Challenging Safe Fast Reactor Based on a Nuclear Burning Wave

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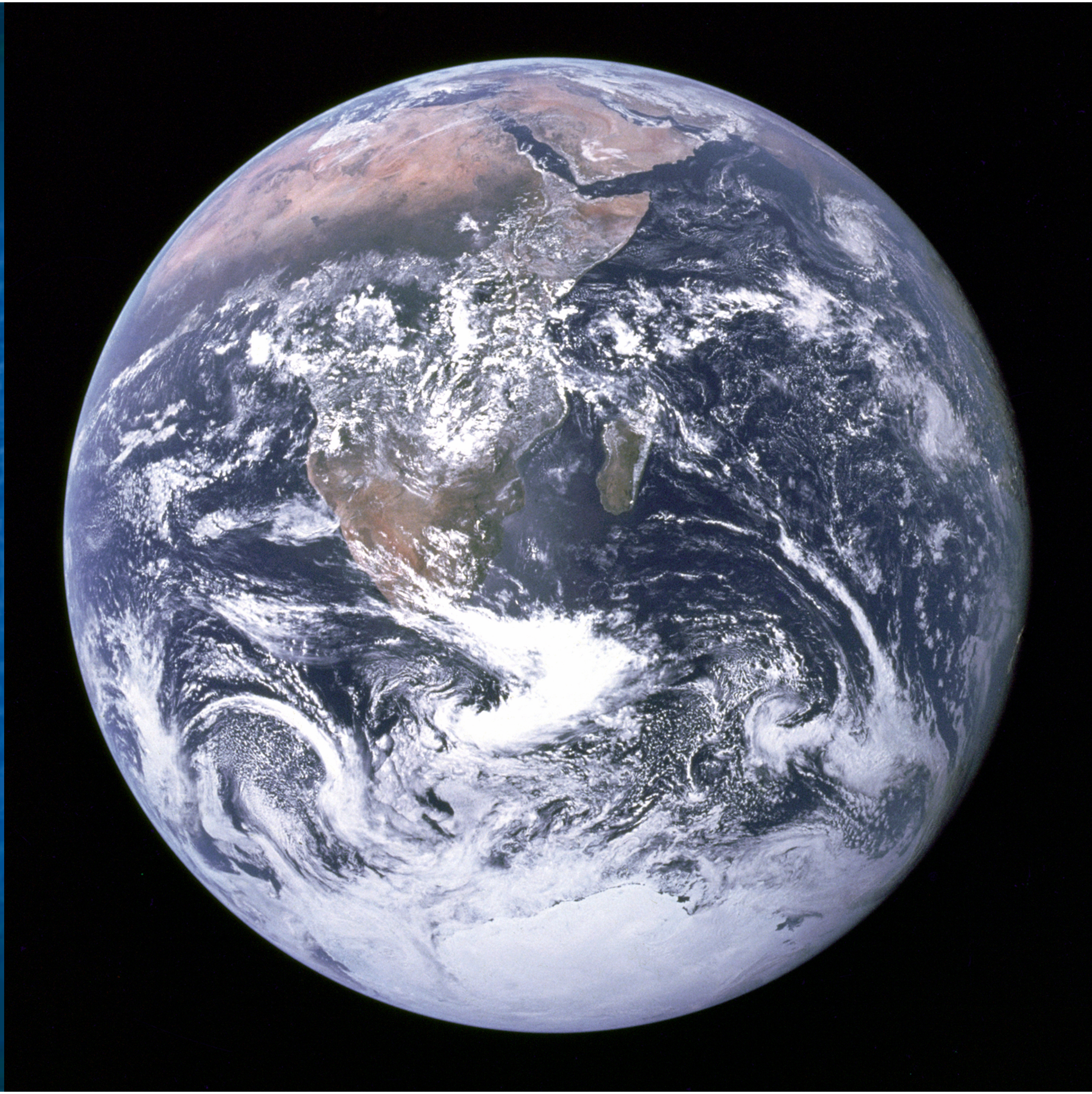
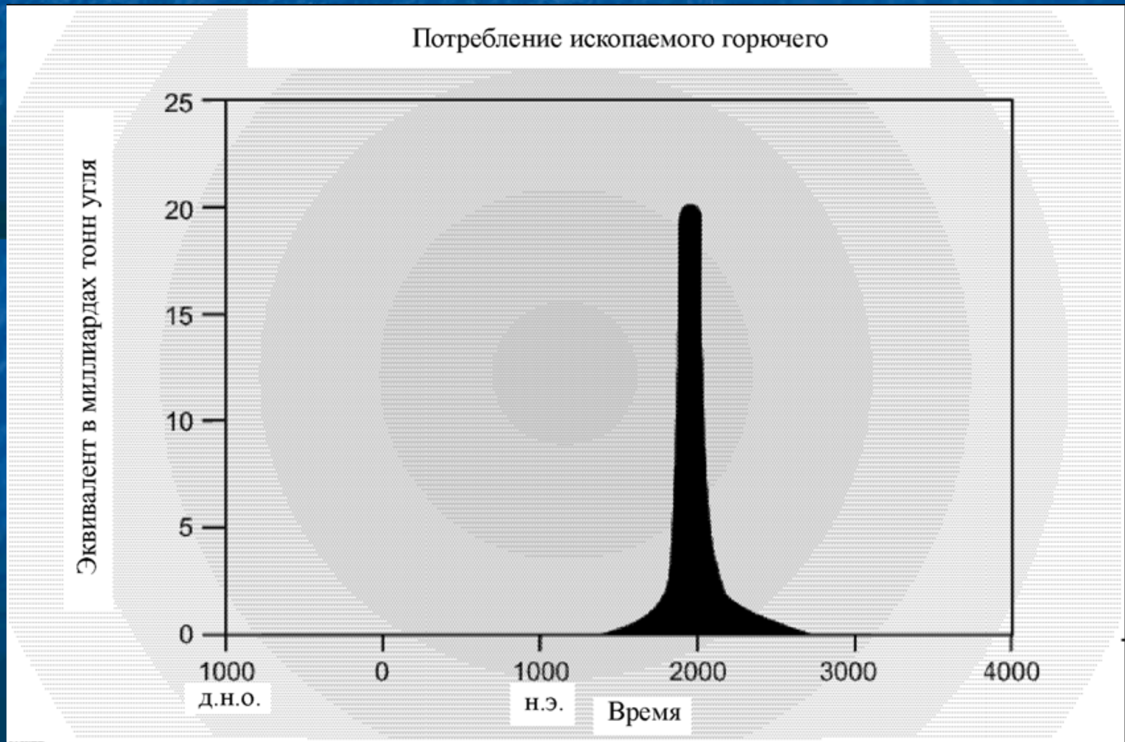
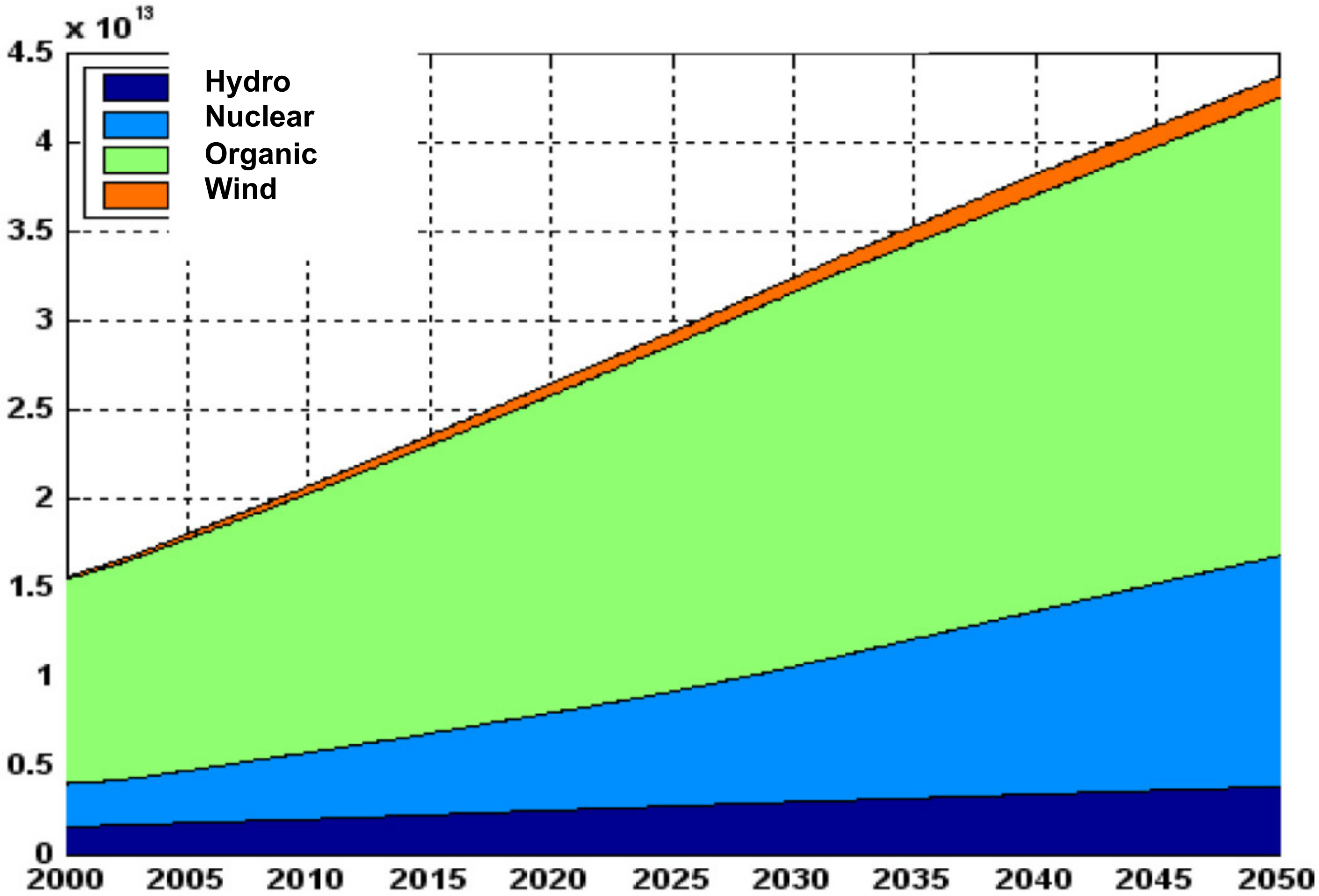


Organic Fuel Consumption



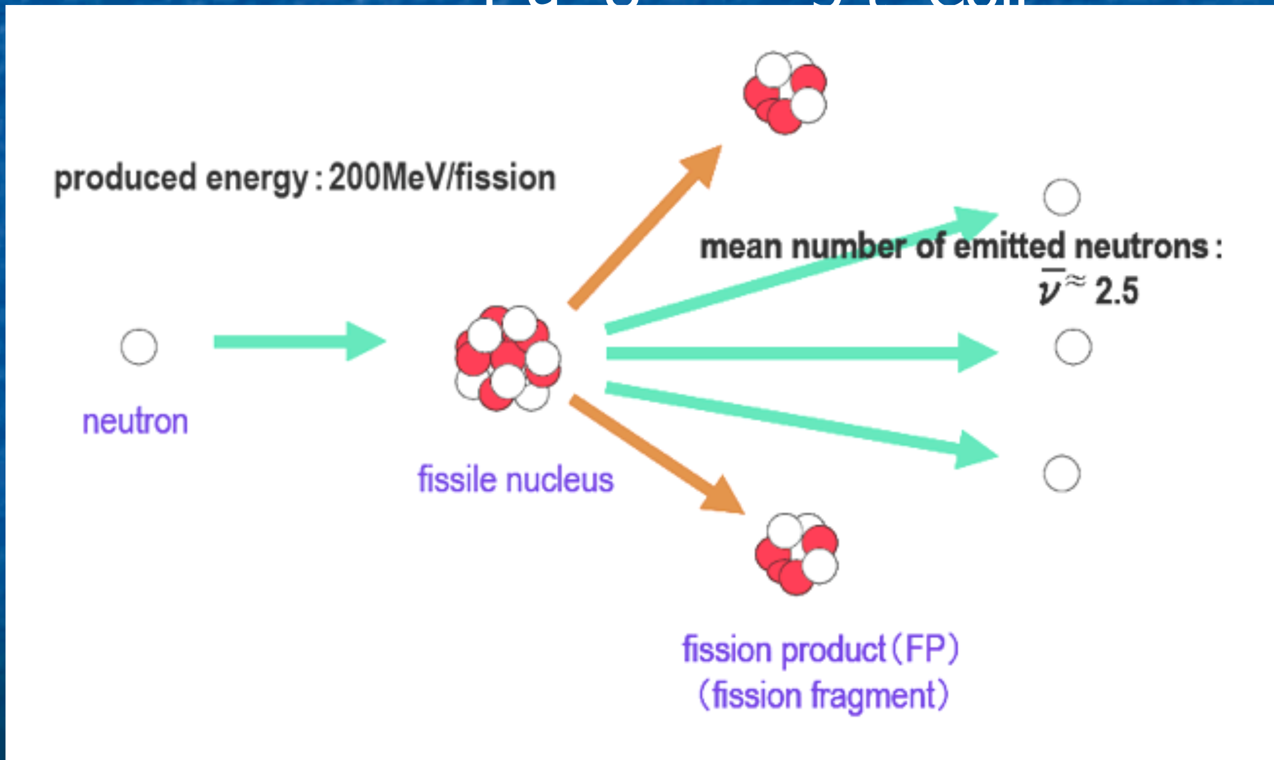
Dynamics of Electricity Production (forecast of IEA & Nuclear)



Nuclear Energy

- Chemical reactions ~ 1 eV (C + O_2 = C O_2)
- Nuclear reactions ~ 100 MeV (10^8 times)

1 g U ~ 5 t Coil



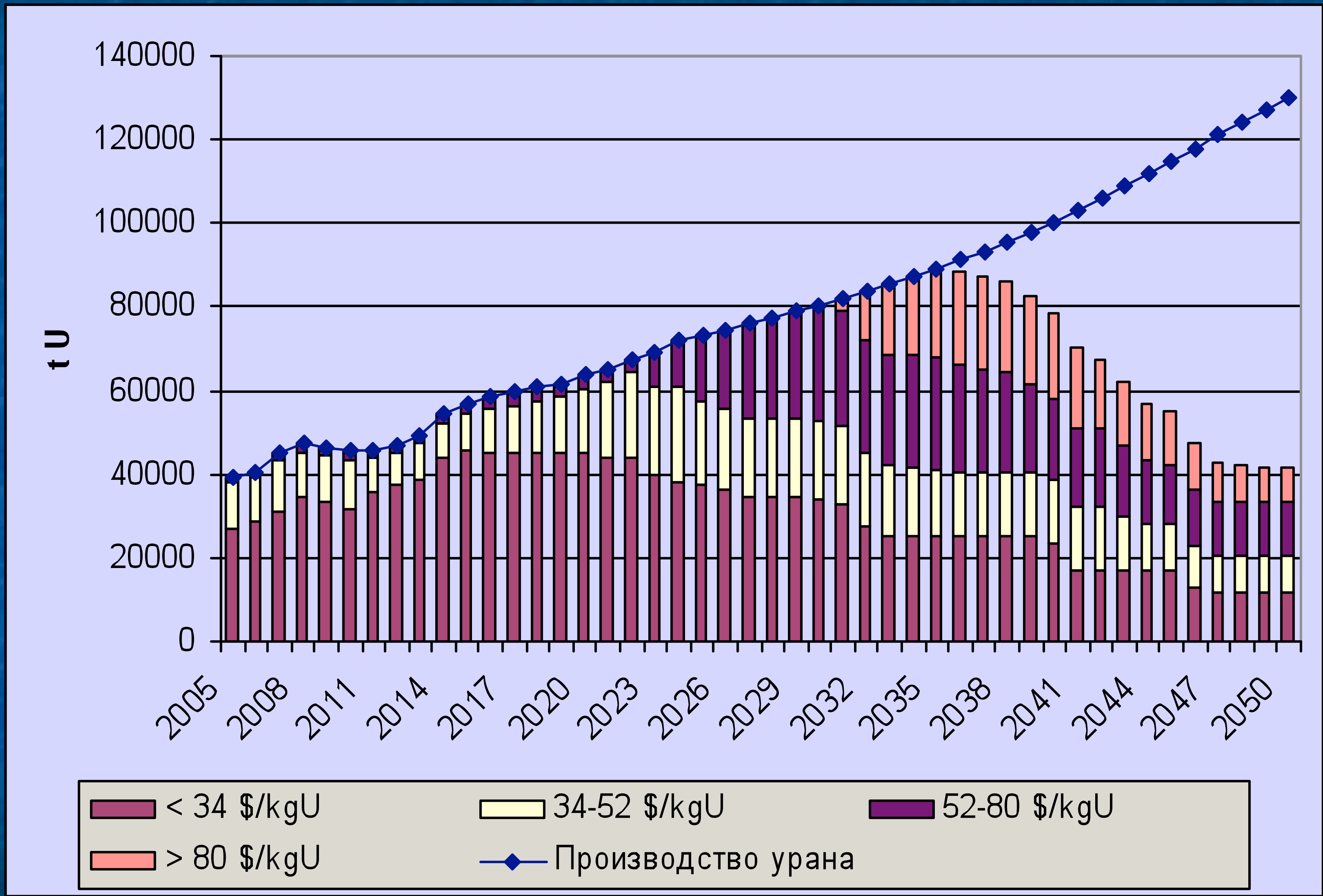
k_{eff} =1 !!!

Nuclear Power Problems

- Safety (after Chernobyl accident)
- Closed fuel cycle (fuel reproduction)
- Ecology problems (nuclear waste)
- Nuclear terrorism

A-Bomb House, Hiroshima

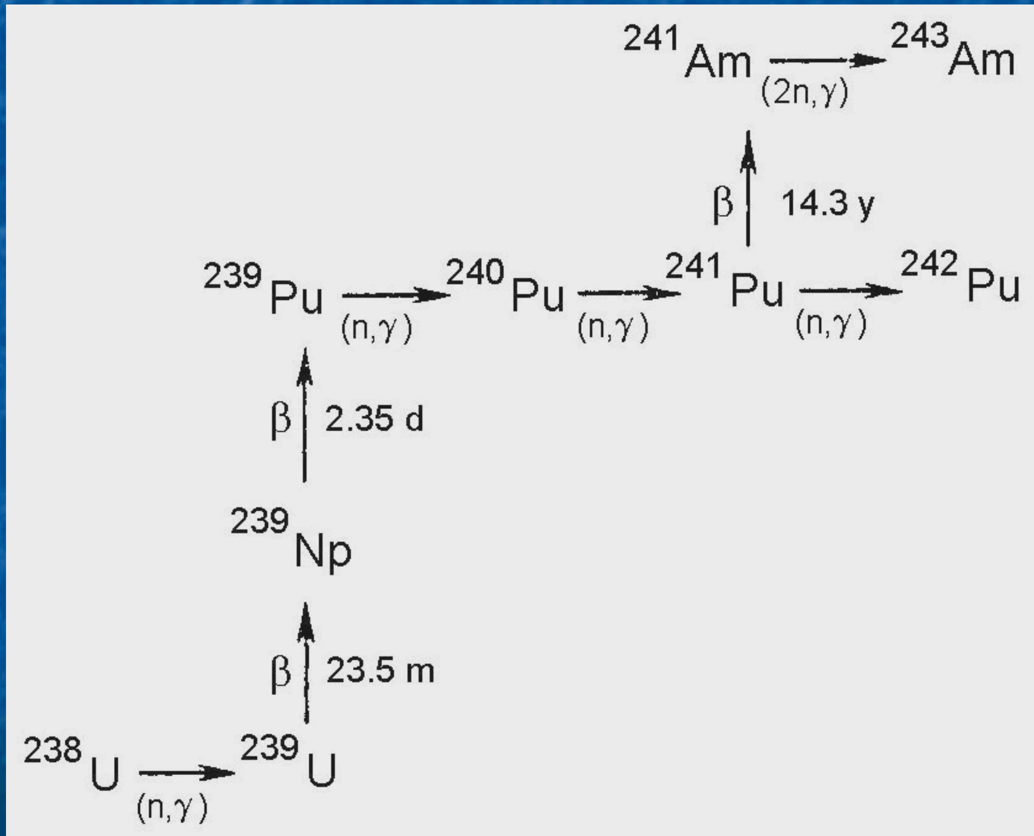
Explored reserves of Uranium



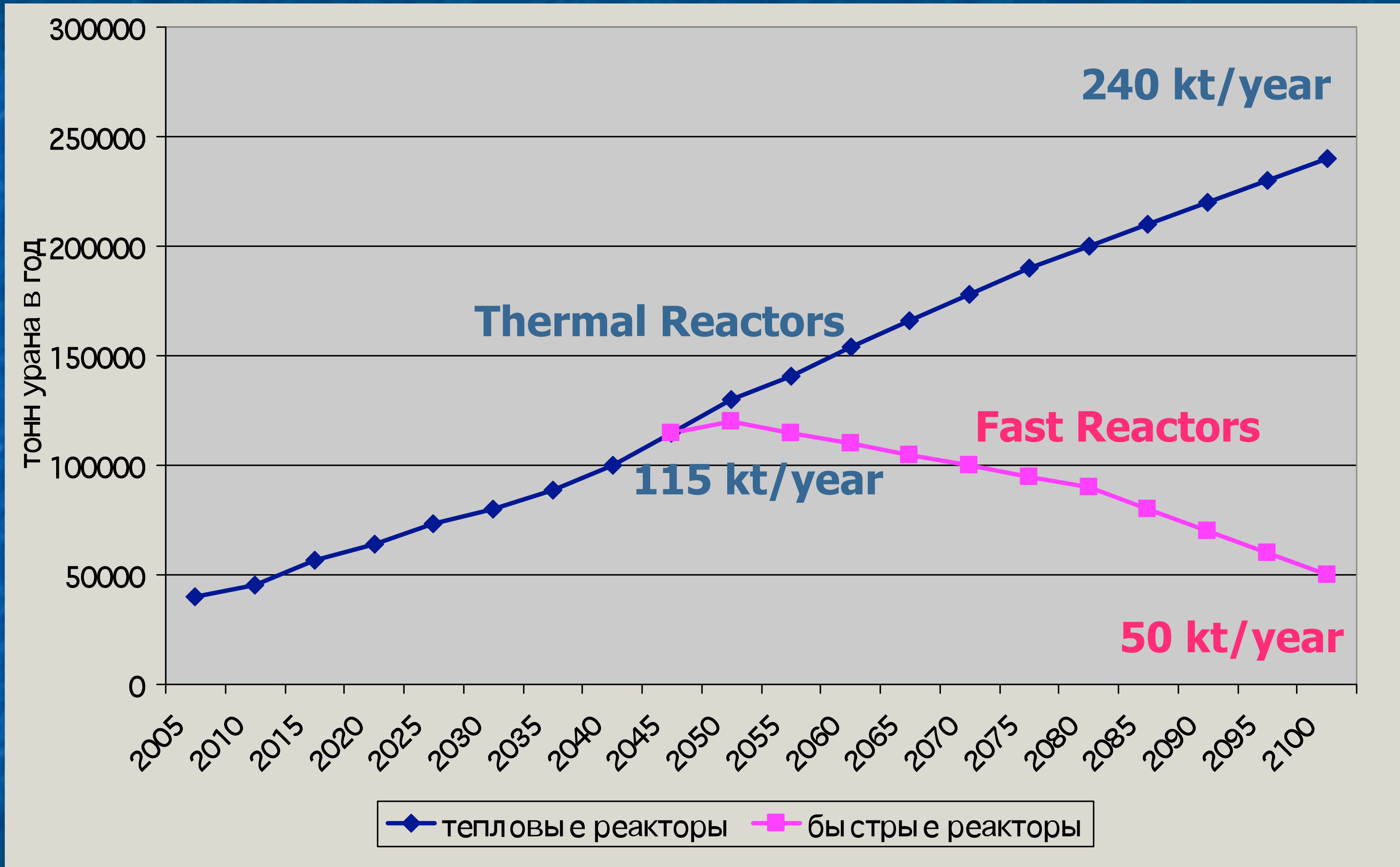
Breeding process in FR:

$$^{238}U + n \rightarrow {}^{239}U \xrightarrow{\beta-} {}^{239}Np \xrightarrow{\beta-} {}^{239}Pu$$

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

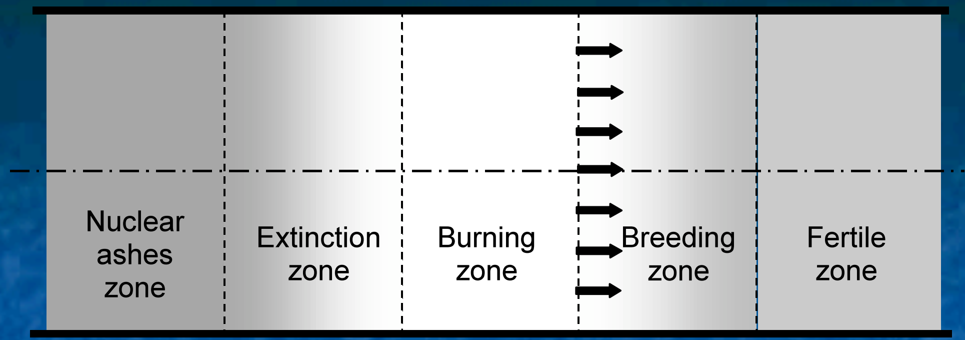


World needs for Uranium (forecast till 2100)



L. P. Feoktistov (1988):

Nuclear Burning Wave



L.P. Feoktistov, 1988. An analysis of a concept of a physically safe reactor. Preprint IAE-4605/4.
L.P. Feoktistov, 1989. Neutron-fissioning wave. Dokl. Akad. Nauk SSSR. 309, 864.

$^{238}U\ (n,\gamma) \rightarrow {}^{239}U\ (\beta) \rightarrow {}^{239}Pu\ (n,\text{fission})\ \ldots$

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

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

$$\frac{\partial N_8}{\partial t} = -vn\sigma_{a8}N_8$$

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

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

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

$$x = z + Vt$$

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

History

1988 - Russia:

L.P. Feoktistov, An analysis of a concept of a physically safe reactor. Preprint IAE-4605/4, 1988.
L.P. Feoktistov, Neutron-fissioning wave. Dokl. Akad. Nauk SSSR. 309 (1989) 864.

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E. Teller, M. Ishikawa, L. Wood, R. Hyde, J. Nuckolls, ICENES-1996, Obninsk, Russia.
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H. Sekimoto, K. Ryu, A new reactor burnup concept “CANDLE”. PHYSOR-2000, Pittsburgh.
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H. Sekimoto, Light a CANDLE. Tokyo Institute of Technology. 2005, 47p.

2000 - Holland Hugo van Dam, Annals of Nuclear Energy, 27 (2000) 1505; 30 (2003) 1495.

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A.I. Akhiezer, N.A. Khizhnyak, N.F. Shulga, V.V. Pilipenko, L.N. Davydov,. PAST, 6 (2001) 272; 276; 279.
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S. Fomin, Yu. Mel’nik, V. Pilipenko, N. Shul’ga, Annals of Nuclear Energy, 32 (2005) 1435.
Nucl. Sci. & Safety in Europe, Springer, 2006, p. 239. : Progress in Nuclear Energy, 50 (2008) 163.
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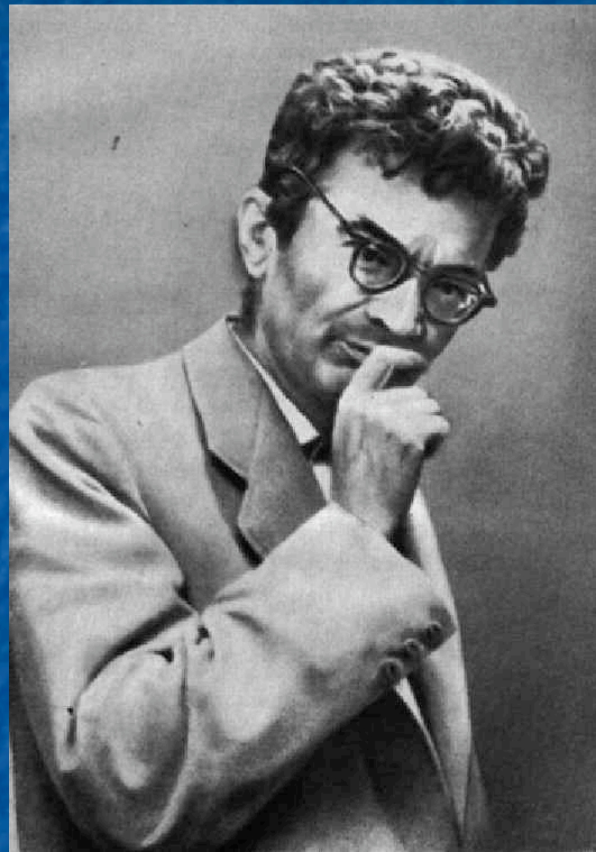
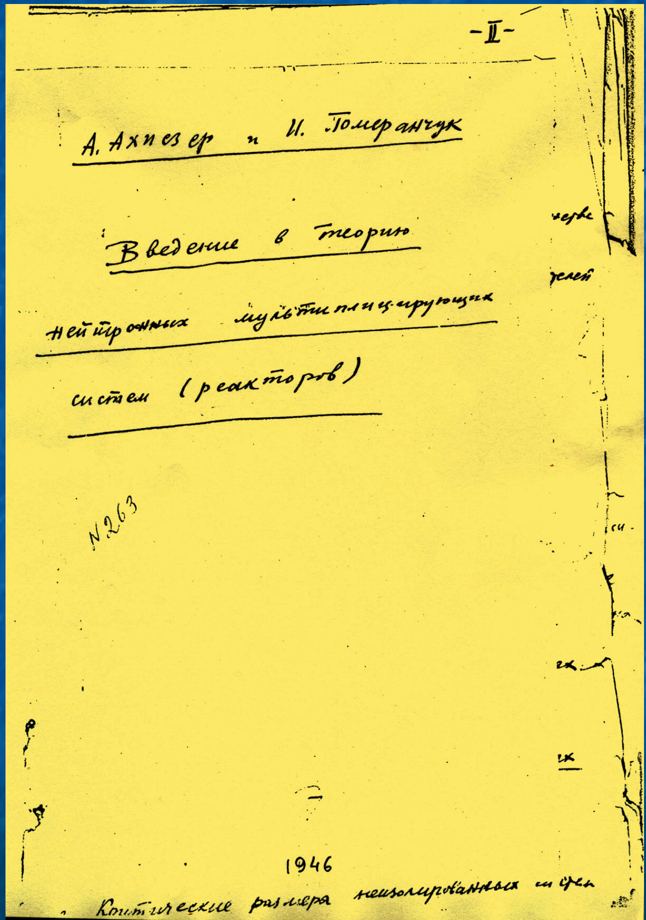
1946 Kharkov - UPhTI (Lab #1)

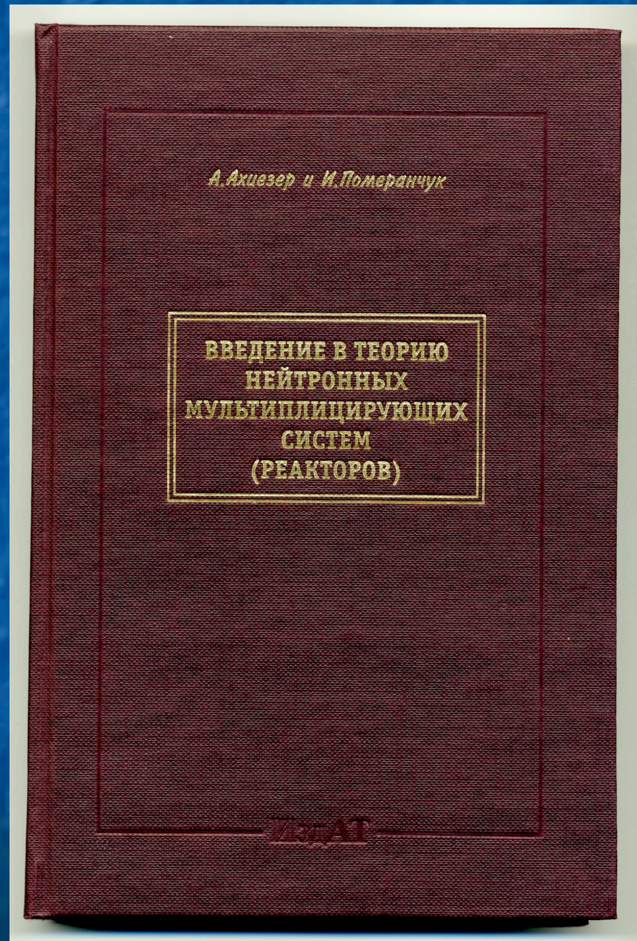
A.I. Akhiezer



I.Ya. Pomeranchuk

1946 - 2001

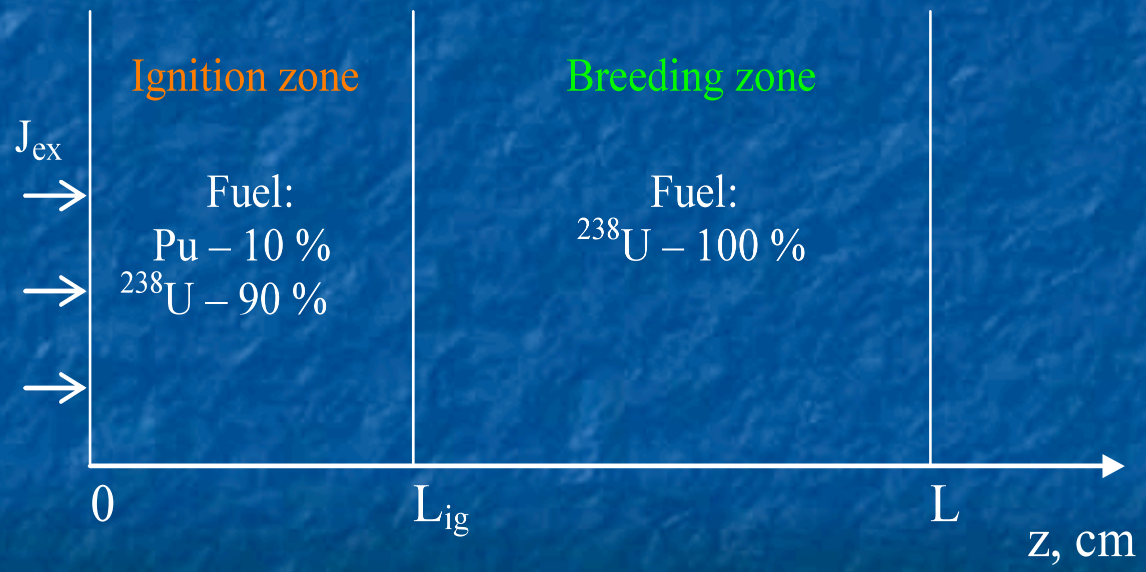

-II-
А. Ахиезер и И. Померанчук
Введение в теорию нейтронных мультиплицирующих систем (реакторов)
N263
1946
Критические размеры неизолированных систем


А.Ахиезер и И.Померанчук
ВВЕДЕНИЕ В ТЕОРИЮ НЕЙТРОННЫХ МУЛЬТИПЛИЦИРУЮЩИХ СИСТЕМ (РЕАКТОРОВ)
ИздАТ

Our goal: To study the space-time evolution of neutron flux in FR in the framework of multigroup diffusion theory, and to clarify the initiation conditions and stability of the nuclear burning wave (NBW) regime in FR.

Model: The model of calculation includes the following set of nonlinear partial differential equations: the non-stationary diffusion equation of neutron transport, the burn-up equations for ten components of the nuclear transformation chain involved in U–Pu cycle and the equations of nuclear kinetics for describing precursor nuclei of delayed neutrons.

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



^{239}Pu : ^{240}Pu : ^{241}Pu : ^{242}Pu = 0.70 : 0.22 : 0.05 : 0.03

Non-stationary case (one-group approximation)

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

$$W(z) = -D\frac{\partial \Phi}{\partial z}; \qquad B_r = \frac{2.405}{R + 0.71/\Sigma_{tr}}; \qquad D(z) = 1/3\Sigma_{tr}(z)$$

$$\overline{\beta} = \sum_l \beta_l (\nu_f \Sigma_f)_l / \nu_f \Sigma_f \qquad \beta_l = \sum_i \beta_l^i$$

$$\Sigma_\alpha(z) = \sum_j \sigma_\alpha^j N^j(z) \qquad \nu_f \Sigma_f(z) = \sum_j \nu_f^j \sigma_f^j N^j(z)$$

$$\Phi(0) - 2W(0) = 2j_{ex} \qquad \Phi(L) + 2W(L) = 0$$

$$\Phi(z, t=0) = 0 \qquad 0 \le z \le L \qquad 0 \le t \le T$$

$T_n \approx 10^{-7}$ s $T_d \approx 1$ min $T_{1/2} \approx 2.35$ days $T \approx 10$ days

Equations of nuclear kinetics for the precursor nuclei of delayed neutrons

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

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

Dynamics of the FR nuclear composition

Table. *The numeration of the nuclei in the ^{238}U–^{239}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

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

$$\frac{\partial N_9}{\partial t} = \Lambda_6 N_6 , \qquad \sigma_{al} = \sigma_{cl} + \sigma_{fl}, \qquad \Lambda_l = \ln 2 / T_{1/2}^l$$

$$\frac{\partial N_{10}}{\partial t} = \sum_{l=1,4,5,6,7} \sigma_{fl} N_l \Phi , \qquad N_l(z, t = 0) = N_{0l}(z)$$

Calculation technique

A rectangular mesh with steps h and τ (uniform for z and with variable step for t) was used. The solutions of the set of the algebraic equations were obtained by finite-difference technique using the implicit difference **Crank-Nicolson scheme**. This symmetric-in-time scheme has an unconditional stability at any relation between space and time steps. It is the unique implicit scheme that has approximation of the second order of accuracy in h and τ . Here n numerates time layer, K is the node of the space mesh.

$$-a^{(K)}\Phi^{n+1}(K-1)+\left(b^{(K)}+\frac{1}{\varpi}\right)\Phi^{n+1}(K)-c^{(K)}\Phi^{n+1}(K+1)=$$

$$=a^{(K)}\Phi^{n}(K-1)-\left(b^{(K)}-\frac{1}{\varpi}\right)\Phi^{n}(K)+c^{(K)}\Phi^{n}(K+1)+V_{n+1}(K)+V_{n}(K)$$

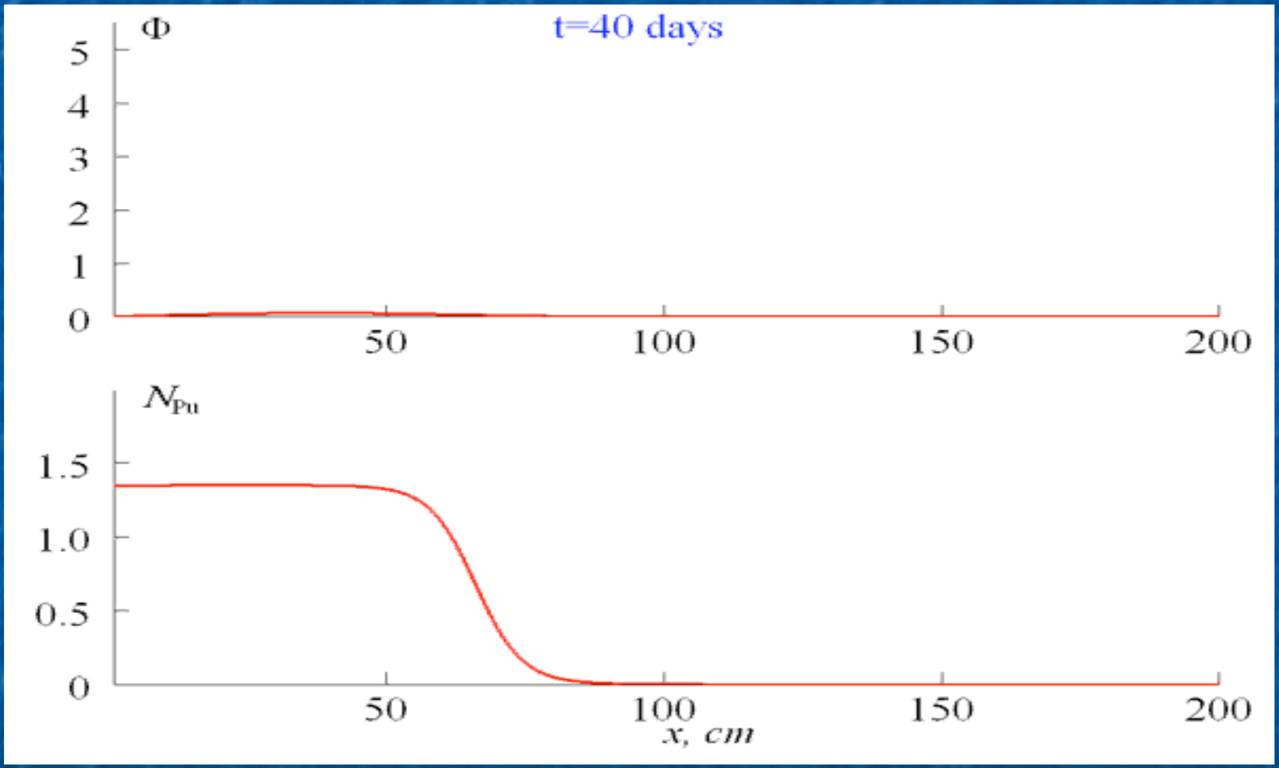
$$V_n(K)=\sum_l \lambda_l C_l^n(K)\,,\quad \Phi^n(K)=\Phi(z_K,t_n)\,,\quad \varpi=v\tau\,.$$

Computing

On the basis of the developed approach a package of original numerical codes has been elaborated for determination of the critical parameters of assemblies under consideration in the one- and multi-group approximations and for simulation of the neutron flux space-time evolution inside FR in the one-group approximation. In calculations we used the BNAB 26-group constants.

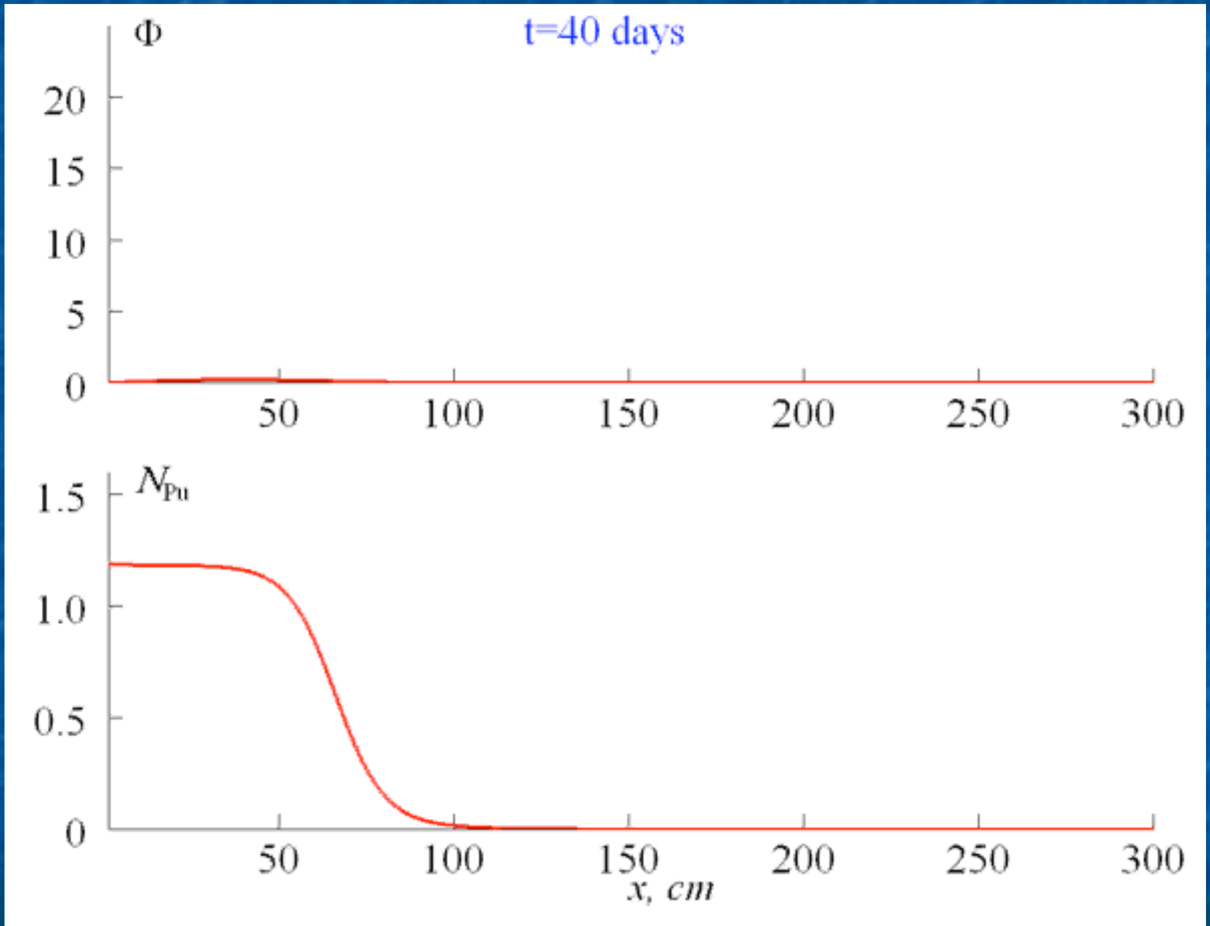
Goldin's solution in FR

Φ, 10^{17} $cm^{-2}s^{-1}$ N_{pu}, 10^{21} cm^{-3}

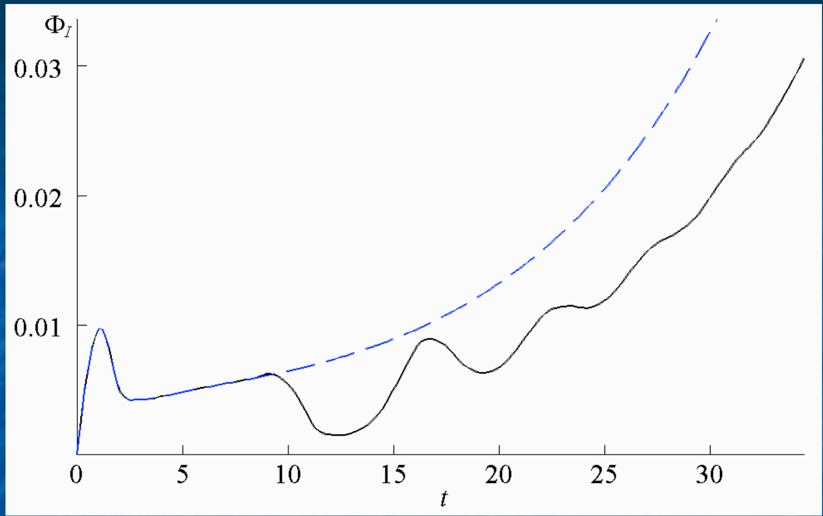


Nuclear burning wave in FR

Φ, 10^{17} cm^{-2}s^{-1} N_{pu}, 10^{21} cm $^{-3}$



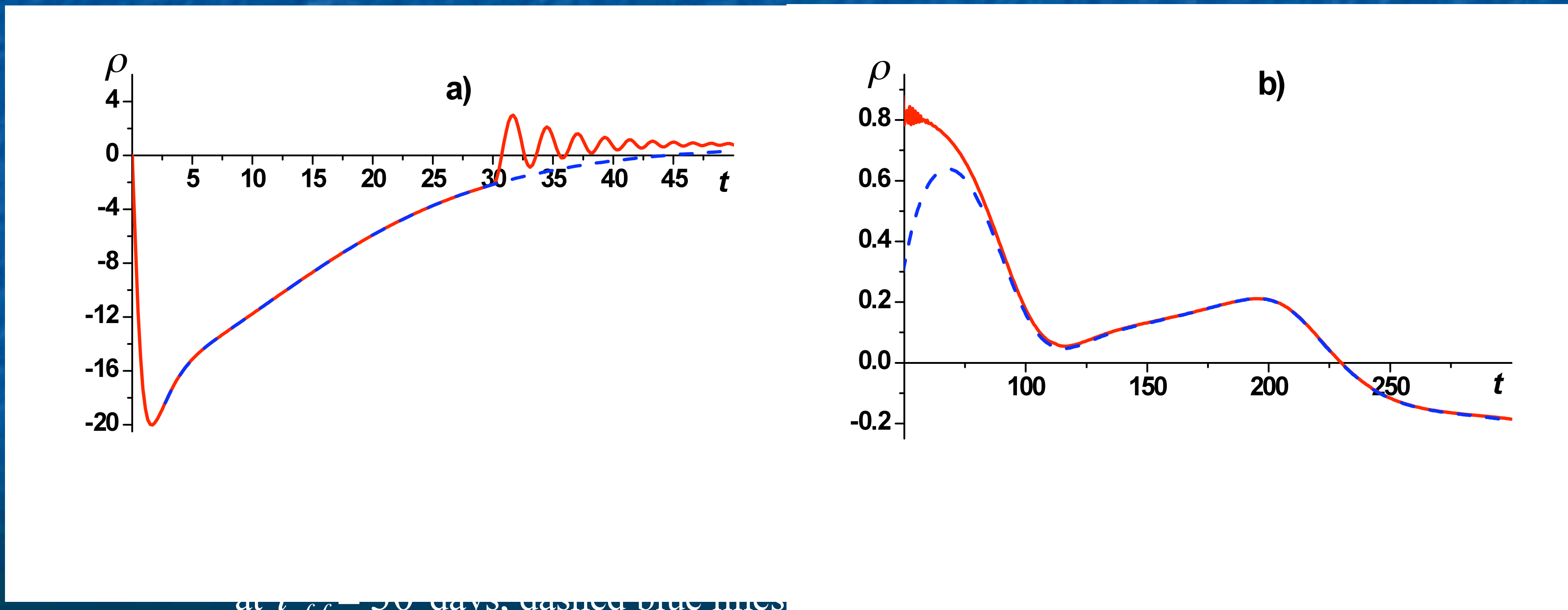
Stability of the burning process



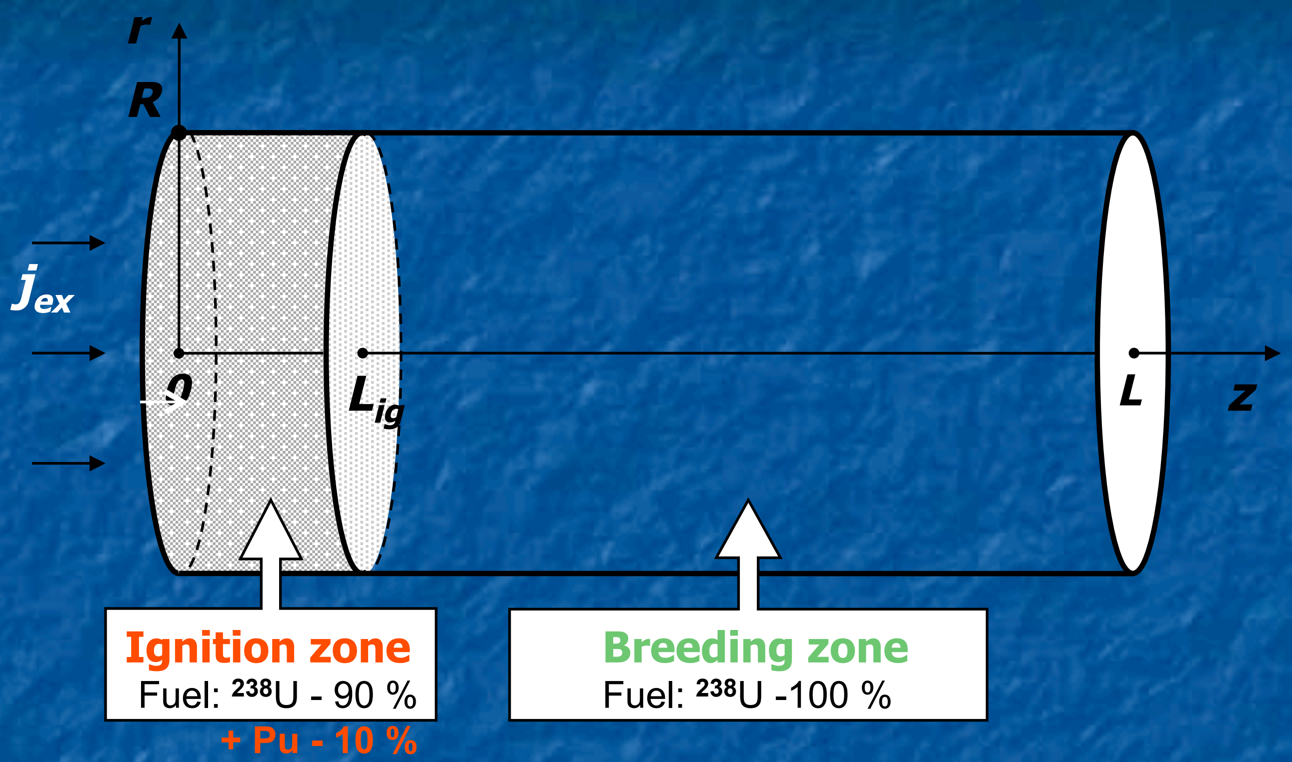
Integrated neutron flux as function of time t (days) at the initial stage of burning.

The solid curve has been calculated with j_{ex} turned off at $t_{off} = 10$ days and the dashed one – without turning j_{ex} off.

Reactivity: $\boxed{\rho = \dfrac{k_{eff} - 1}{k_{eff}}}$



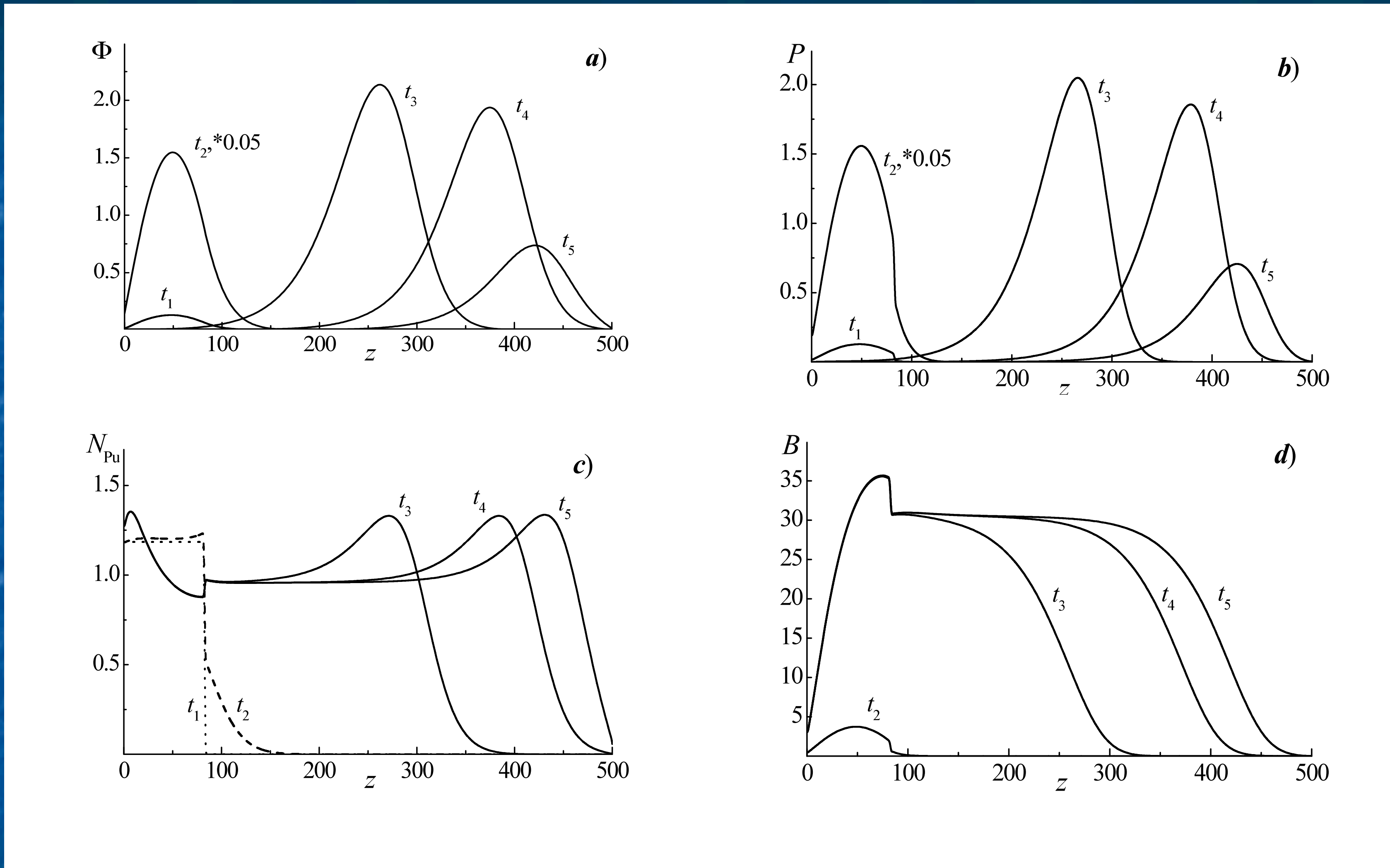
Nuclear burning wave in 5m length cylindrical FR



Composition: U-Pu fuel - 44 %, coolant Na – 36 %, constructional material Fe – 20 %

External neutron flux: $j_{ex} = 6 \cdot 10^{11}$ cm^{-2}s^{-1}

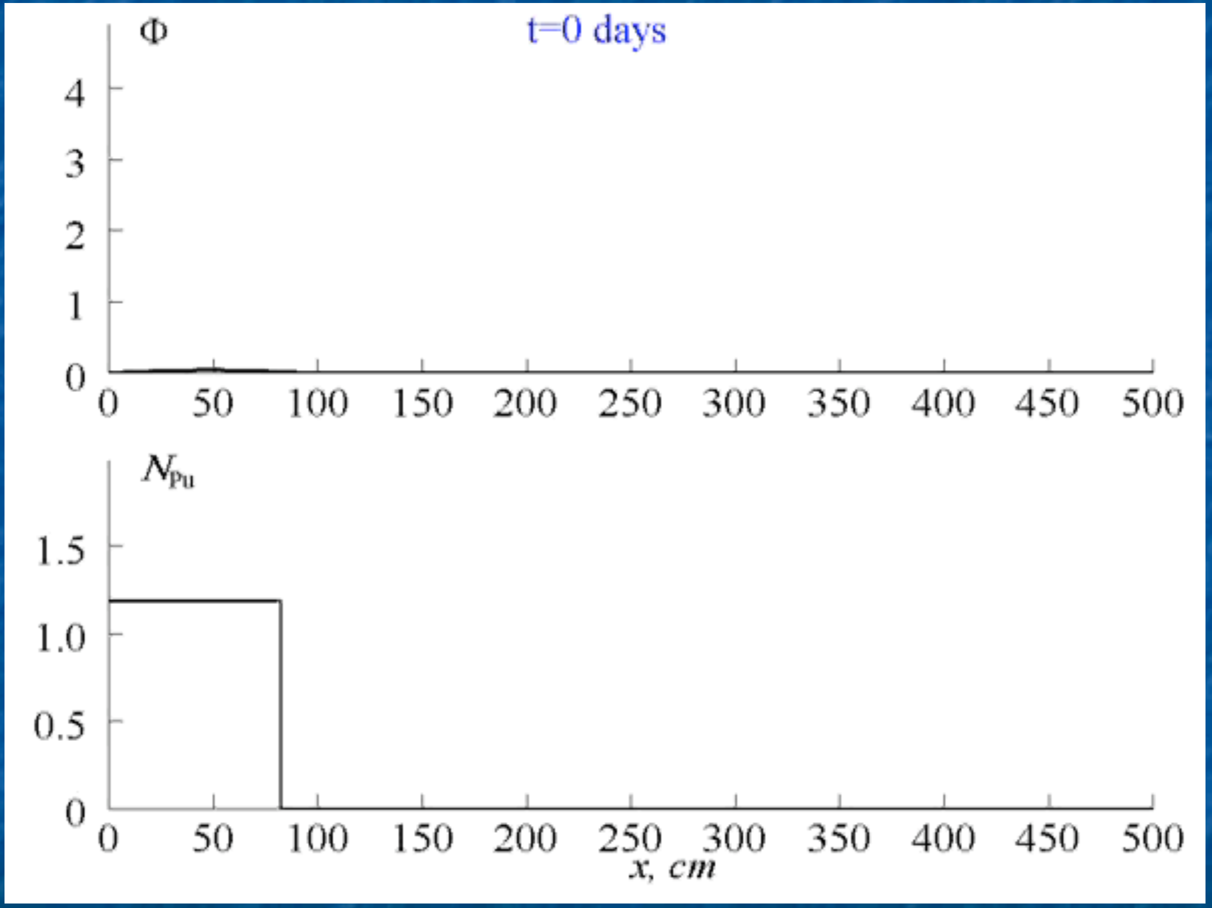
Results for the 5m length cylindrical FR



(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.

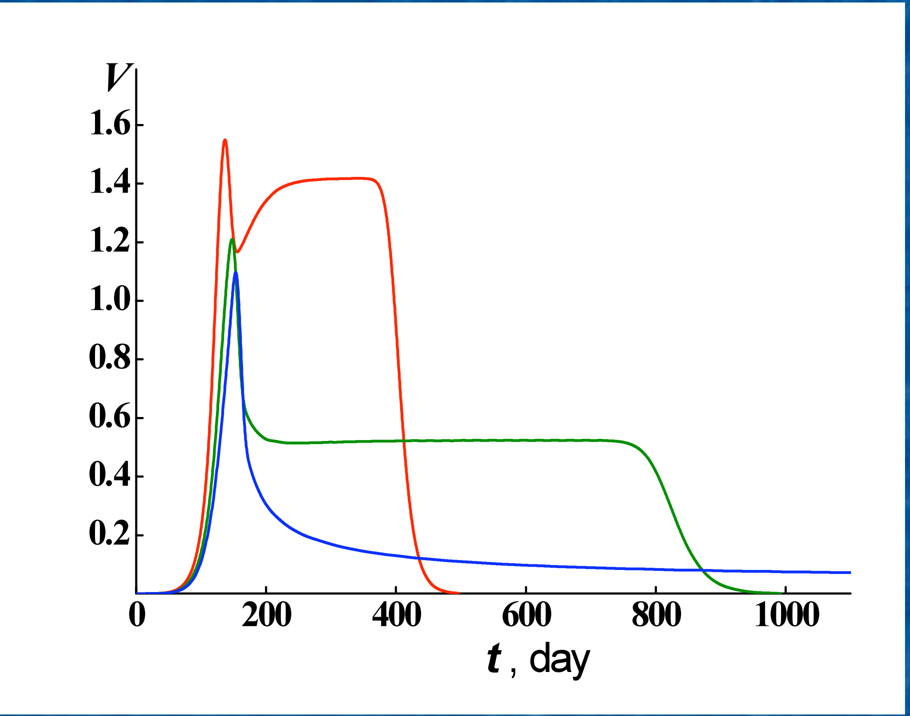
Nuclear burning wave in 500 cm length and 110 cm radius cylindrical FR

Φ, 10^{17} $cm^{-2}s^{-1}$ N_{pu}, 10^{21} cm^{-3}

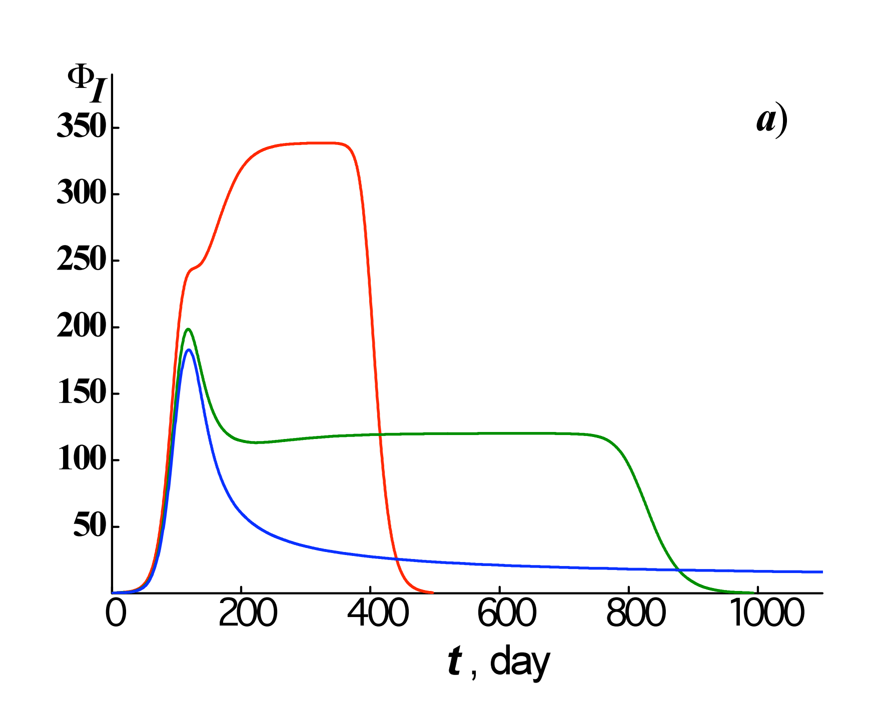


Nuclear burning wave in 5m length cylindrical FR for different reactor radius *R*

NBW velocity V, cm/day

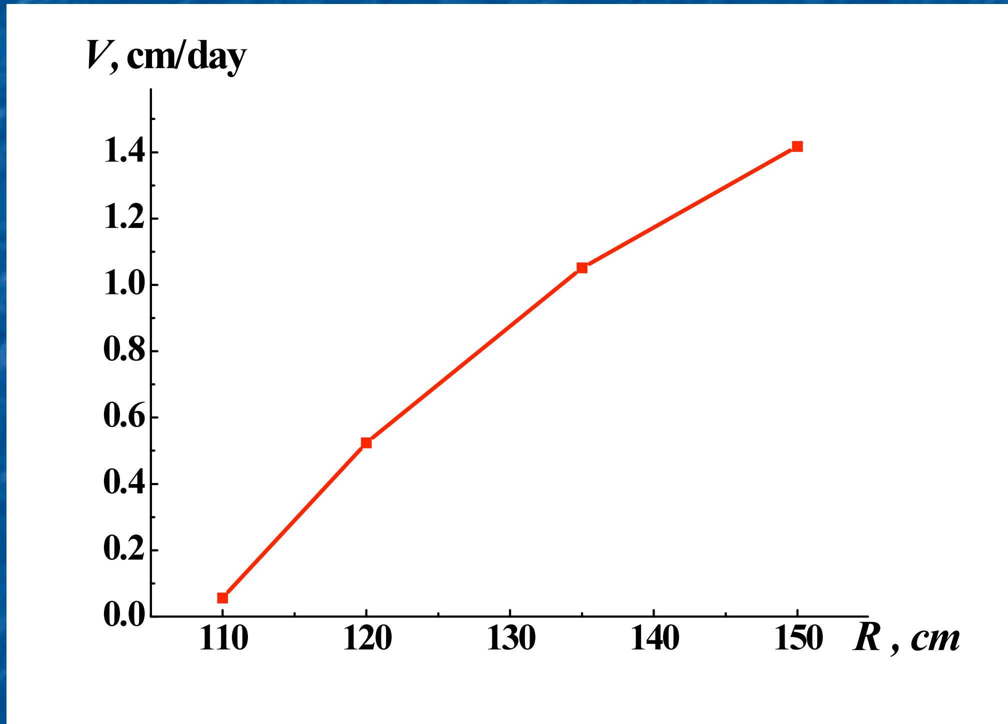


Integral neutron flux Φ_I, $\times 10^{17} cm^{-1} s^{-1}$

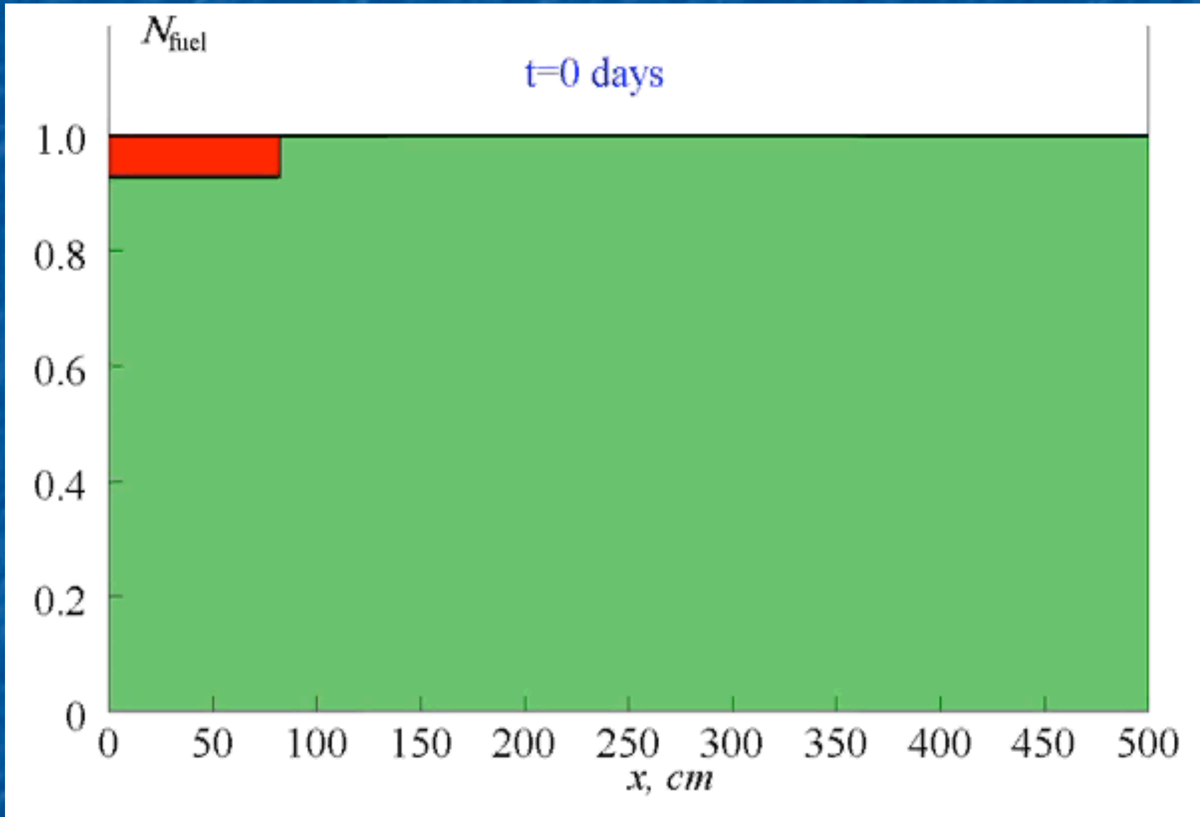


R = 150 cm (red line) ; 120 cm (green line) ; R = 110 cm (blue line)

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



Fuel burn-up

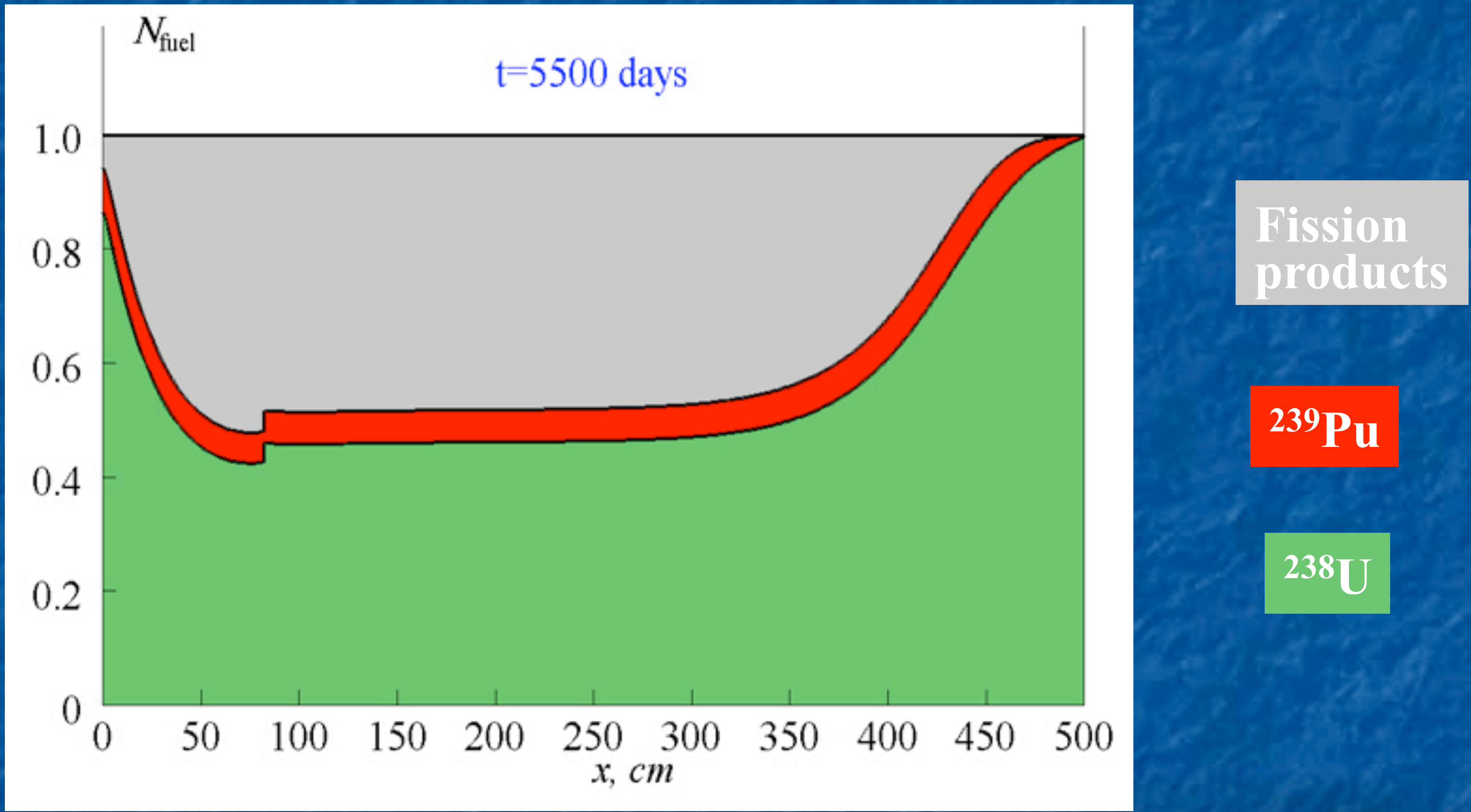


Fission products

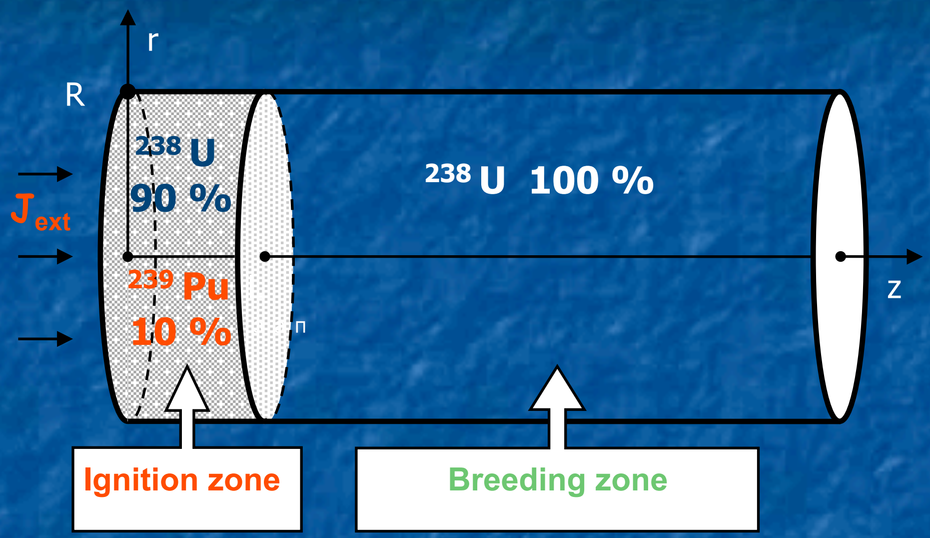
^{239}Pu

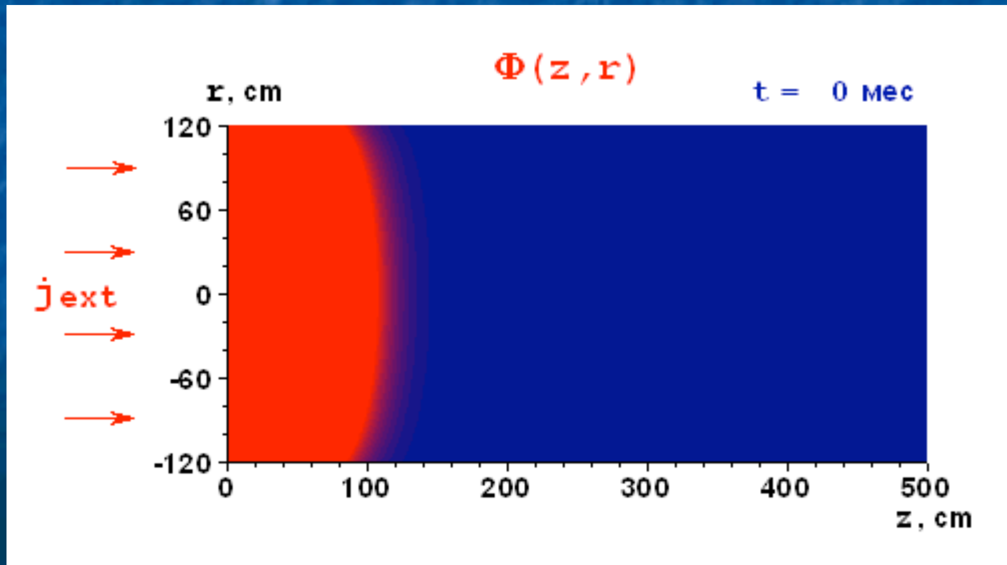
^{238}U

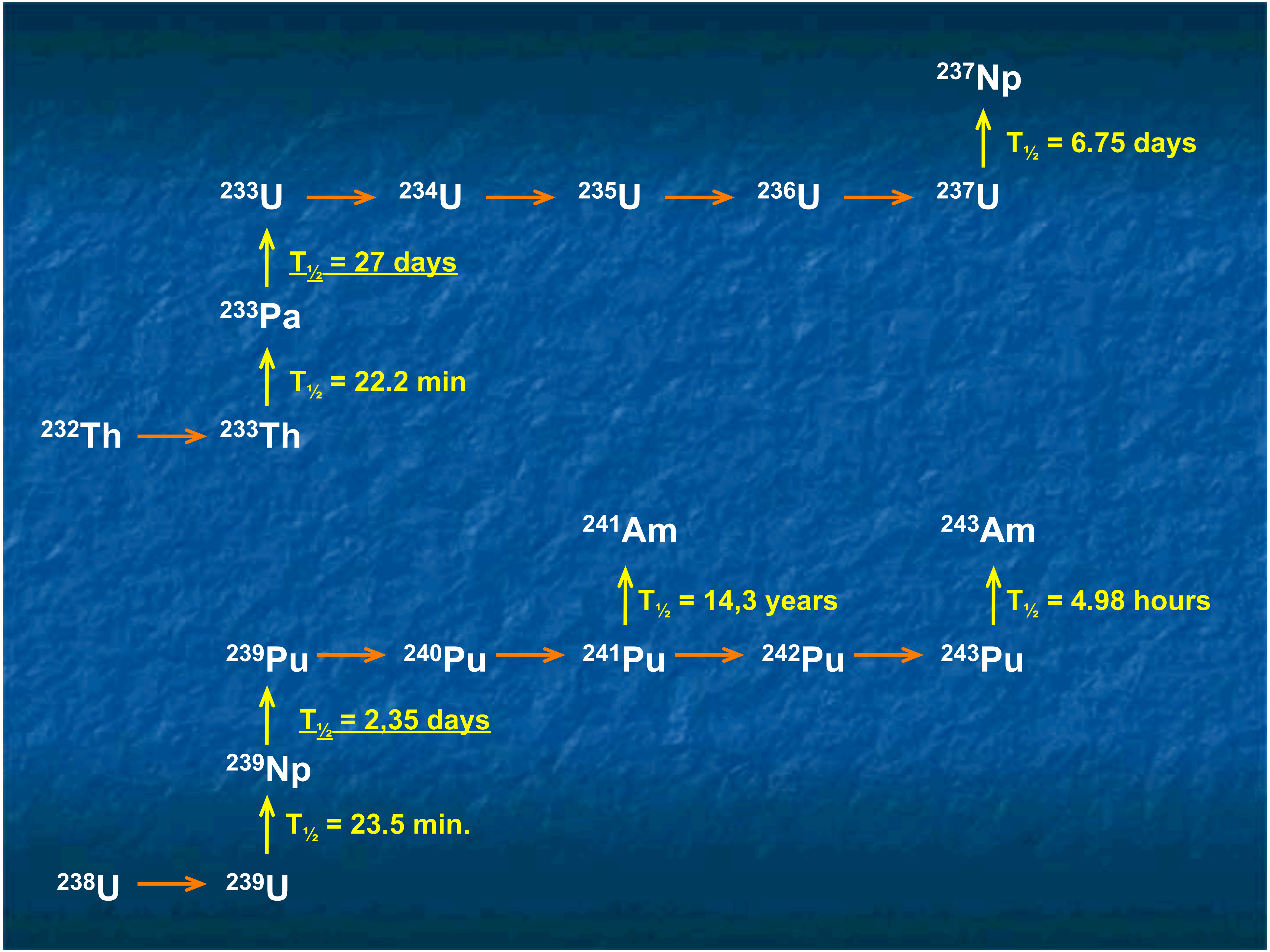
Fuel burn-up


N_{fuel}
t=5500 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

2D calculations of the neutron flux evolution in cylindrical fast reactor R=120 cm & L= 500 cm

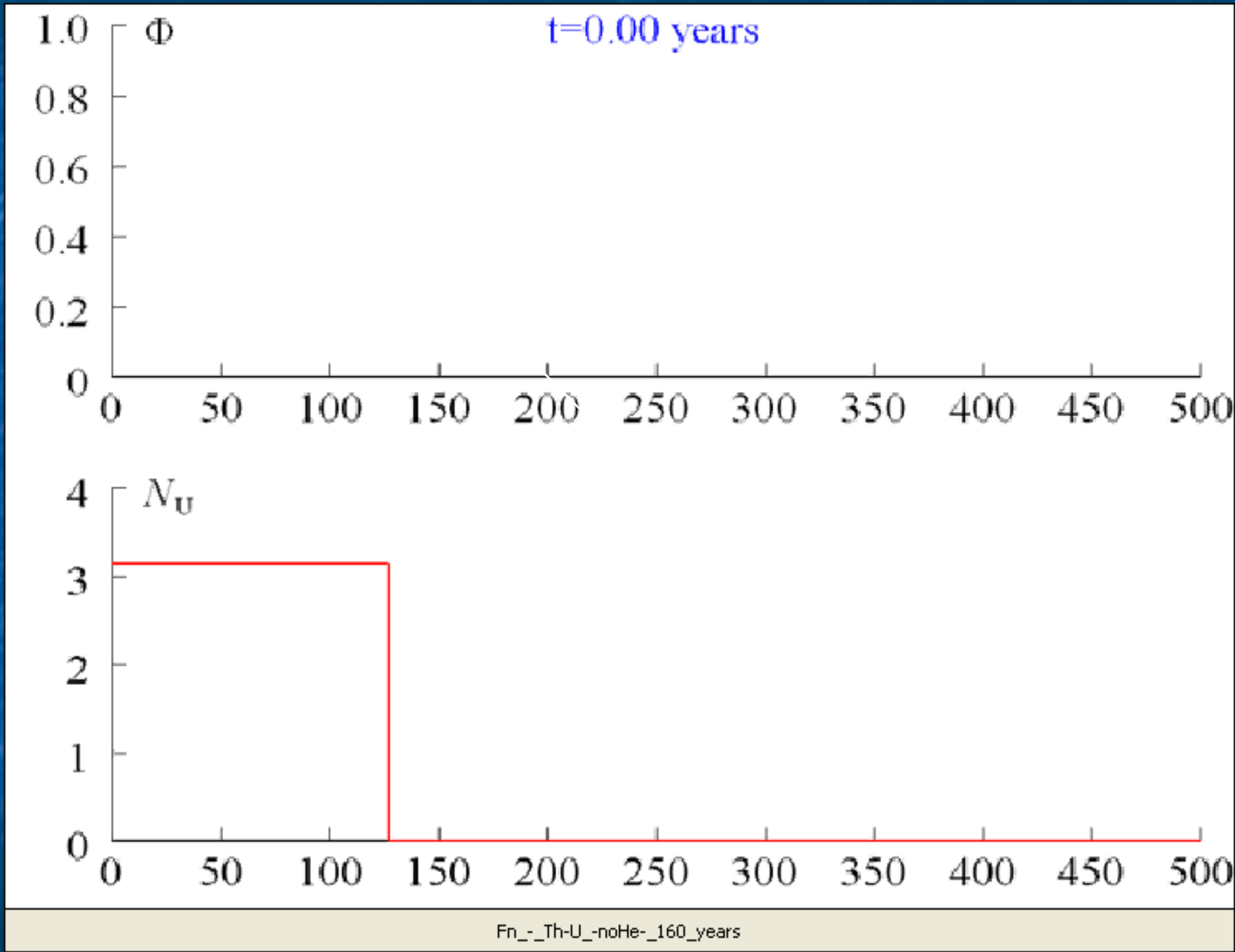


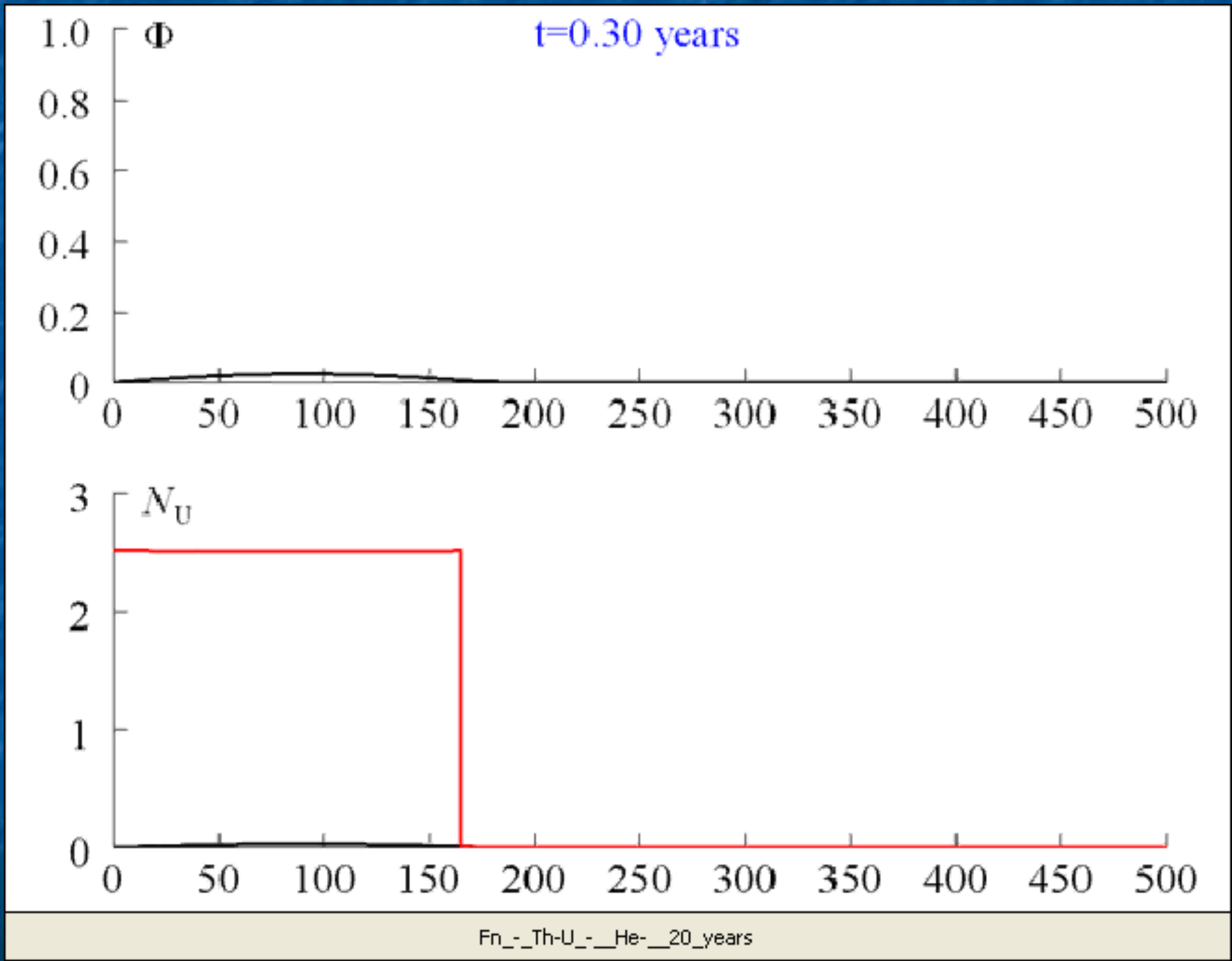




^{237}Np
$T_{1/2}$ = 6.75 days
^{233}U → ^{234}U → ^{235}U → ^{236}U → ^{237}U
$T_{1/2}$ = 27 days
^{233}Pa
$T_{1/2}$ = 22.2 min
^{232}Th → ^{233}Th
^{241}Am
^{243}Am
$T_{1/2}$ = 14,3 years
$T_{1/2}$ = 4.98 hours
^{239}Pu → ^{240}Pu → ^{241}Pu → ^{242}Pu → ^{243}Pu
$T_{1/2}$ = 2,35 days
^{239}Np
$T_{1/2}$ = 23.5 min.
^{238}U → ^{239}U

Nuclear Burning Wave in Th-U medium





t=0.30 years
1.0
0.8
0.6
0.4
0.2
0
Φ
0 50 100 150 200 250 300 350 400 450 500
3
2
1
0
N_U
0 50 100 150 200 250 300 350 400 450 500
Fn_-_Th-U_-__He-__20_years

Conclusion

Main features of the reactor working in the NBW regime:

- Self-sustained critical state due to the negative reactivity feedback **(internal safety)**
- No necessity of permanent control & fuel reloading **(underground location)**
- Fuel is the natural or depleted uranium **(^{238}U)**
- Fuel burn-up depth is about **50 %**
- Intensive accumulation of Pu (≈10% along the reactor) **(fuel recycling)**
- Nuclear waste incineration **(ecology)**
- NBW velocity is about **22 cm/year** for reactor radius R = 110 cm
- Neutron flux at the stable NBW regime **$\approx 2 \cdot 10^{16}$ см$^{-2}$ с$^{-1}$**
- Power density **$\approx$ 2 kW cm^{-3}**
- Total power **≈ 2 GW**
- No NBW regime for Th-U fuel cycle

Thank you for attention !