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

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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):

Concept & Analytical approach

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

\[
\frac{\partial N_8}{\partial t} = -vn \sigma_{a8} N_8 ; \quad \frac{\partial N_9}{\partial t} = v n \sigma_{a8} N_8 - \frac{1}{\tau_\beta} N_9
\]

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

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

\[
T_{1/2} \approx 2.35 \text{ days}
\]

\[
N_{Pu}^{eq} > N_{Pu}^{cr}
\]

\[
x = z + Vt
\]

Goldin & Anistratov (USSR, 1992): Nuclear Burning Wave

Edward Teller (USA, 1997): Traveling Wave Reactor

Hiroshi Sekimoto (Japan, 2001): CANDLE

Deterministic approach

U-Pu fuel cycle

1d non-stationary problem

Th-U fuel cycle

Deterministic approach

Stationary problem: \( x = z + Vt \)
**Nuclear fuel reproduction**

**Th-U fuel cycle**

- $^{232}\text{Th}$ → $^{233}\text{Th}$
  - $T_{1/2} = 22.2$ min
- $^{233}\text{Th}$ → $^{233}\text{U}$
  - $T_{1/2} = 27$ days
- $^{233}\text{U}$ → $^{233}\text{Pa}$
  - $T_{1/2} = 6.75$ days

**U-Pu fuel cycle**

- $^{238}\text{U}$ → $^{239}\text{U}$
  - $T_{1/2} = 23.5$ min
- $^{239}\text{U}$ → $^{239}\text{Pu}$
  - $T_{1/2} = 2.35$ days
- $^{239}\text{Pu}$ → $^{240}\text{Pu}$ → $^{241}\text{Pu}$ → $^{242}\text{Pu}$ → $^{243}\text{Pu}$
  - $T_{1/2} = 14.3$ years
  - $T_{1/2} = 4.98$ hours
- $^{241}\text{Am}$ → $^{243}\text{Am}$
  - $T_{1/2} = 4.98$ hours

**Th-U fuel cycle**

- $^{237}\text{Np}$
  - $T_{1/2} = 6.75$ days
2D Non-Stationary Theory of Nuclear Burning Wave


Non-Stationary Nonlinear Multi-Group Diffusion Equation of Neutron Transport

\[
\frac{1}{v^g} \frac{\partial \Phi^g}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} D^g \frac{\partial \Phi^g}{\partial r} - \frac{\partial}{\partial z} D^g \frac{\partial \Phi^g}{\partial z} + \left( \Sigma^g_a + \Sigma^g_{in} + \Sigma^g_{mod} - \Sigma^g_{\rightarrow g} \right) \Phi^g - \Sigma^g_{mod} \Phi^{g-1} =
\]

\[
= \chi_f \sum_{g'=1}^{G} (v_{f} \Sigma_{f})^{g'} \Phi^{g'} - \sum_{j} \chi_{d}^{j} \sum_{l} \beta_{l}^{j} \sum_{g'=1}^{G} (v_{f} \Sigma_{f})_{l}^{g'} \Phi^{g'} + \sum_{j} \chi_{d}^{j} \sum_{l} \lambda_{l}^{j} C_{l}^{j} + \sum_{g'=1}^{G} \Sigma_{\rightarrow g}^{g'} \Phi^{g'}
\]

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

\[
\frac{\partial N_{l}}{\partial t} = - \left( \sum_{g} \sigma_{al}^{g} \Phi^{g} + \Lambda_{l} \right) N_{l} + \left( \sum_{g} \sigma_{c(l-1)}^{g} \Phi^{g} + \Lambda_{(l-1)} \right) N_{(l-1)} \quad (l = 1 \pm 8);
\]

\[
\frac{\partial N_{9}}{\partial t} = \Lambda_{6} N_{6}
\]

of Precursor Nuclei of Delayed Neutrons

\[
\frac{\partial C_{l}^{j}}{\partial t} = - \lambda_{l}^{j} C_{l}^{j} + \beta_{l}^{j} \sum_{g} (v_{f} \Sigma_{f})_{l}^{g} \Phi^{g}
\]

Metal fuel (44%)  Pb-Bi coolant (36%)
CM - Fe (20%)

\[j_{ext} \sim 10^{15} \text{ cm}^{-2} \text{s}^{-1}\]
\[t_{off} = 400 \text{ days}\]
NBW Reactor: $R = 117$ cm, $L = 500$ cm, $t_{\text{off}} = 950$ days

\[
\Phi, 10^{17} \text{ cm}^{-2} \text{ s}^{-1}
\]

\[
N_{\text{Pu}}, 10^{21} \text{ cm}^{-3}
\]

\[t = 0 \text{ months}\]
NBW reactor with mixed Th-U-Pu fuel

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

Example: Metallic fuel $^{232}\text{Th}$ (62%) + $^{238}\text{U}$ (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 (!)

Graphs showing the flux and changes in neutron populations over time.
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 $\rho$ (dollars) with time $t$ (days) along the variation of the volume-averaged neutron flux $F_{av}$ ($\times 10^{15}$ cm$^{-2}$ c$^{-1}$)
Stability of the NBW Regime

(enriched region in the breeding zoon)
Stability of the NBW Regime

62% Th, R=230 cm,  5% brick,  z=300÷320 cm

62% Th, R=230 cm, 10% brick,  z=300÷320 cm
Smooth Startup of the NBW Reactor

Smooth Startup of the NBW Reactor

$P$, GW

$\Phi$, $10^{17}$ cm$^{-2}$ s$^{-1}$

$N$, $10^{21}$ cm$^{-3}$

$N_{238U} \times 0.125$

$N_{239Pu}$

$N_{Ta}$

$N_{Pu}$, $10^{21}$ cm$^{-3}$

$Z$, cm

$Z$, cm
Shutdown and Restart of the NBW Reactor

\[ \rho, \ \$, \quad P, \ GW \]

\[ \Delta N_{Pu} \]

\[ t, \ days \]
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 \(^{232}\text{Th}\) and \(^{238}\text{U}\) utilization as a fuel
- fuel burn-up depth for both \(^{238}\text{U}\) and \(^{232}\text{Th}\) \(\approx 50\%\) (one through cycle !)
- neutron flux in active zone \(\approx 2 \cdot 10^{15}\) n/cm\(^2\)s
- neutron fluence during the whole reactor campaign \(\approx 3 \cdot 10^{24}\) n/cm\(^2\)
- energy production density in active zone \(\approx 200\) W/cm\(^3\)
- total power at the steady-state regime \(\approx 1.2\) GWt
- wave velocity at the steady-state regime \(\approx 2\) 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
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:**

  ![Diagram showing the process of a two-zone TWR with blocks labeled as Fresh DU feed fuel, Bred feed fuel replaces burning region, Add fresh feed fuel: original state restored, and Burning region with Discharge used fuel.]

Repeat as long as desired.
Reactors Start to Spread in Waves Around the World

Map of World’s Nuclear Power Plants
List of our publications on the NBW reactor:

S. Fomin et al., ICENES (2005) (Brussels, Belgium) paper IC058.
S. Fomin et al., ICAPP’06 (2006) (Reno, USA) paper 6157.
S. Fomin et al., ICAPP’07 (2007) (Nice, France) paper 7499.
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., 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!