high exposures (>200 dpa), high temperatures (700$^0$C) and at super high levels of helium and hydrogen:

**Fusion**: **He** – 300 appm/y, **H** - 800 appm/y

**ADS" Spallation": He** – 3500 appm/y, **H** - 4000 appm/y

- Due to high swelling of austenitic steels (life-limited by swelling to 150 dpa) the nuclear materials community has moved toward ferritic and ferritic/martensitic alloys.

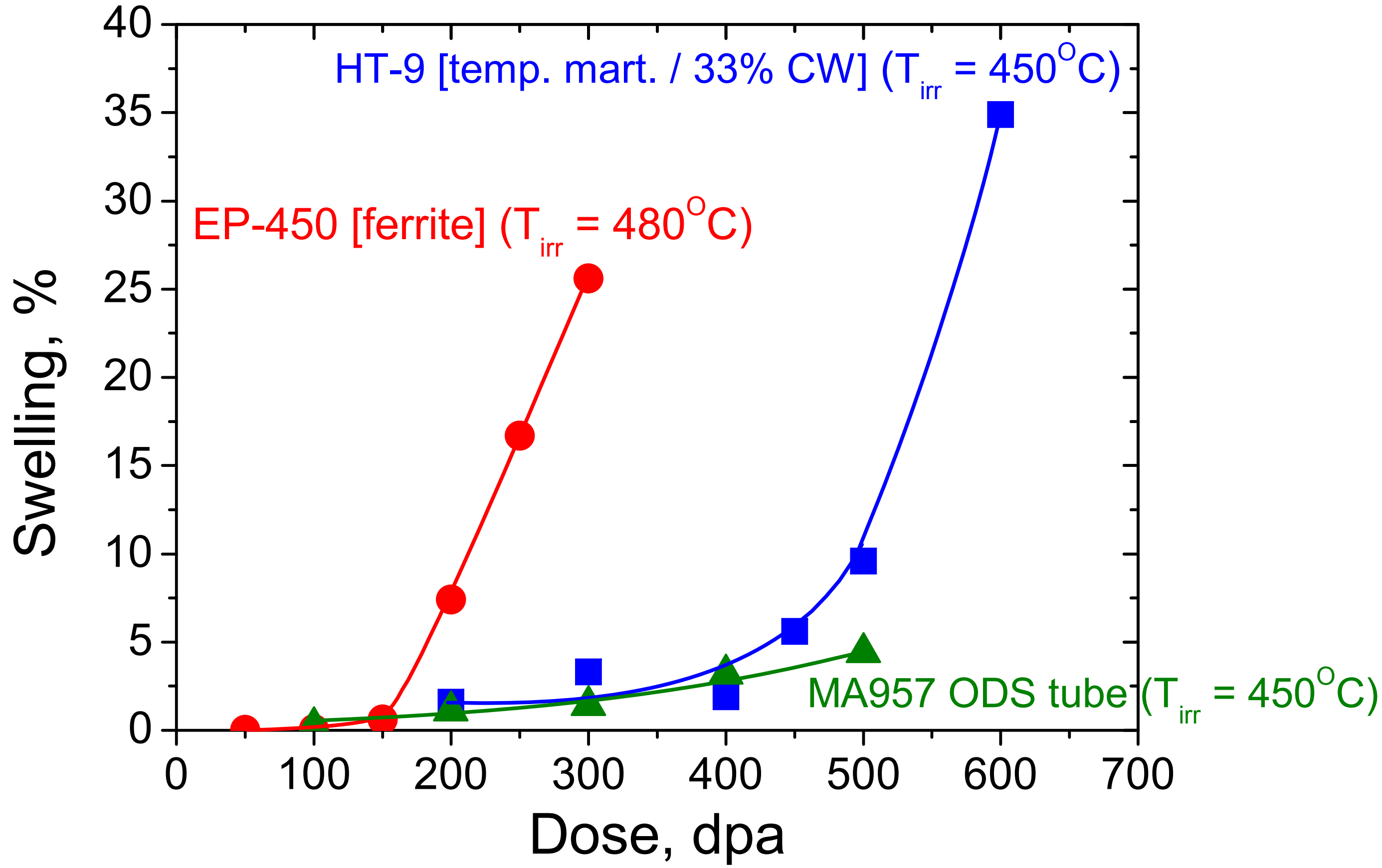
**Aus SS (Fe-Ni-Cr)** **F/M (Fe-Cr)**




Austenitic alloys were irradiated with ions about 25 years ago, but were not published in the West.

F/M alloys were irradiated in KIPT during several years.

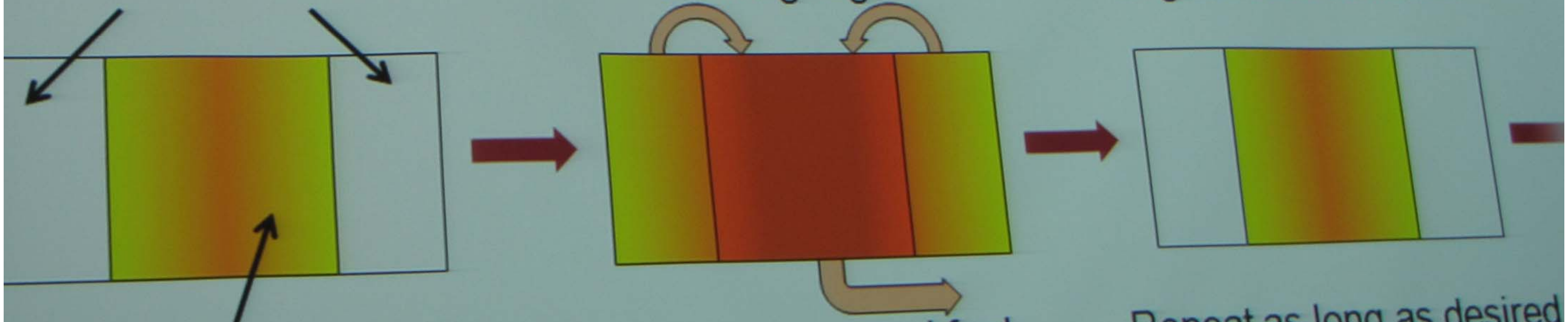
# Dose dependence of swelling of three ferritic-martensitic steels




**Denuded zone effect in very narrow grains depresses the overall swelling somewhat.** (ODS - Oxide dispersion-strengthened)

# 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

# TP-1 Design Parameters

| | |
|---|---|
| Power Level | 1200 $MW_{th}$ / 500 $MW_e$ |
| Operating Temperatures | 360°C / 510°C |
| Availability | 90% average over 5 yr period |
| Minimum Lifetime | 40 years |
| Fuel Type | U-Zr alloy pins in HT-9 clad (130 MTU core) |
| Primary Pumps | Mechanical (2) |
| Intermediate Heat Exchanger | Printed Circuit (4) |

02/11/20