National Science Center
“Kharkov Institute of Physics and Technology”

HIGH EFFICIENCY OF MIXED Th-U FUEL UTILISATION IN INNOVATIVE NUCLEAR BURNING WAVE REACTOR

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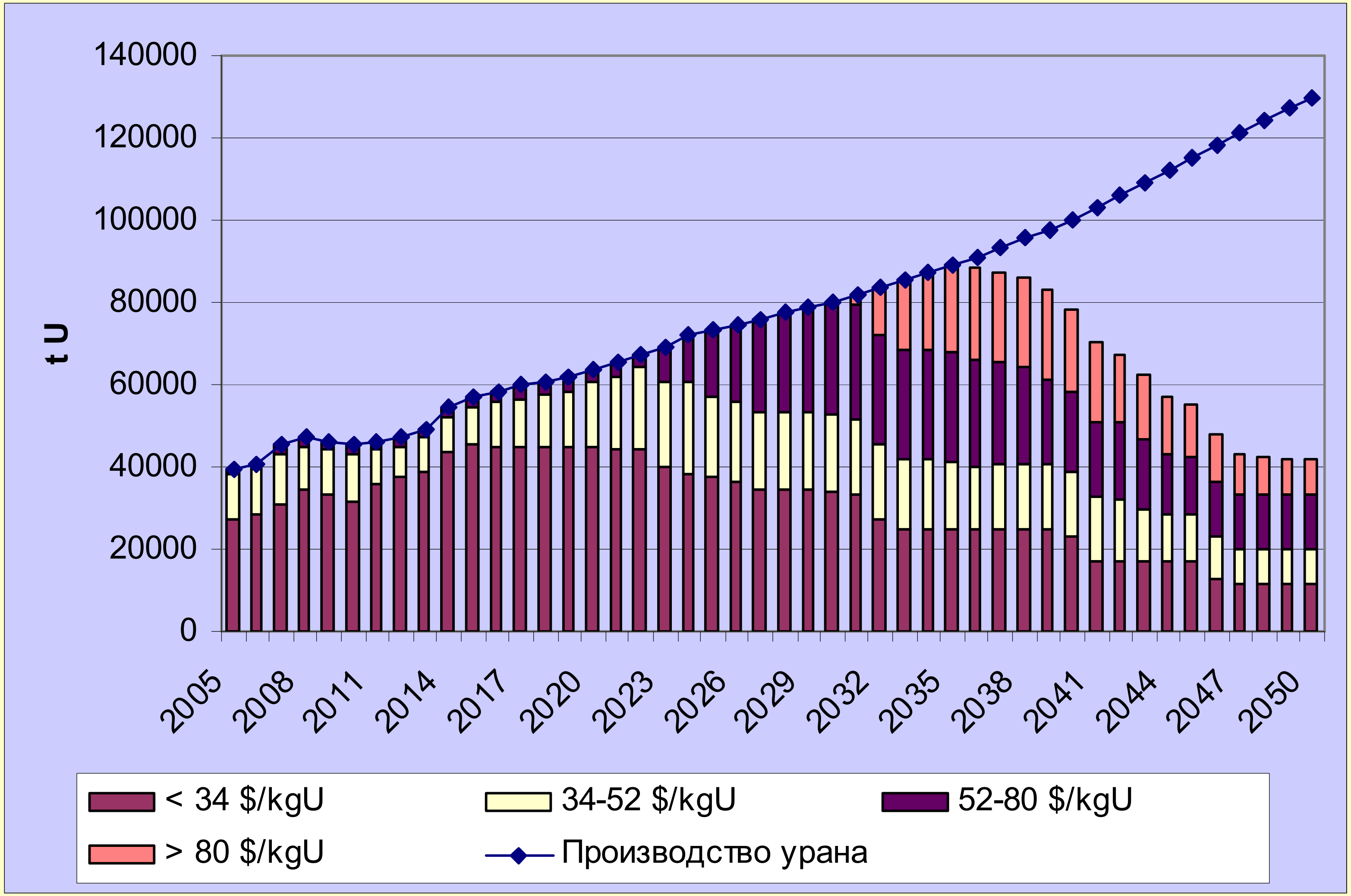
Nuclear Power Problems

Atomic Bomb House, Hiroshima

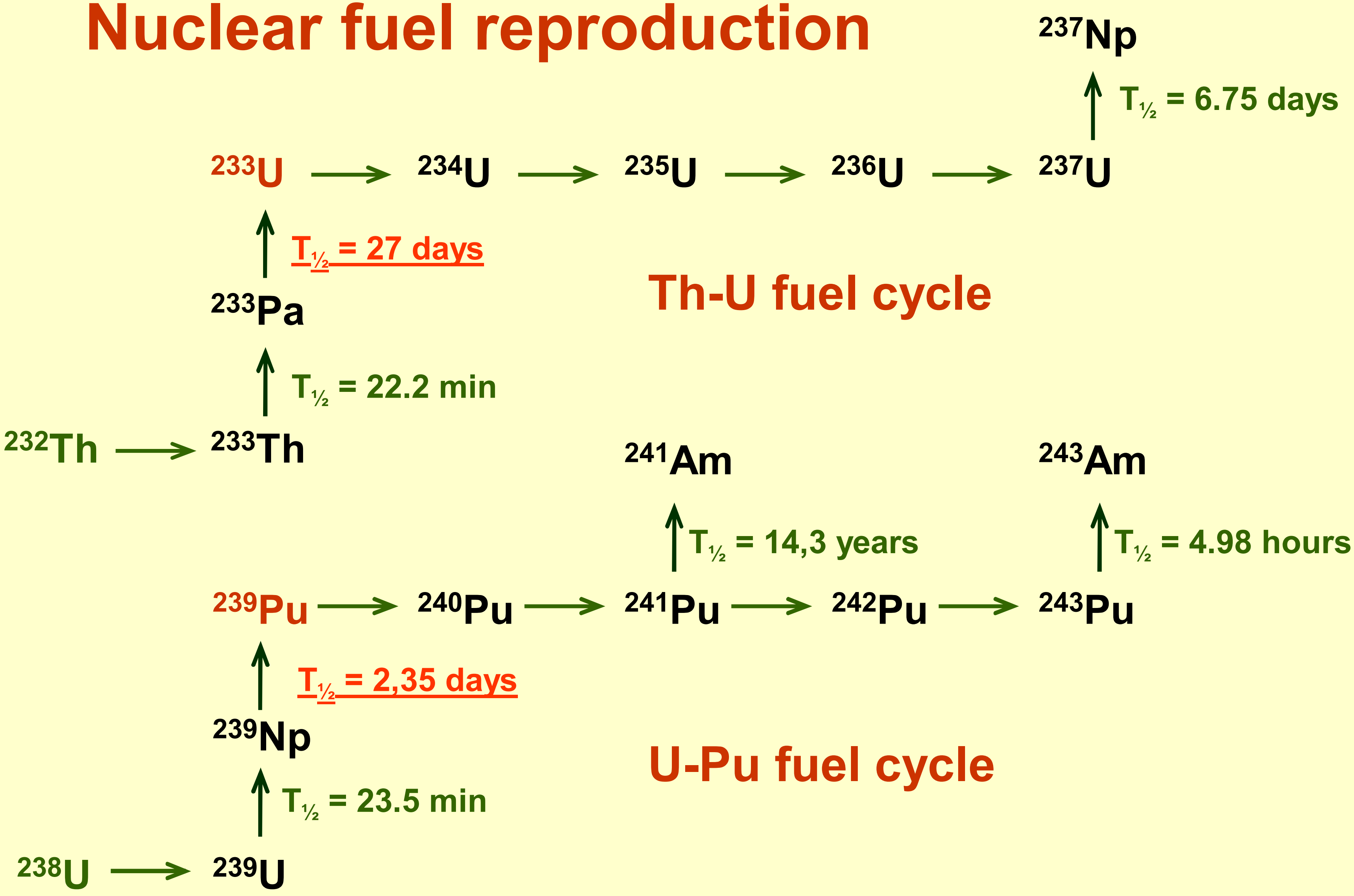
- **Safety !!!** (after Chernobyl accident)
- **Closed fuel cycle** (fuel reproduction)
- **Ecological problems** (nuclear waste utilization)
- **Nonproliferation of fissile materials** (nuclear terrorism resistance)

Explored Earth reserves of Uranium



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

Nuclear fuel reproduction



^{237}Np

T$_{½}$ = 6.75 days

^{233}U → ^{234}U → ^{235}U → ^{236}U → ^{237}U

T$_{½}$ = 27 days

^{233}Pa

Th-U fuel cycle

T$_{½}$ = 22.2 min

^{232}Th → ^{233}Th

^{241}Am

^{243}Am

T$_{½}$ = 14,3 years

T$_{½}$ = 4.98 hours

^{239}Pu → ^{240}Pu → ^{241}Pu → ^{242}Pu → ^{243}Pu

T$_{½}$ = 2,35 days

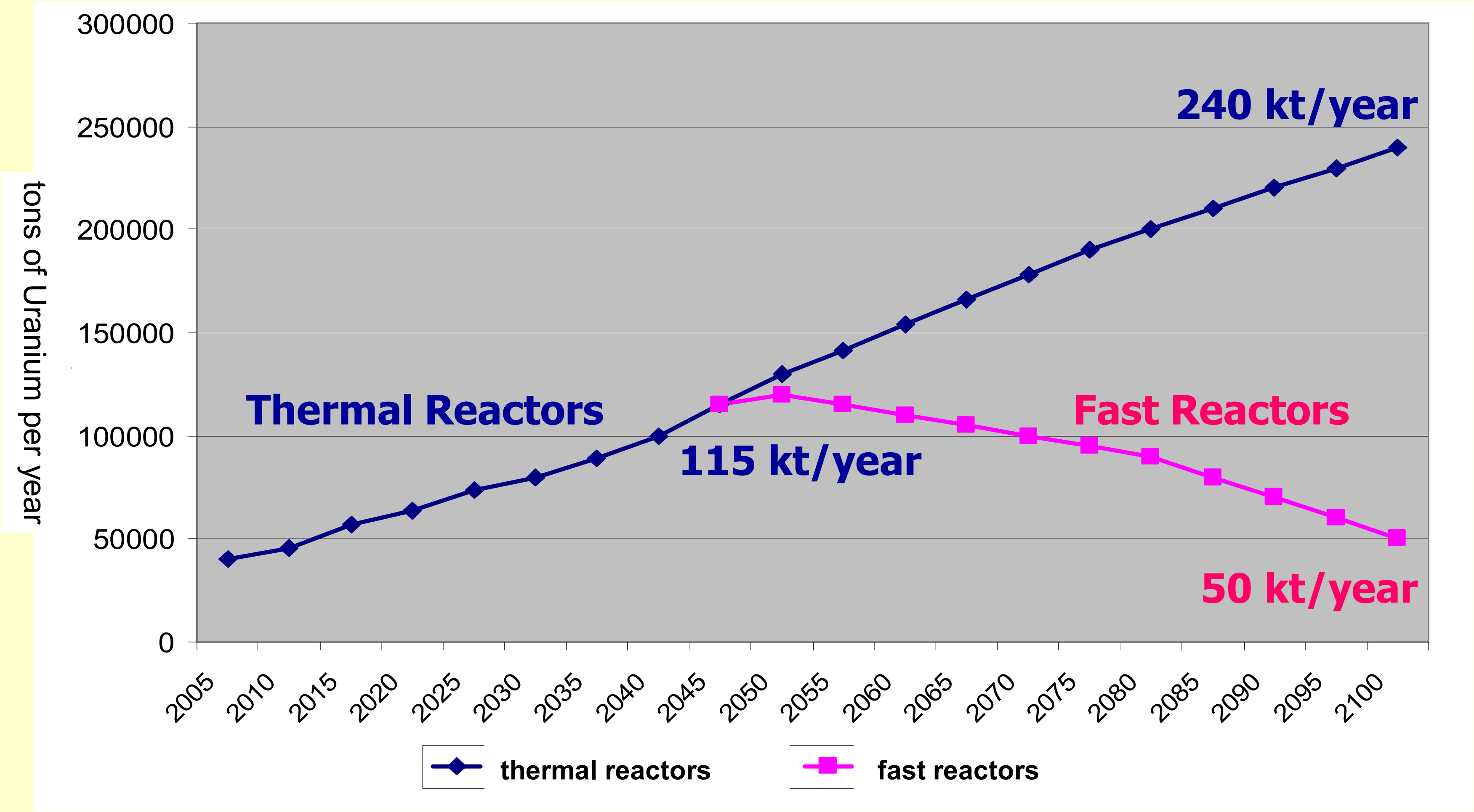
^{239}Np

U-Pu fuel cycle

T$_{½}$ = 23.5 min

^{238}U → ^{239}U

Forecast world demand for Uranium up to 2100



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.

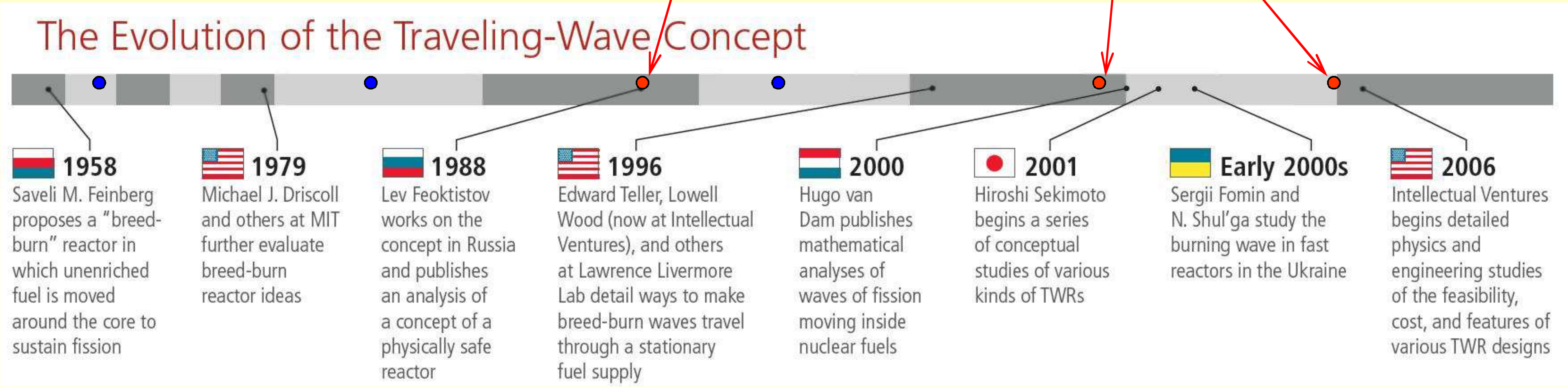
J.S.Slesarev, V.A.Stukalov, S.A.Subbotin, 1984: "Problems of development of fast reactors self-provision without fuel reprocessing", Atomkernenenergie, Kerntechnik, v.45, p.58.

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.
……


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

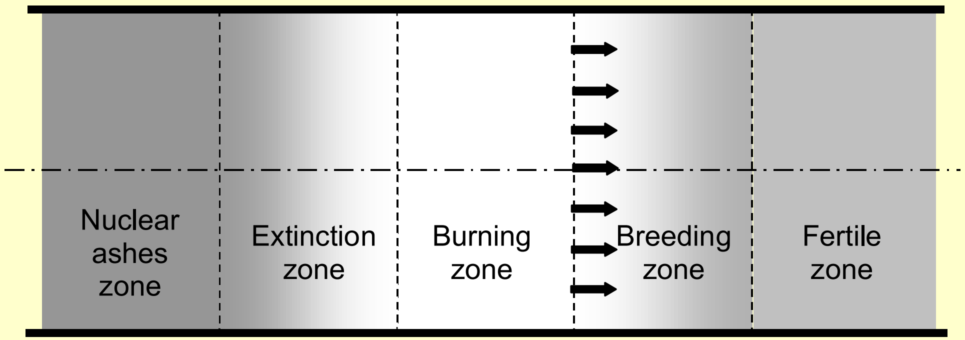
Early 2000s Sergii Fomin and N. Shul’ga study the burning wave in fast reactors in the Ukraine

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

Lev Feoktistov (USSR, 1988):

Nuclear Burning Wave

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



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

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

Concept & Analytical approach

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

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

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

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

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

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

$$x = z + Vt$$

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**

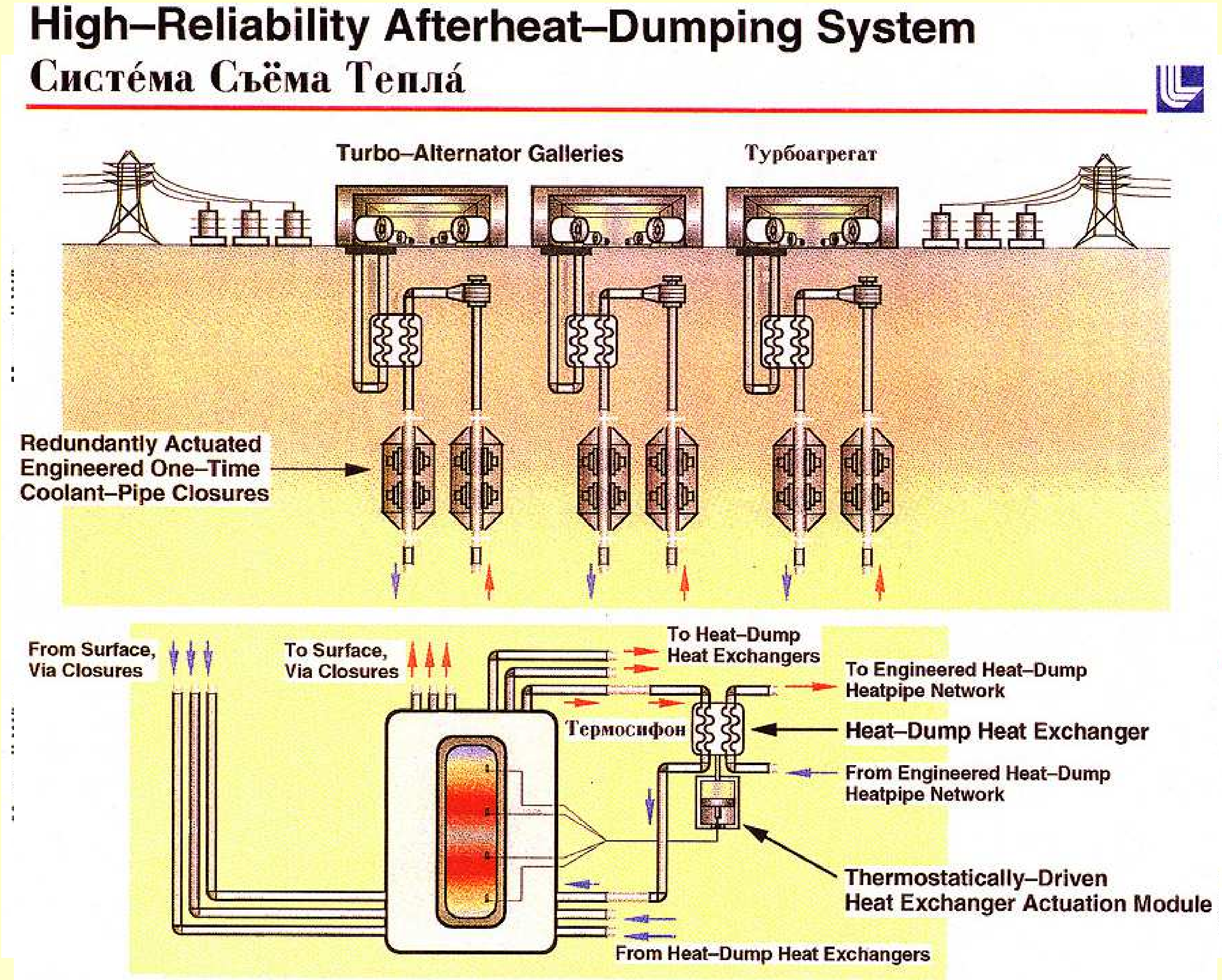
E.Teller. Preprint UCRL-JC-129547, LLNL,1997. **Th-U** fuel cycle

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 (LLNL, USA) 1997: Traveling Wave Reactor

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

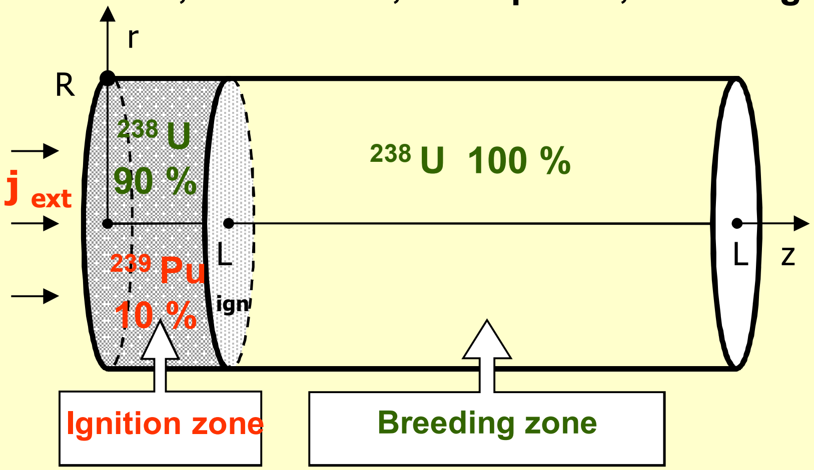


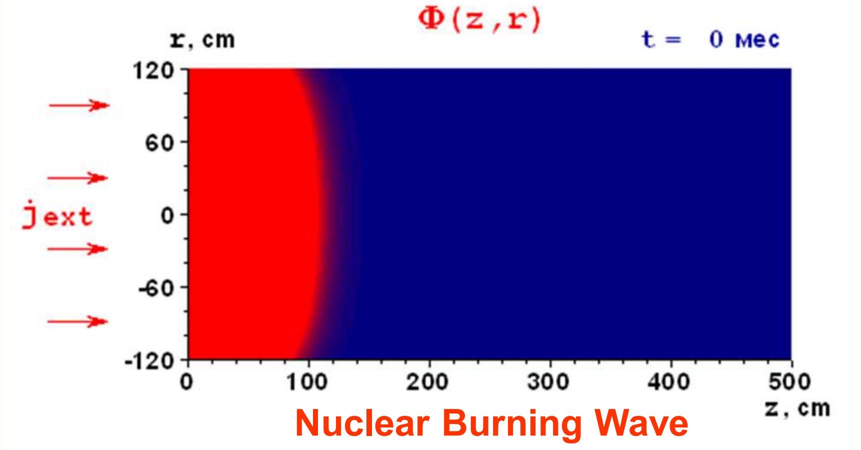
High–Reliability Afterheat–Dumping System

Система́ Съёма Тепла́

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)





Nuclear Burning Wave

Non-Stationary Non-Linear 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

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

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

of Precursor Nuclei of Delayed Neutrons

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

Metal fuel (44%)

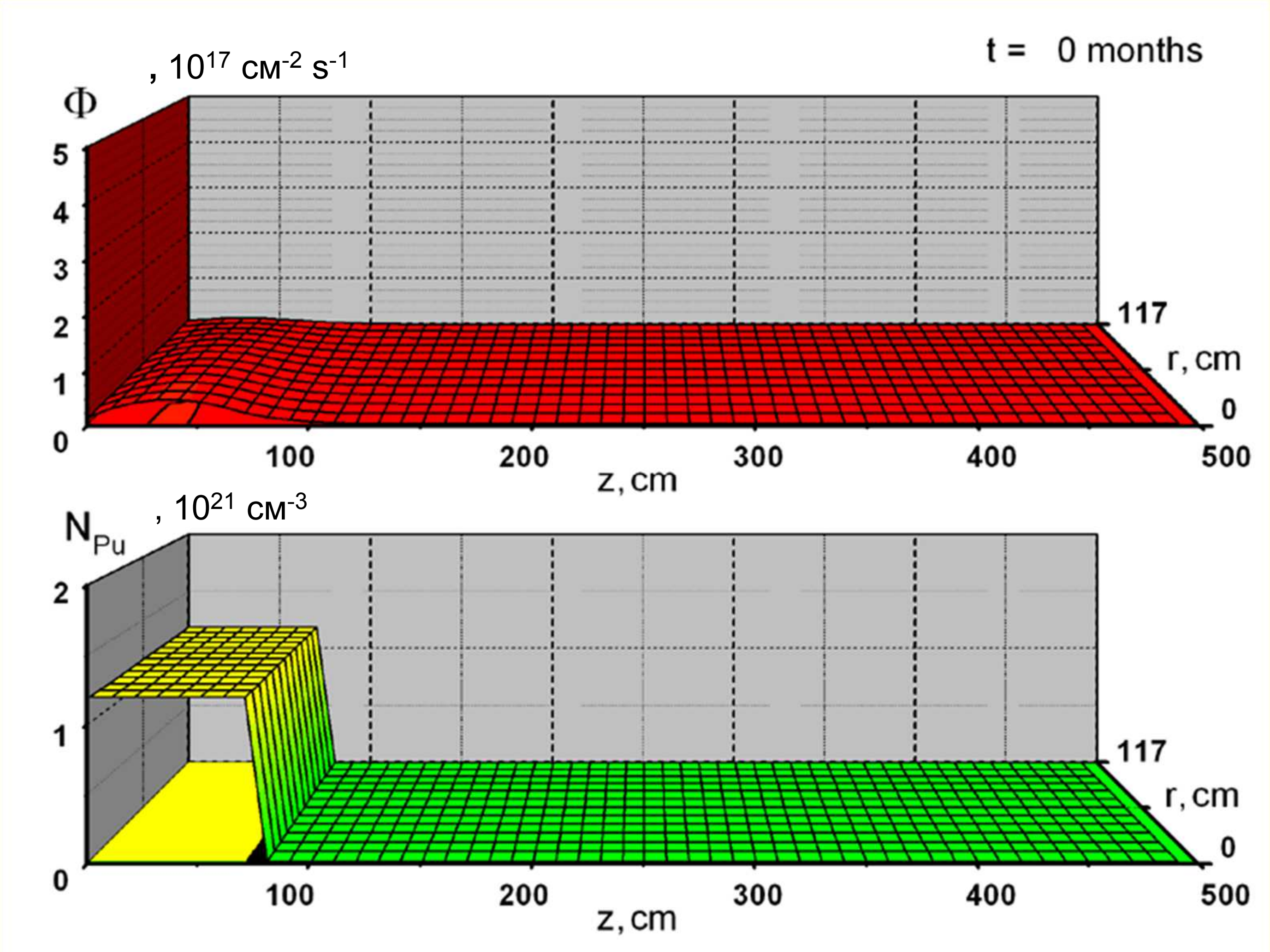
Pb-Bi coolant (36%)

CM - Fe (20%)

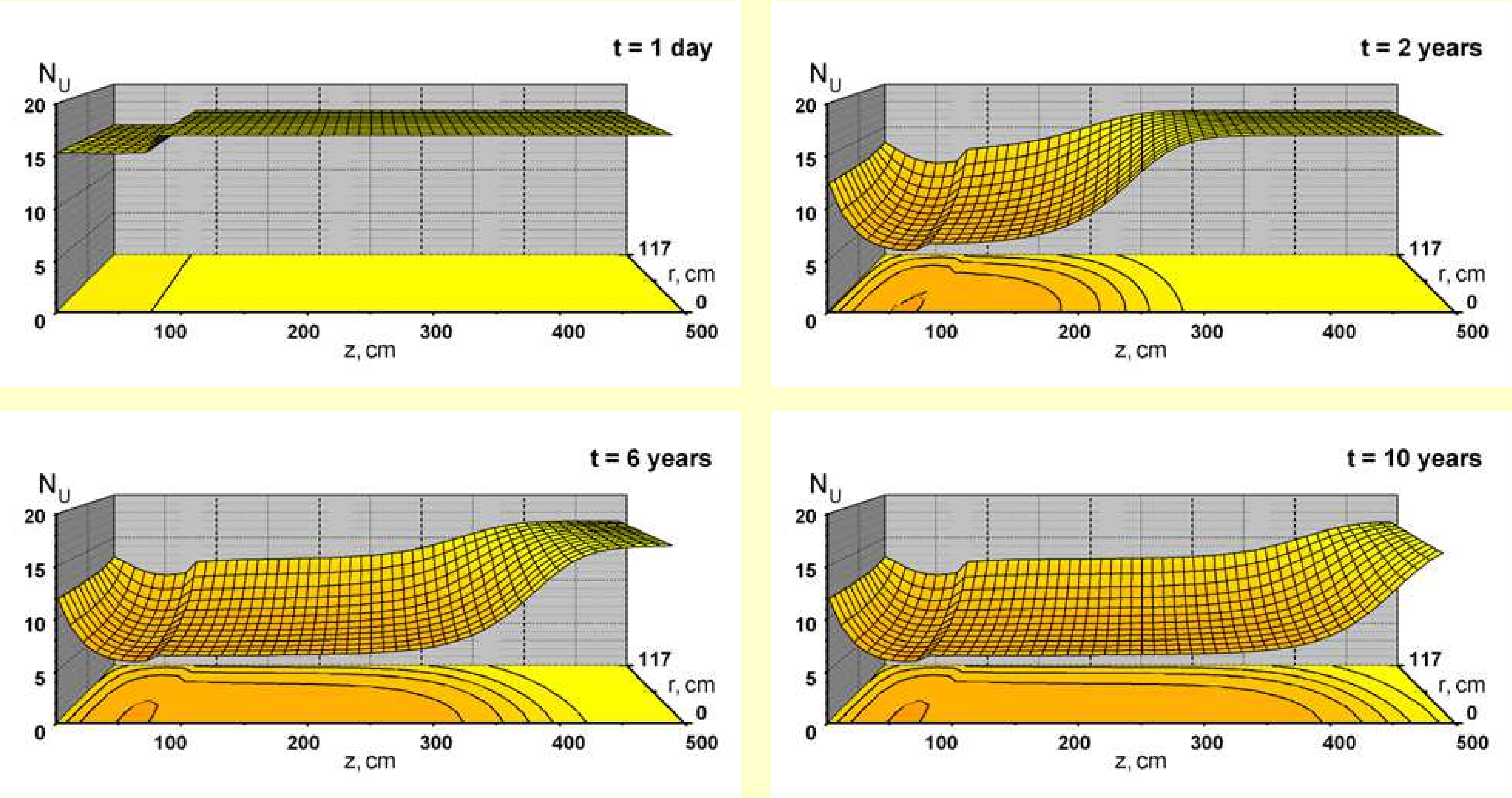
Nuclear Burning Wave in Fast Reactor with U-Pu Fuel

Reactor radius R=117cm, Reactor composition (volume fractions):
Fuel (^{238}U) = 44%, Coolant (Pb-Bi) = 36%, Constr. material (Fe) = 20%

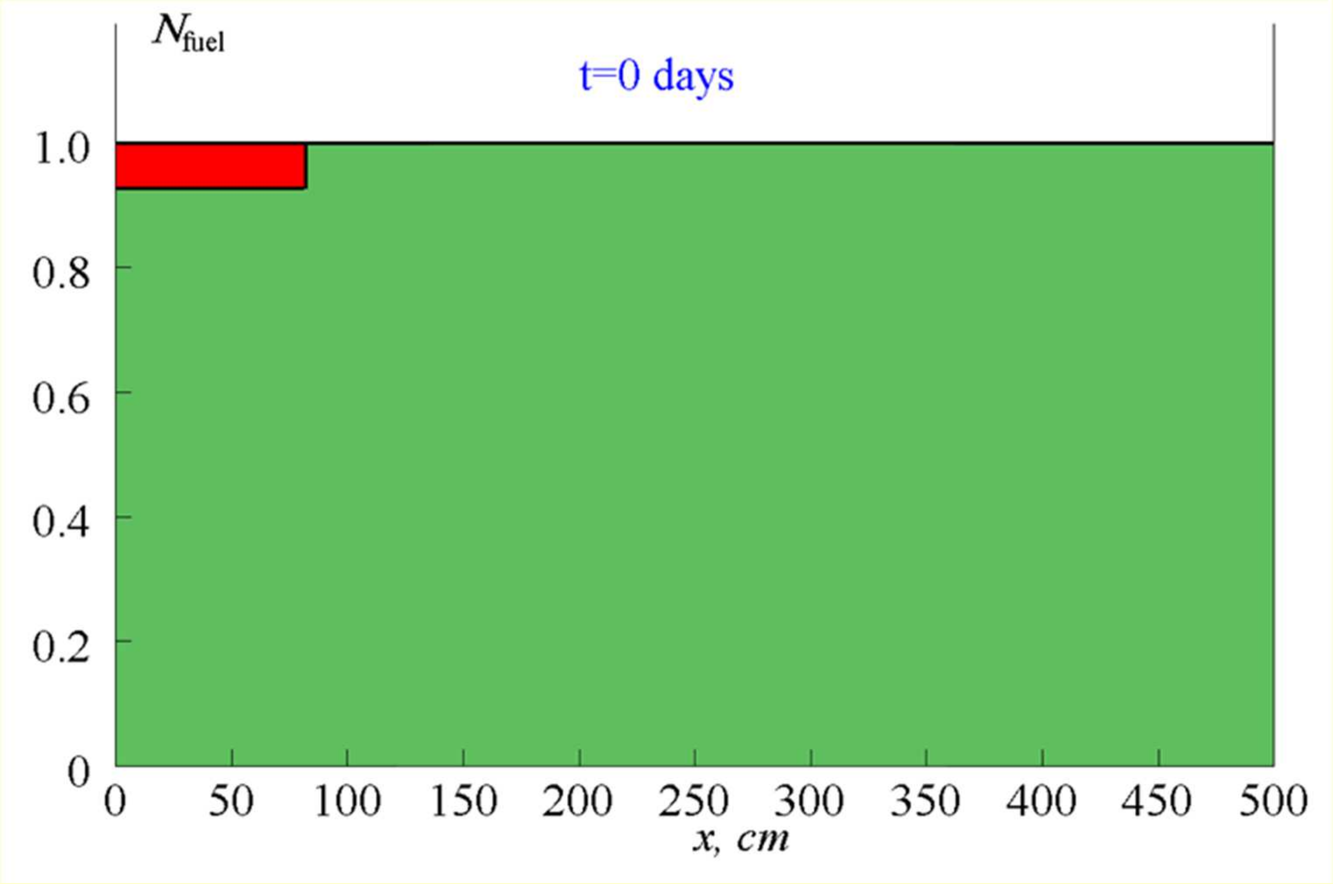
Neutron Flux Φ (r, z, t) & Plutonium Concentration N_{Pu} (r, z, t)



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



Fuel burn-up



Fission products

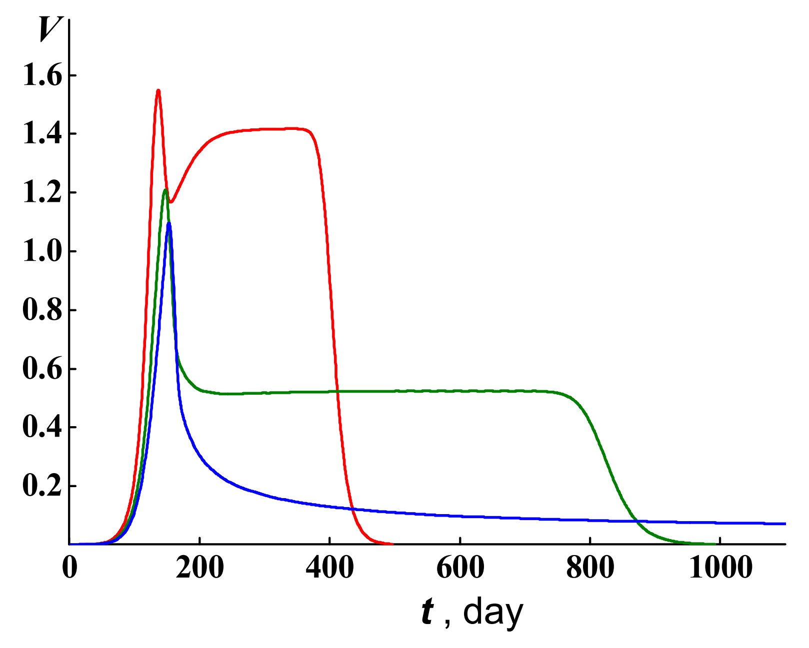
^{239}Pu

^{238}U

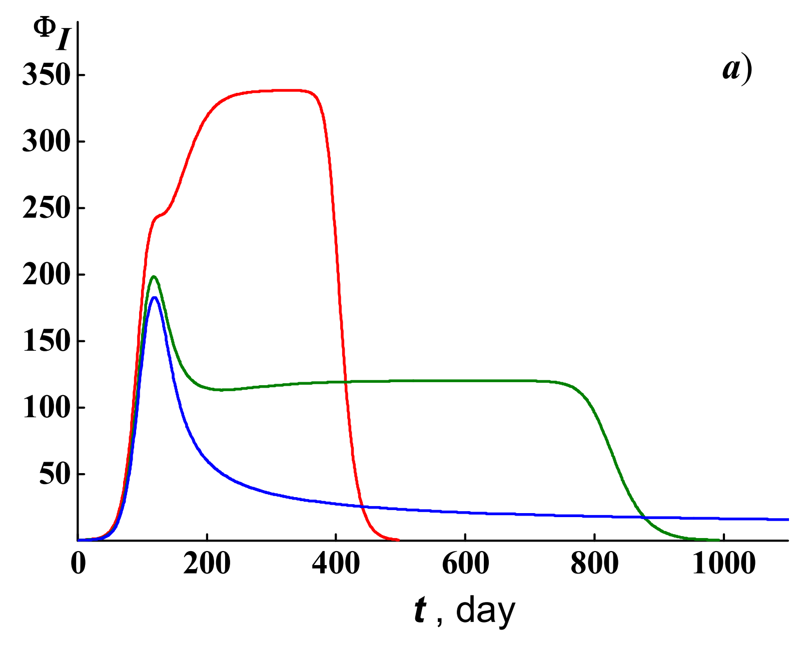
Nuclear burning wave in 5m length cylindrical FR for different reactor radius *R*

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

NBW velocity *V*, cm/day



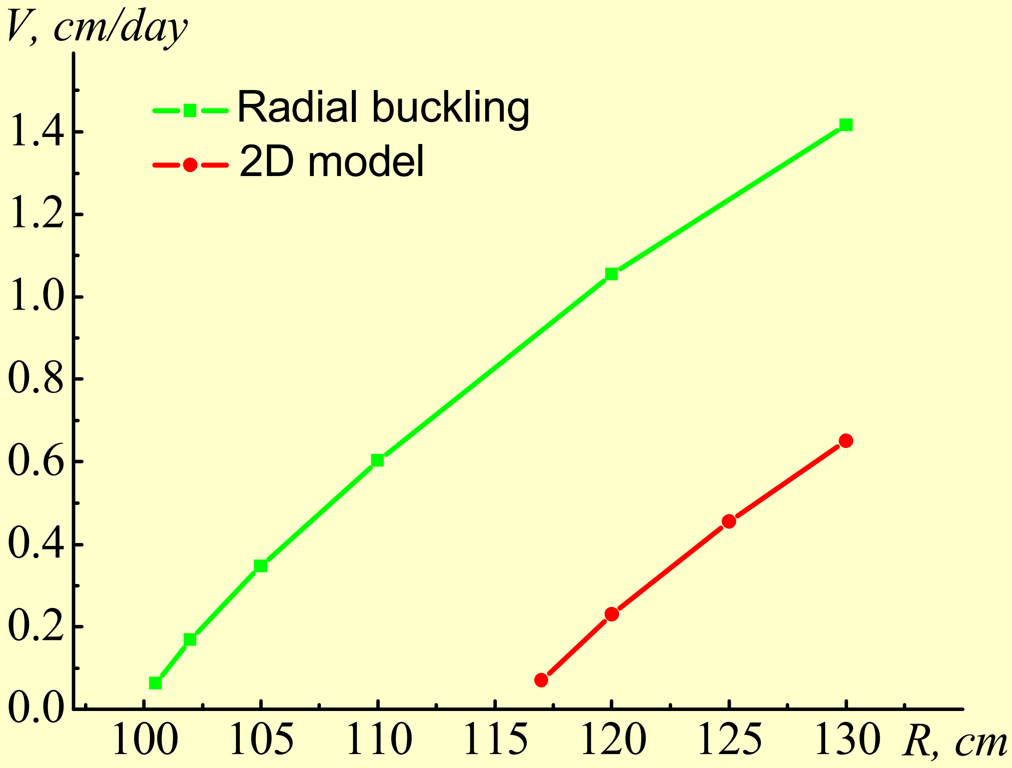
Integral neutron flux Φ_I, ×10^{17}cm^{-1}s^{-1}



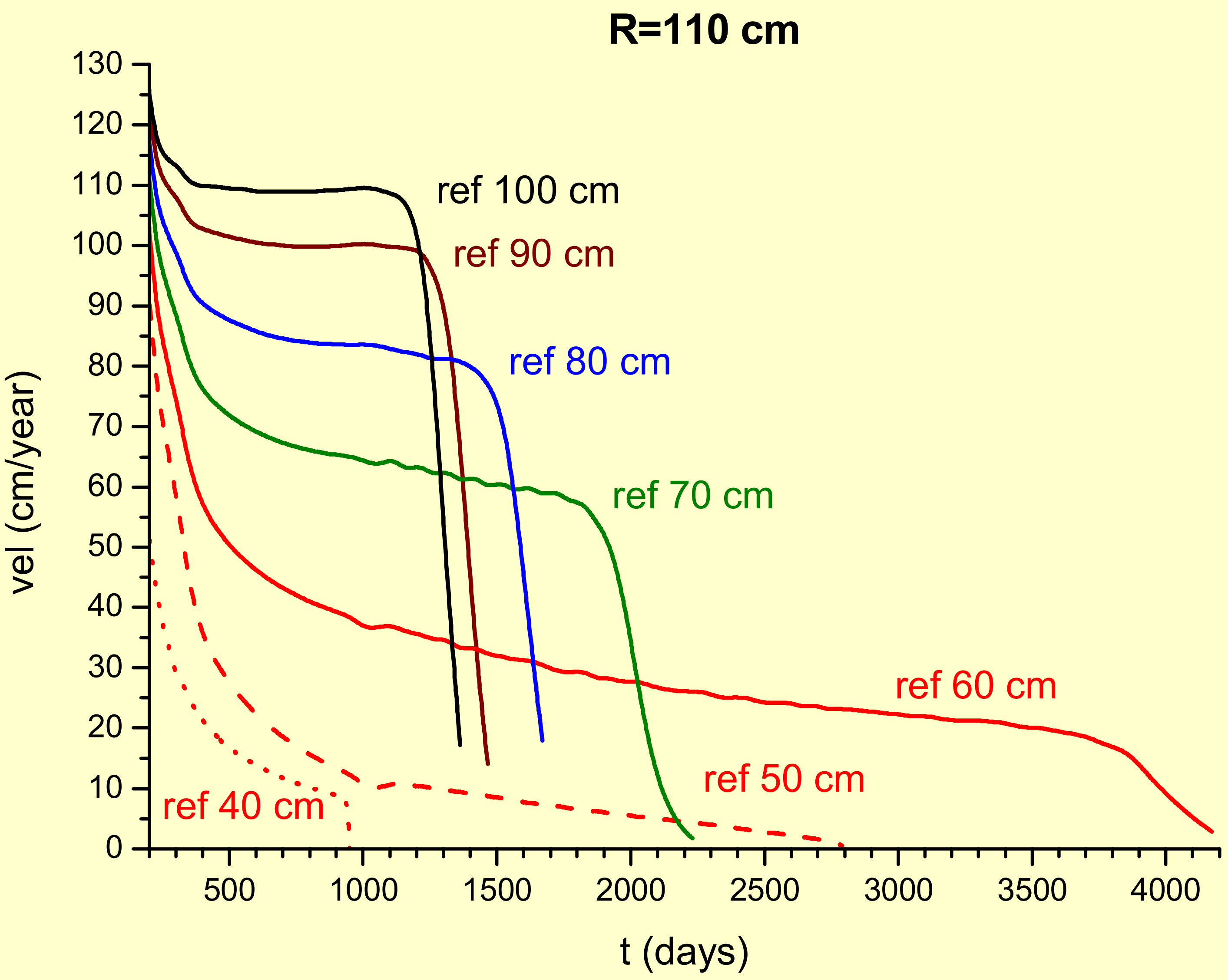
R = 150 cm (red line) ; **120 cm (green line)** ; **R = 110 cm (blue line)**

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

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

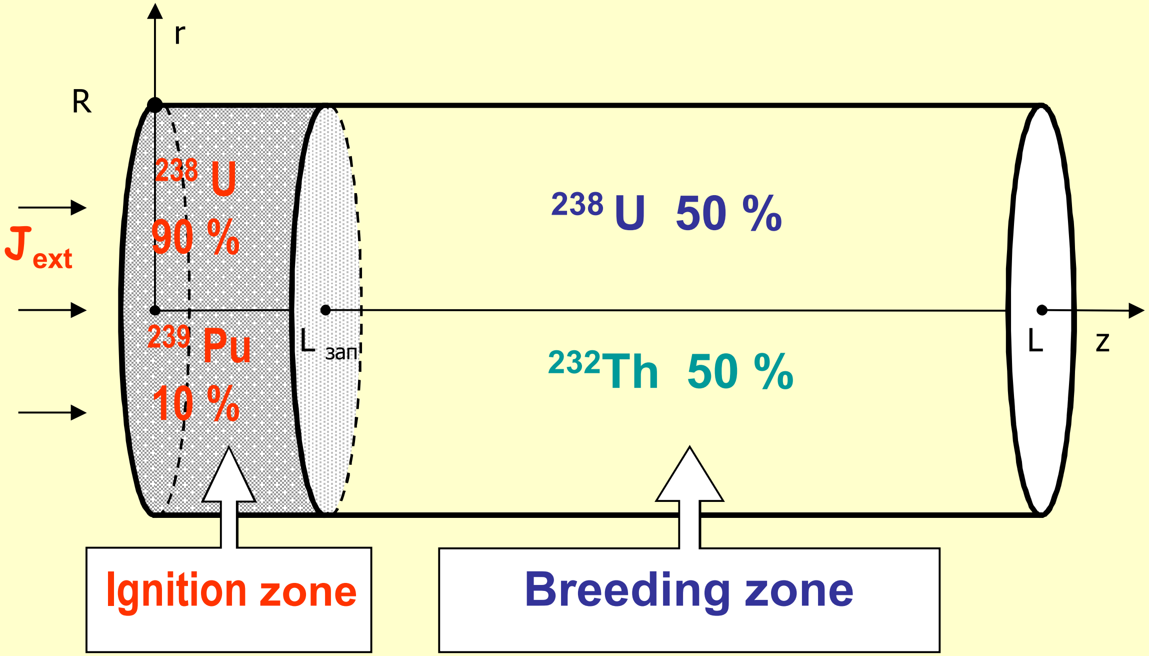


Reactor Power Control by Reflector Efficiency



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 = 0.35; Coolant (Pb-Bi eutectic) vol. frac. = 30%, Constr. materials (Fe) vol. frac. = 15%; R = 390 cm



NBW reactor with mixed Th-U-Pu fuel cycle

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

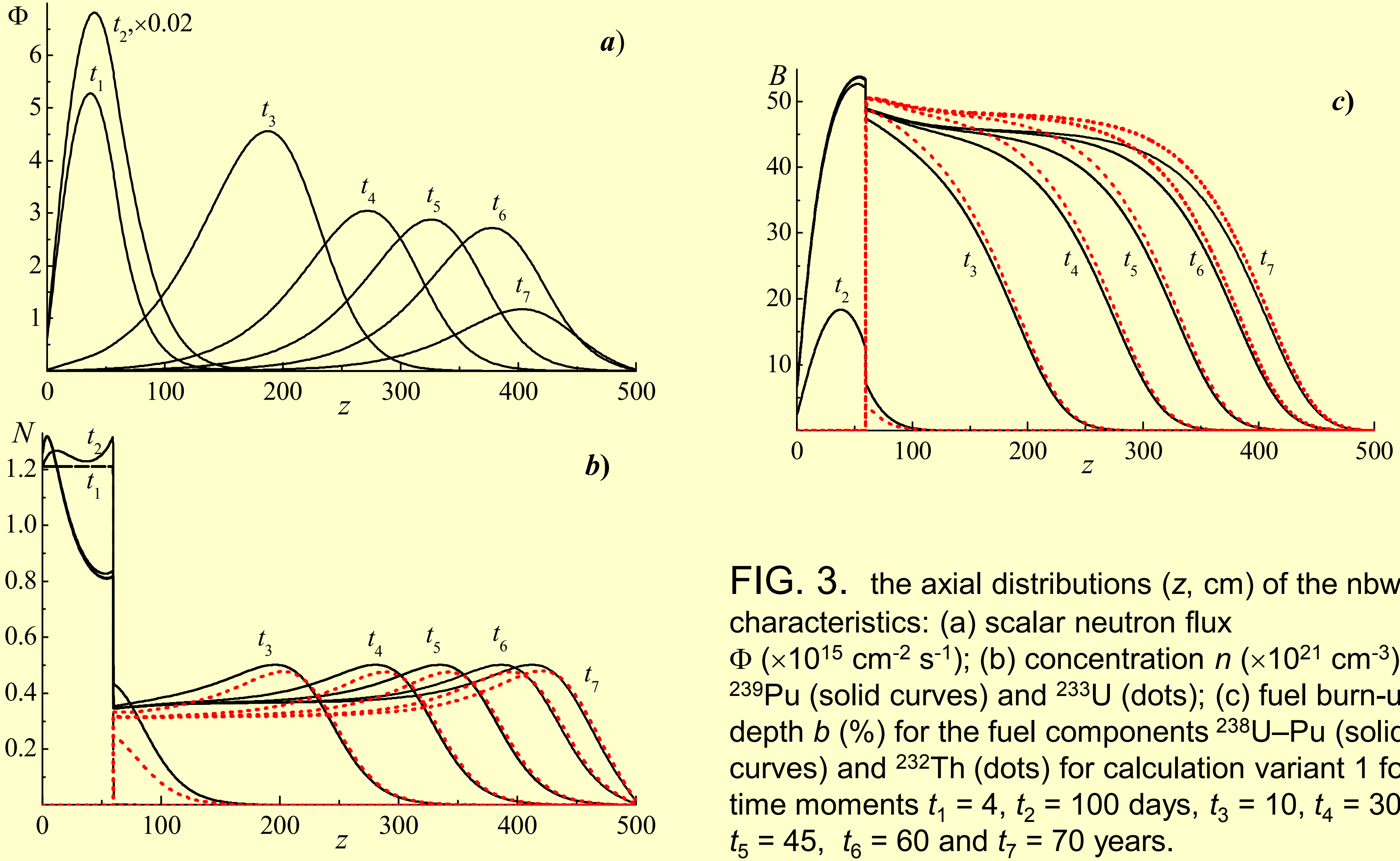
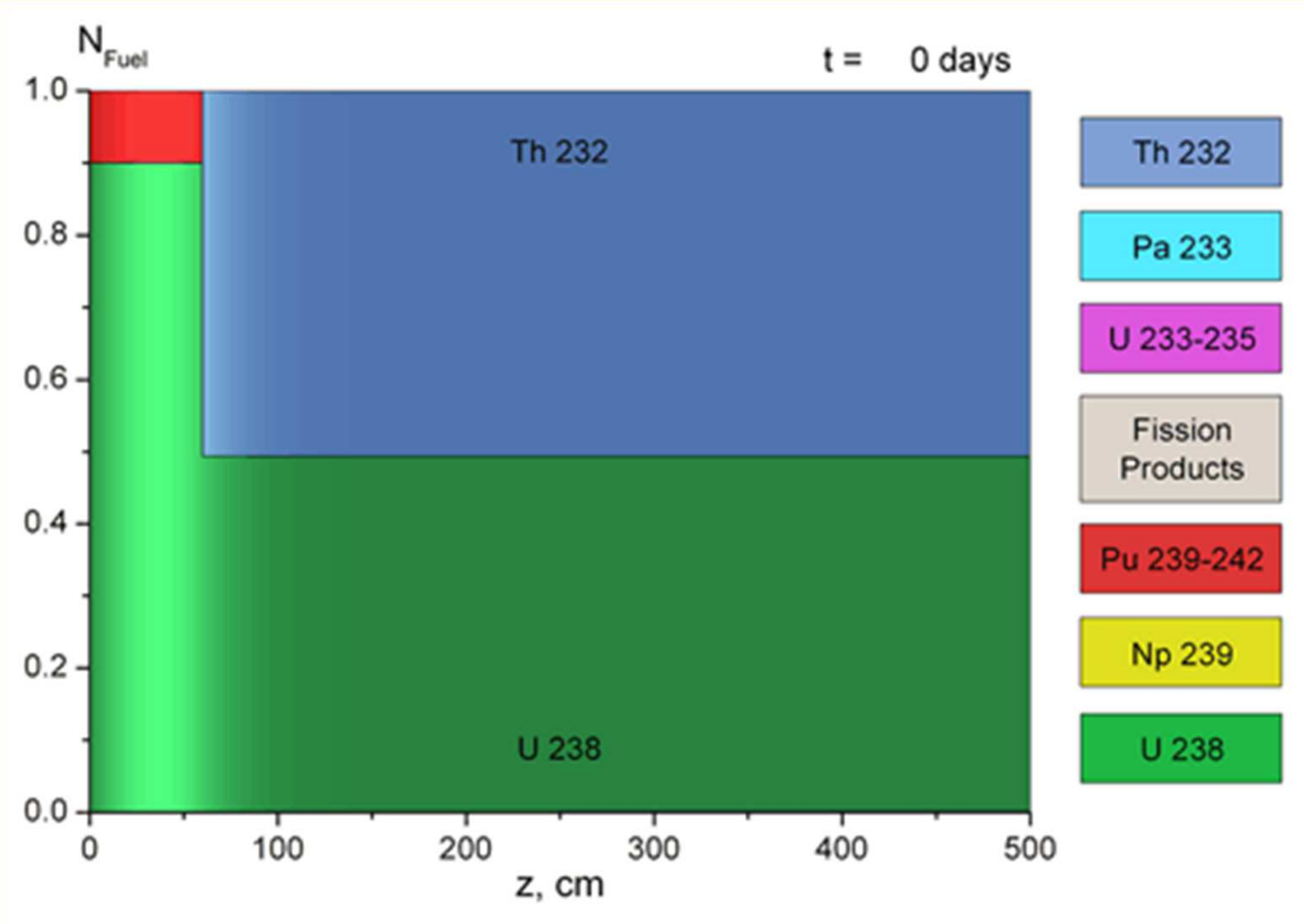
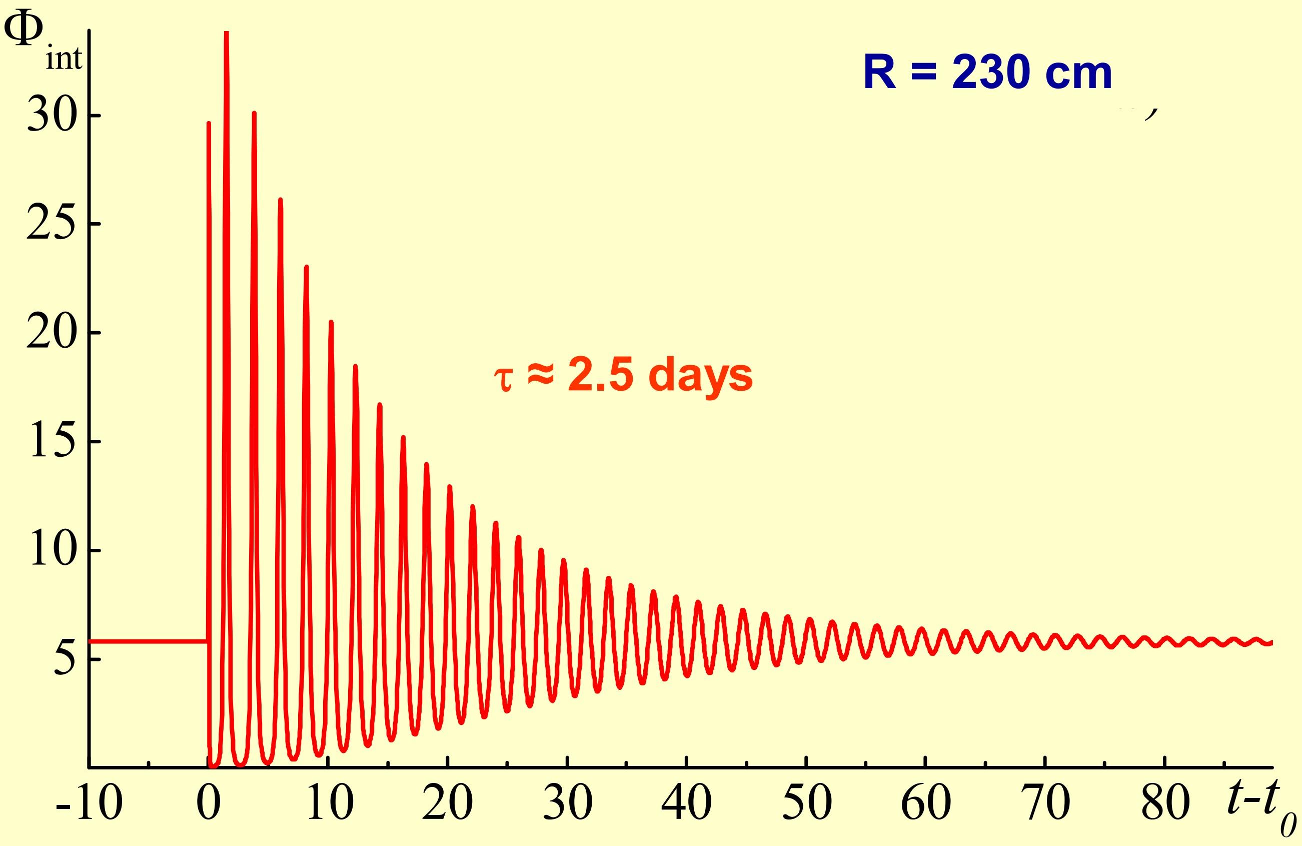


FIG. 3. the axial distributions (z, cm) of the nbw characteristics: (a) scalar neutron flux Φ ($\times 10^{15}$ cm^{-2} s^{-1}); (b) concentration n ($\times 10^{21}$ cm^{-3}) for ^{239}Pu (solid curves) and ^{233}U (dots); (c) fuel burn-up depth b (%) for the fuel components ^{238}U–Pu (solid curves) 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



Stability of the NBW Regime

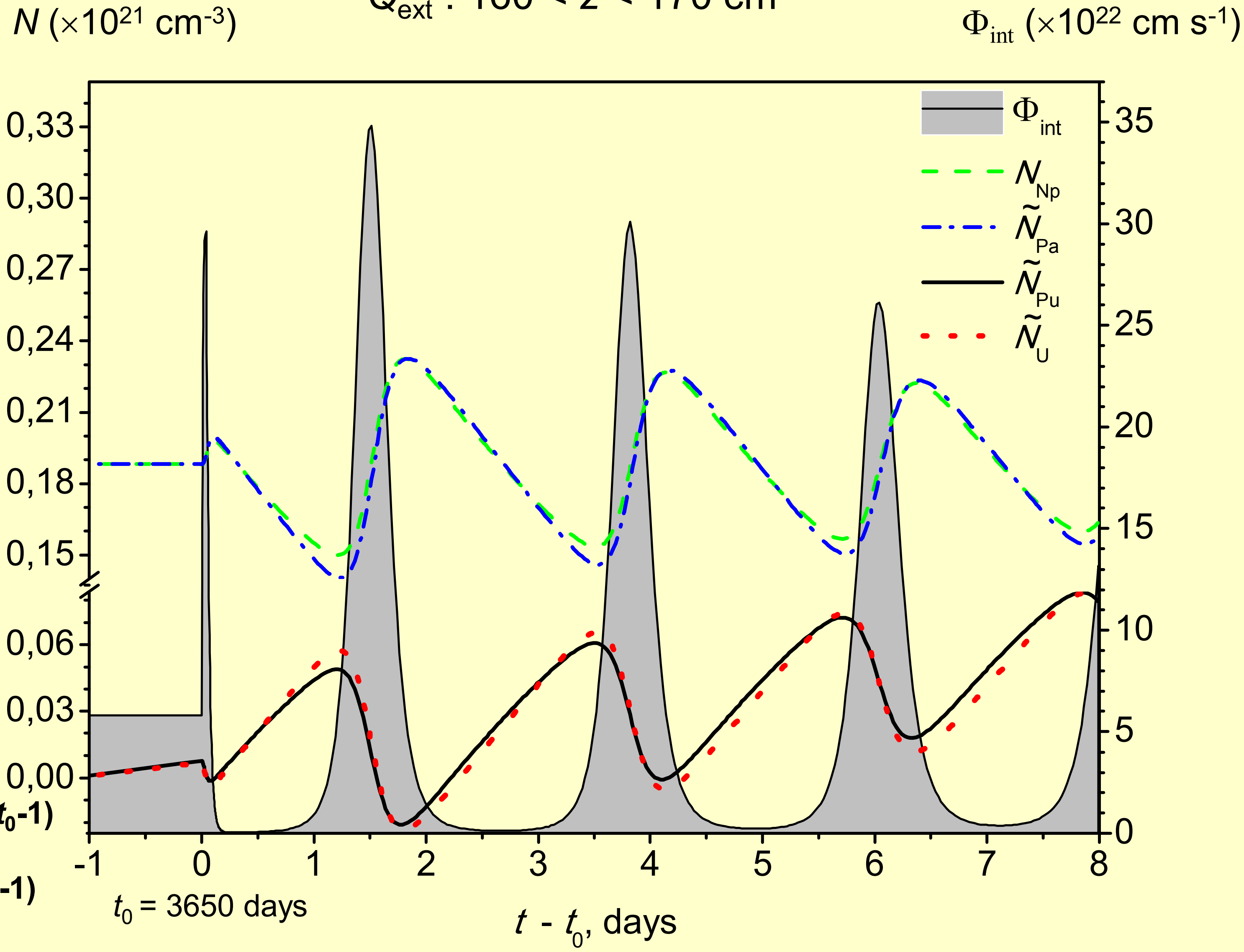


Perturbation of integral neutron flux F_{int} ($\times 10^{22}$ cm/s) caused by an external neutron source via time t (days). The source with intensity $Q_{ext} = 2\times 10^{11}$ (cm^{-3} s^{-1}) starts at t_0 = 3650 days, lasts during 1 hour and is situated at $160 < z < 170$ cm

Negative Reactivity Feedback

R = 230 cm

Q_{ext} : $160 < z < 170$ cm



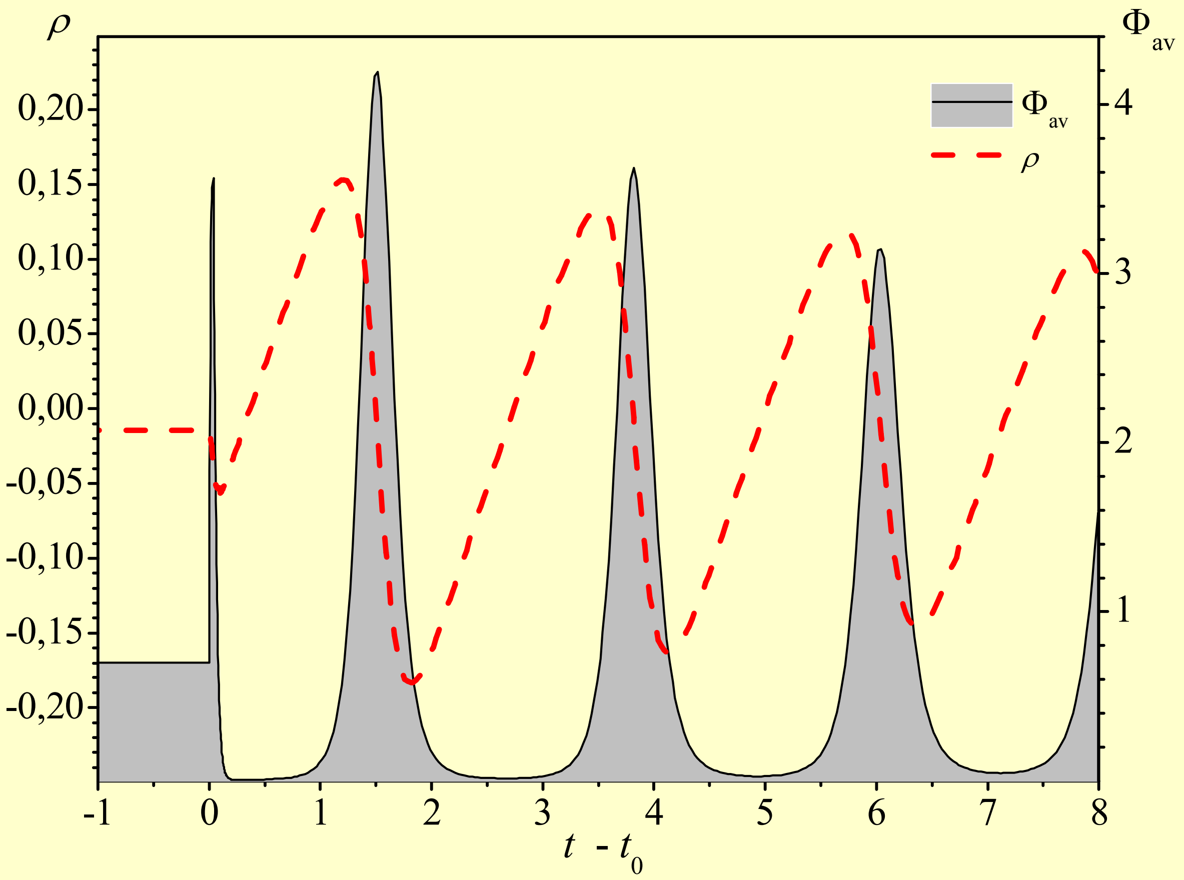
$\tilde{N}_{Pa} = N_{Pa}(t) - 2{,}2$

$\tilde{N}_{Pu} = N_{Pu}(t) - N_{Pu}(t_0 - 1)$

$\tilde{N}_{U} = N_{U}(t) - N_{U}(t_0 - 1)$

$Q_{ext} = 2 \times 10^{11}$ (cm^{-3} s^{-1}) $\Delta t = 1$ hour

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} (×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 (human factor excluding)**
- **long-term (decades) operation without refueling and external control**
- **possibility of ^{232}Th and ^{238}U utilization as a fuel**
- **production of ^{239}Pu (4%) and ^{233}U (4%) for a "future" reactor fuel**
- **fuel burn-up depth for both ^{238}U and ^{232}Th ≈ 50%**
- **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 GW**
- **wave velocity at the steady-state regime ≈ 2 cm/year**
- **possibility of nuclear waste burn out (expected)**

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

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

S. Fomin et al., IC Global 2009, Paris, France (2009) Paper #9456.

S. Fomin et al., ICAPP 2010, San Diego, USA (2010) Paper #10302.

S. Fomin et al., *Progress in Nuclear Energy*, 53 (2011) 800-805.

S. Fomin et al., JKNU, 1041, "Nuclear, Particles, Fields" #2/58 (2013) 49-56.

S. Fomin et al., IAEA IC FR-13, Paris, France (2013) in print.

INTERNATIONAL ATOMIC ENERGY AGENCY

Nuclear Burning Wave Benchmark Specifications for the IAEA Coordinated Research Projects

Analytical and Experimental Benchmark Analysis on Accelerator Driven Systems & Technical Working Group – Fast Reactors

Compiled By
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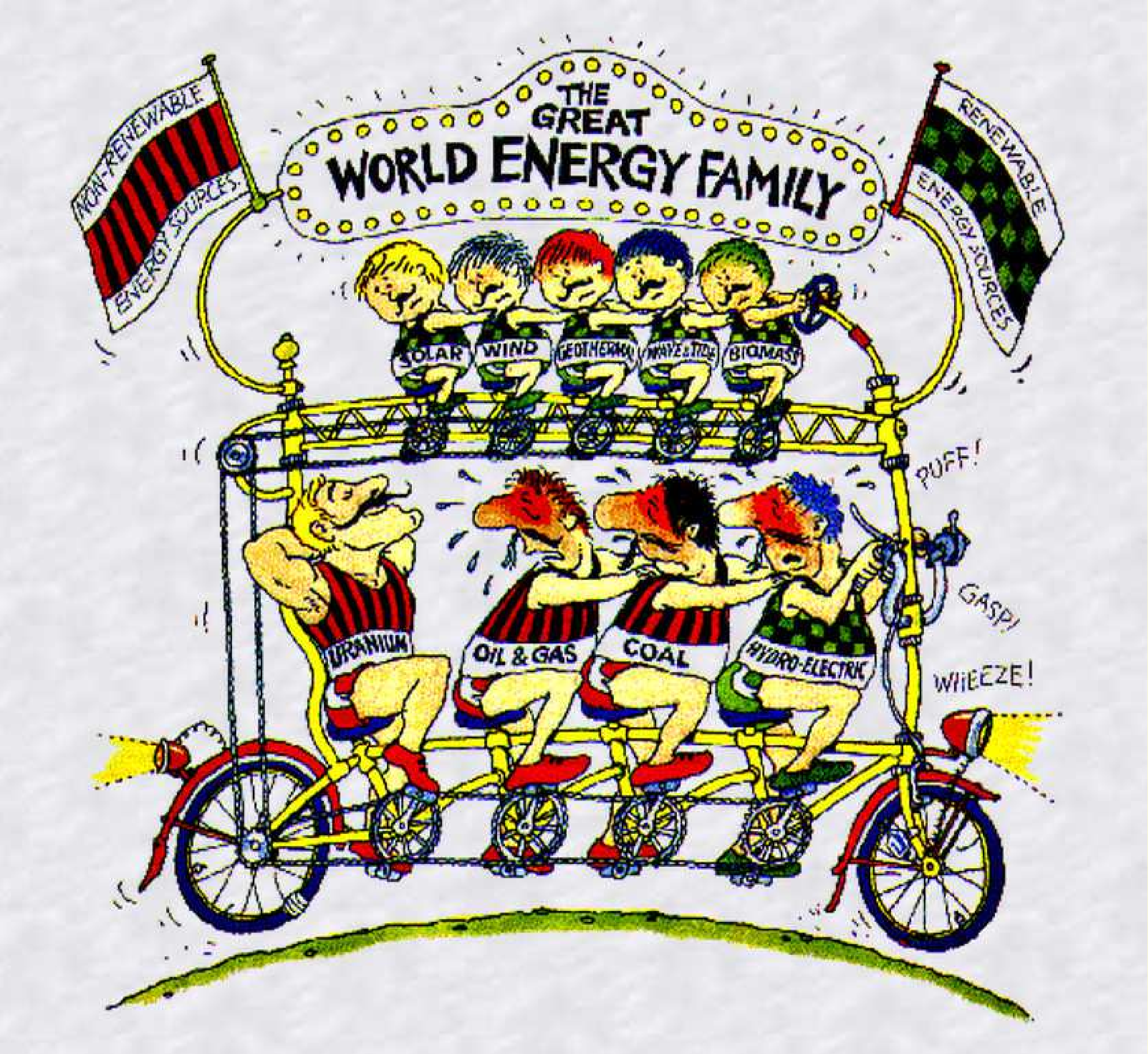
Issued 2009-03-30

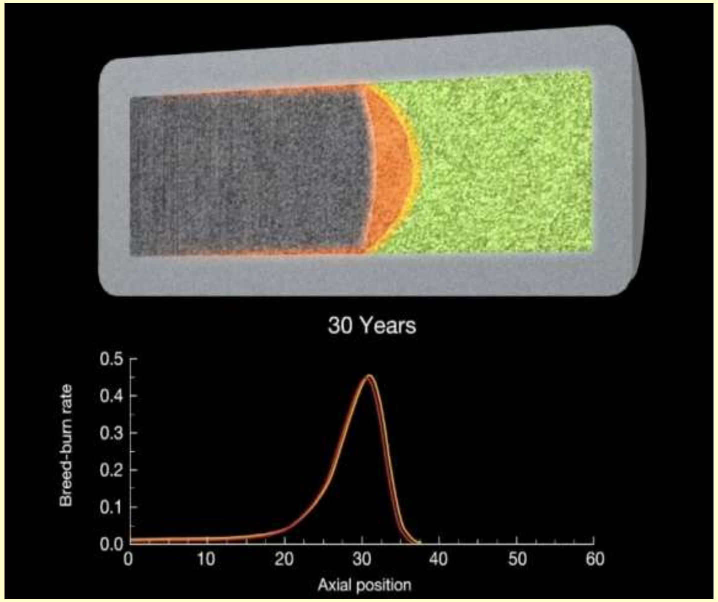


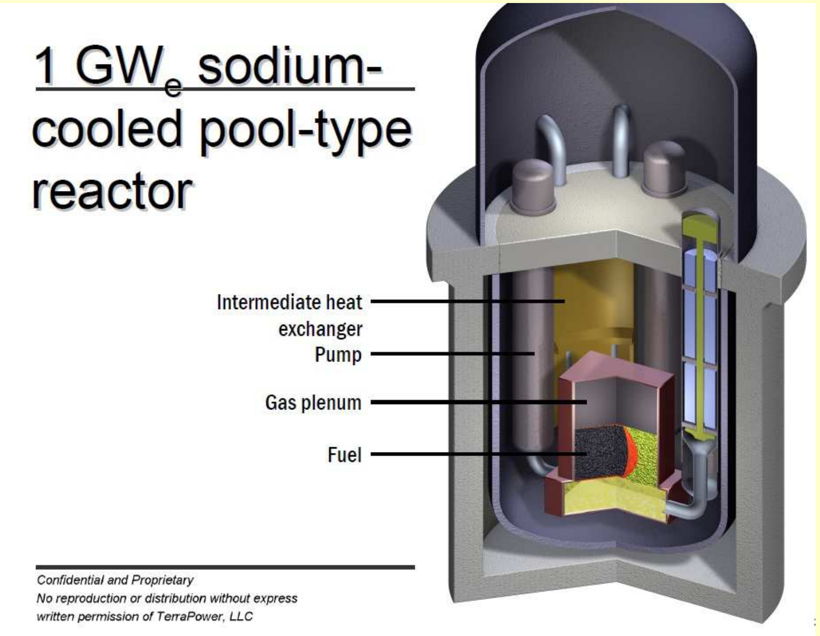
Thank you for attention !

TerraPower

Technology Entertainment Design, USA (February 12, 2010)

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





1 GW_e sodium-cooled pool-type reactor

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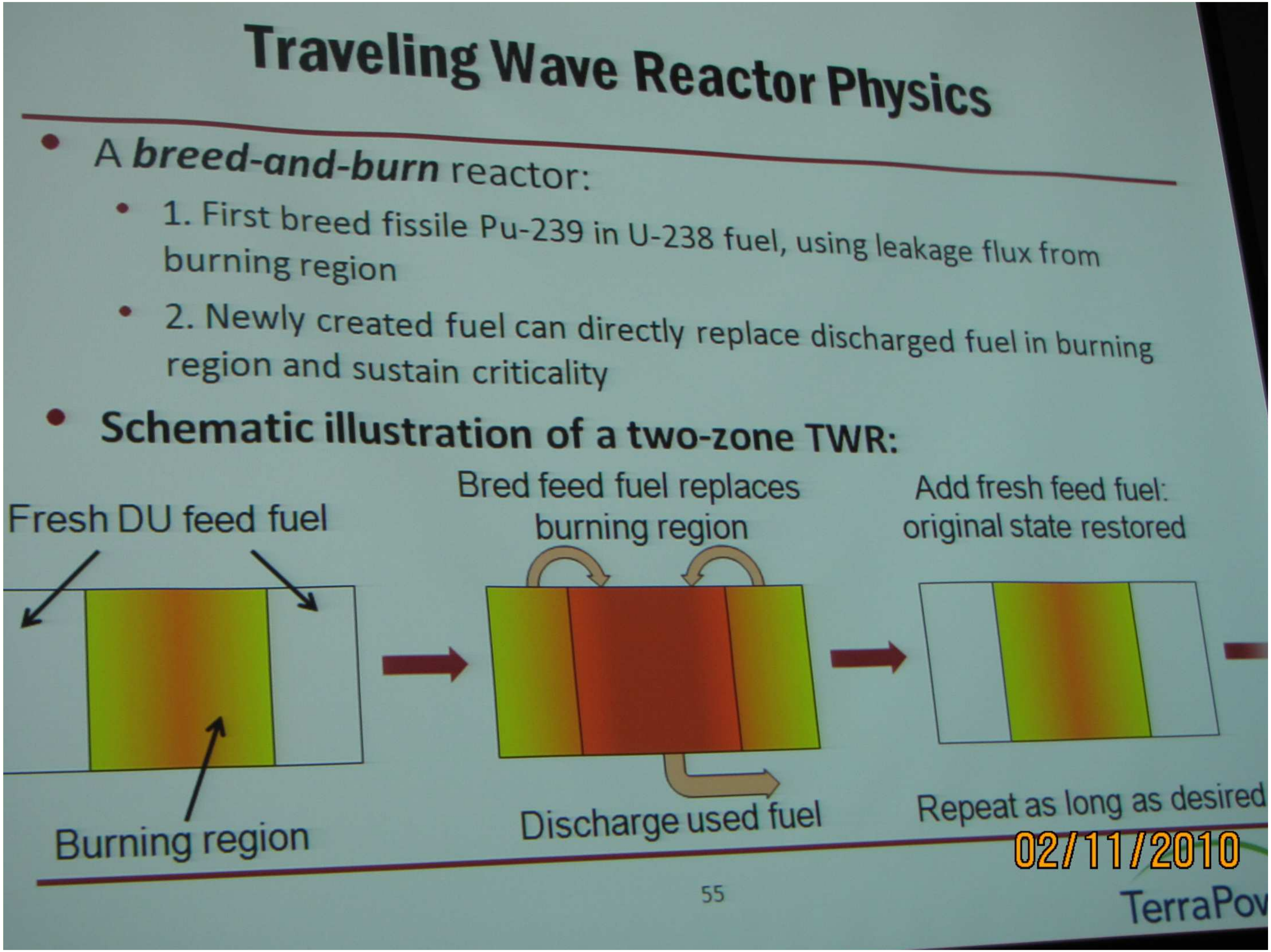


Traveling Wave Reactor Physics

- 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:**

Fresh DU feed fuel

Burning region

Bred feed fuel replaces burning region

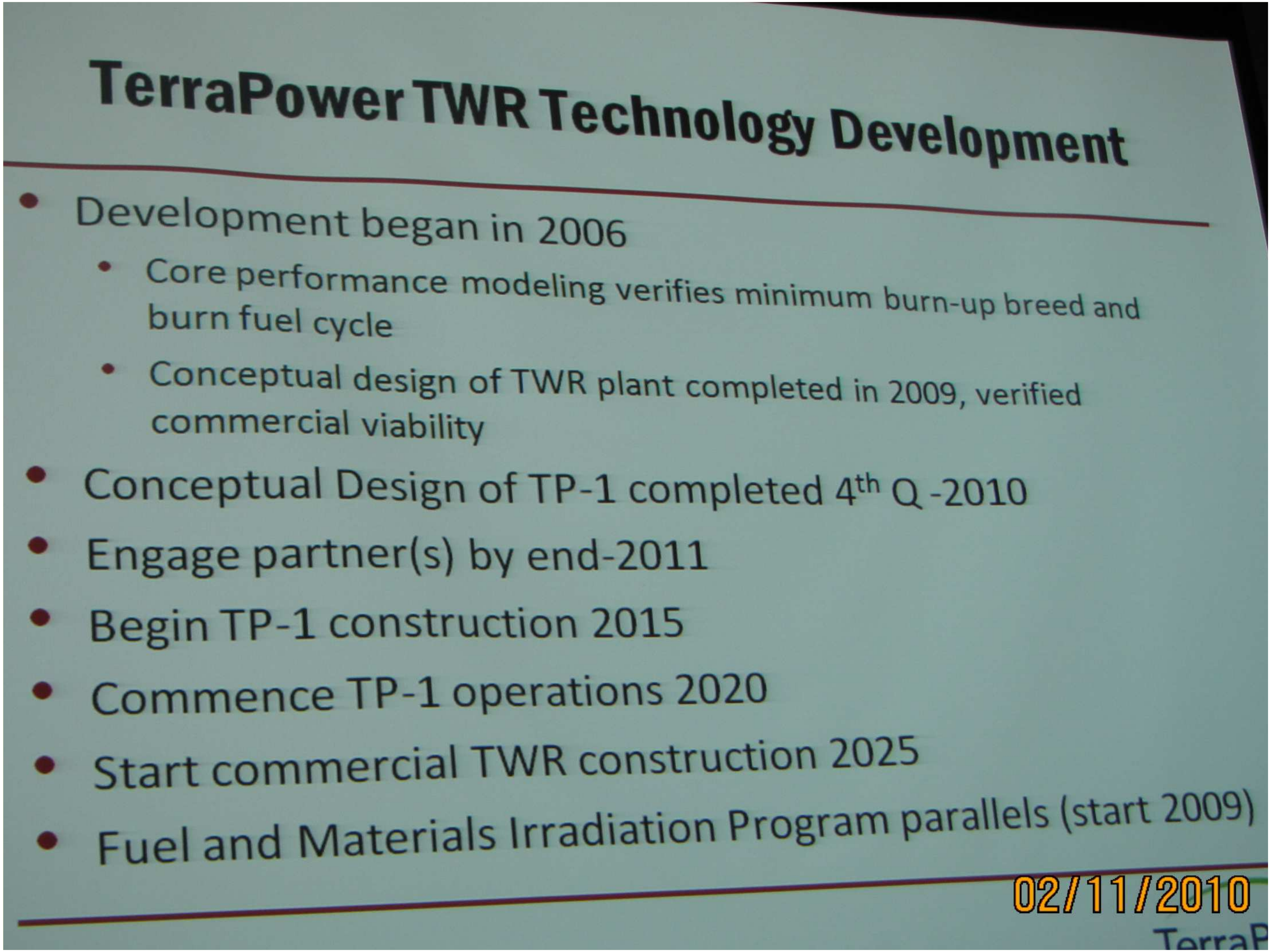
Discharge used fuel

Add fresh feed fuel: original state restored

Repeat as long as desired

02/11/2010

TerraPow

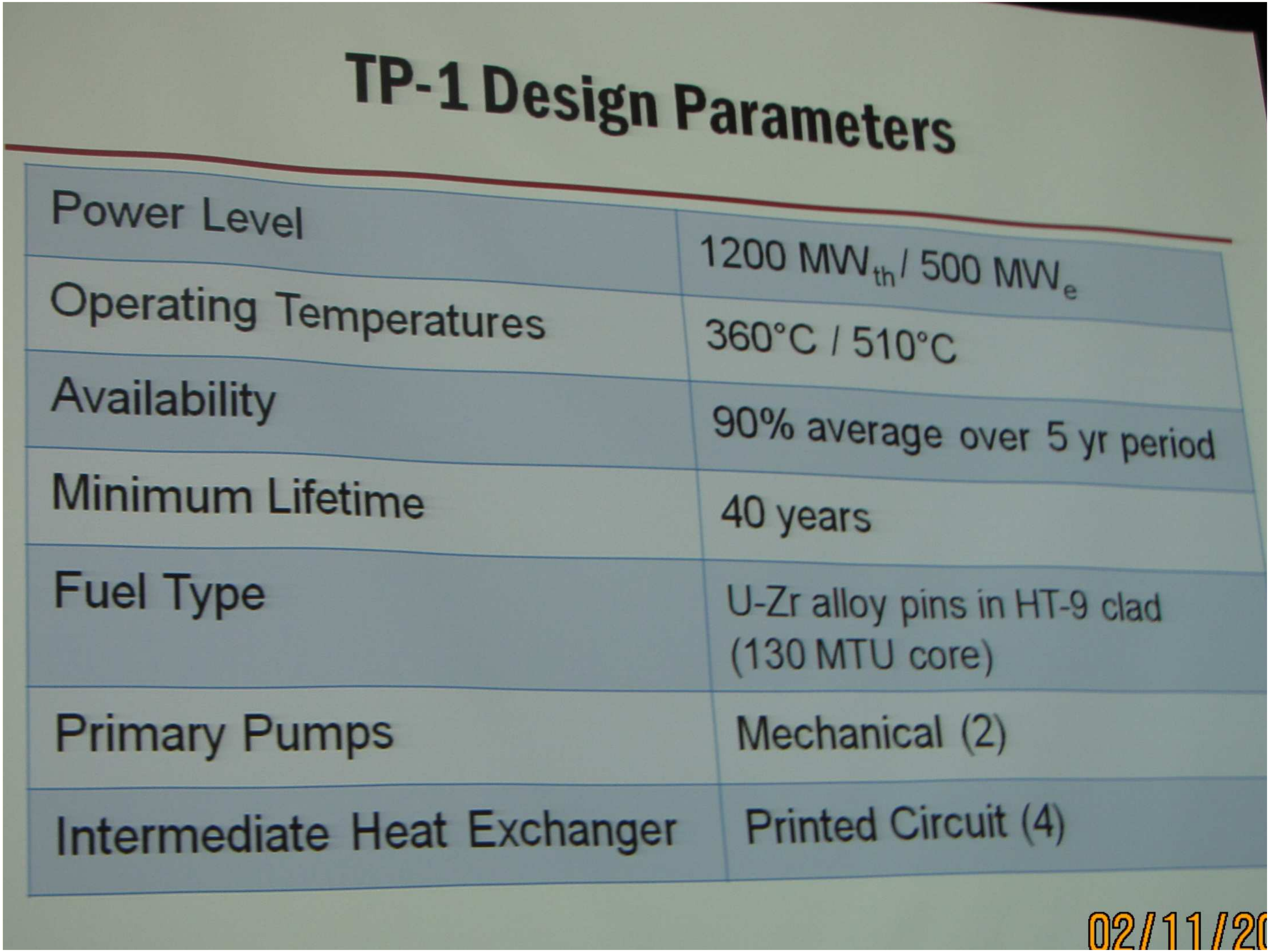


TerraPower TWR Technology Development

- Development began in 2006
  - Core performance modeling verifies minimum burn-up breed and burn fuel cycle
  - Conceptual design of TWR plant completed in 2009, verified commercial viability
- Conceptual Design of TP-1 completed 4th Q -2010
- Engage partner(s) by end-2011
- Begin TP-1 construction 2015
- Commence TP-1 operations 2020
- Start commercial TWR construction 2025
- Fuel and Materials Irradiation Program parallels (start 2009)

02/11/2010

TerraP

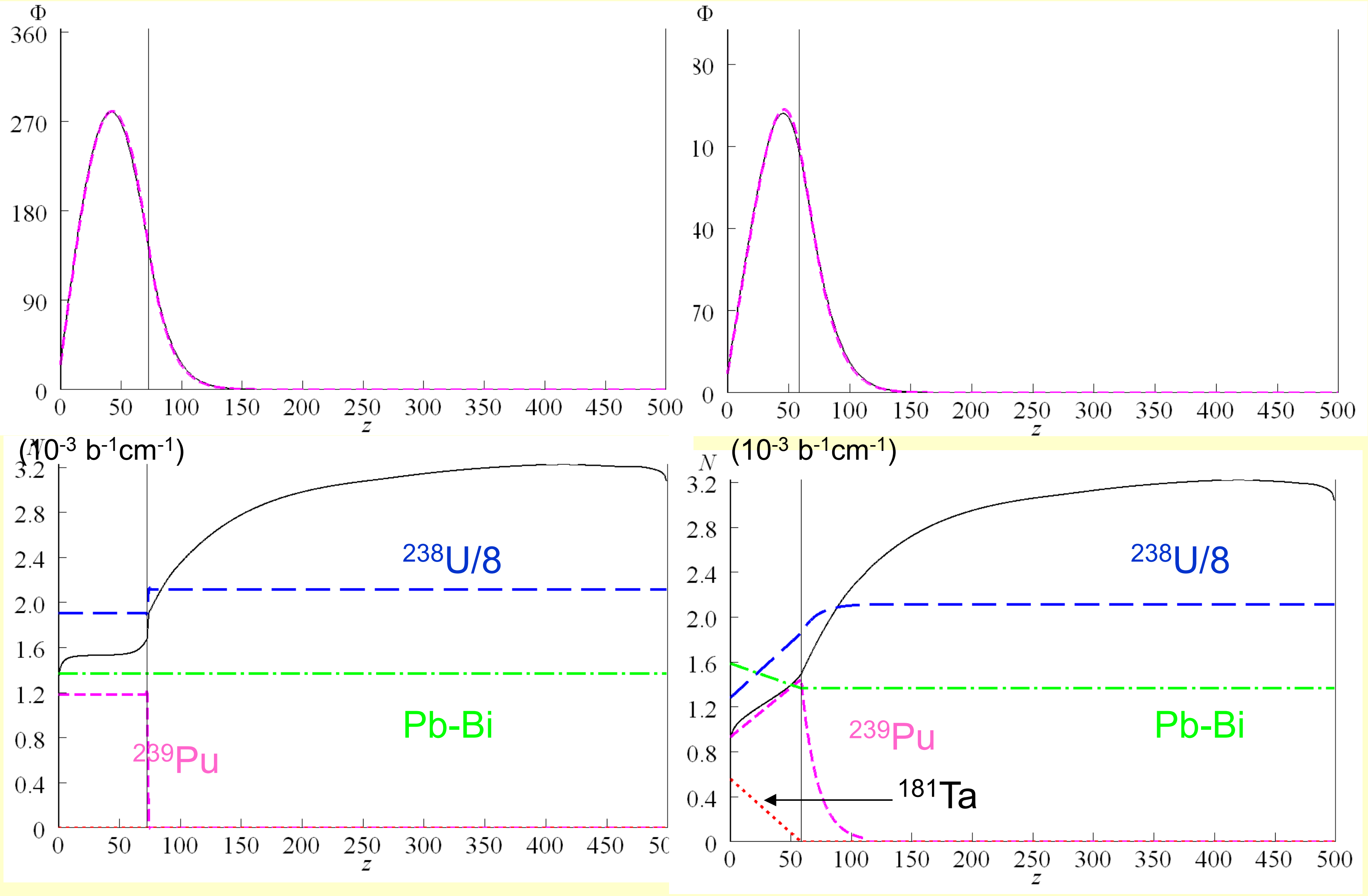


TP-1 Design Parameters

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)

Startup problem of the NBW Reactor

Neutron flux Φ, $b^{-1}day^{-1}$



Smooth Startup of the NBW Reactor