A Breakthrough for Step Forward - Nano-particle Fueled Fluid Fast Reactor

T. K. Kim, H. Connaway, C. Grandy
USNIC – Argonne Special Technical Symposium
Advanced Reactor Outlook: Sunny, Five Degrees & Bright Minds Ahead
Chicago, January 28-29, 2014
Content

- Motivation of Nano-fueled Fluid Fast Reactor (NFFFR)
- Overview of NFFFR
- Feasibility of NFFFR Core Concept
- Conclusions
- Questions (Future Works)
Motivation of Nano Particle Applications
Motivated Question - So What?

- **How about Fast Reactor?**
  - **Fast reactor development**
    - After first self-sustaining nuclear chain reaction was demonstrated in CP-1 in 1942 at Chicago, E. Fermi had a vision of closed nuclear fuel cycle with fast neutrons (see Fermi’s paper)
    - World's first electricity from nuclear energy was produced by EBR-I
    - SFR technology is demonstrated with 400 operating-years worldwide
  - **Demonstrated Inherently safety features**
    - Passive safety potential of metallic fast reactor was demonstrated in EBR-II on April 3, 1986 for unprotected severe accidents (such as station blackout)
  - **Multiple missions of U.S. fast reactor programs**
    - Flexible actinide management for fuel cycle missions (GNEP)
    - Enhance natural resource utilization (50-70s SFR programs)
    - Sustainable nuclear fuel cycles (DOE-NE Nuclear Energy R&D Roadmap)

- **Development of Nano-particle Fueled Fluid Fast Reactor (NFFFR) was motivated by a simple question,**
  - “Why not commercial fast reactor in United States even though fast reactor development started earlier than Light Water Reactors, inherent safety features were demonstrated, and fast reactors can achieve multiple missions such as fissile breeding and nuclear waste burning?”
  - So what? US does not have a commercial fast reactor...
THE FUTURE OF ATOMIC ENERGY

by

E. Fermi

This document consists of 6 + 1 pages.
Date Released: May 27, 1946

desirable. On the other hand $^{236}\text{U}$ plays a very essential role in the pluto-
nium production. Indeed $^{236}\text{U}$ is transformed during the reaction into pluto-
nium by the mechanism represented in the following nuclear process:

\[ \text{U}^{238} + n \rightarrow \text{U}^{239} \]
\[ \text{U}^{239} \rightarrow \text{Pu}^{239} + \alpha \]
\[ \text{Pu}^{239} \rightarrow \text{Pu}^{239} + \alpha \]
Reasons for Why Not Yet?

- **Cost**
  - LWRs are well operating worldwide and evolved generation-by-generation. So, why need new kind reactor without significant benefit of cost reduction. For moving forward to fast reactor from thermal reactor, fast reactor capital cost should be order of magnitude smaller than that of LWRs.

- **Reprocessing and Separation**
  - It is hard to solve proliferation issue when used fuel are chemically reprocessed
  - However, in order to achieve a sustainable fuel cycle using fast reactor technology, reprocessing of used fuel is required. In particular, separation of fission products from actinides is crucial to maintain criticality

- **Potential accident causes**
  - After Fukushima accident, public expects perfectly safe reactor
  - Public may not accept accident causes (such as sodium-cooled reaction) that are potentially existed in advanced nuclear reactors

- **Need a breakthrough idea for step forward**
  - To resolve three major issues, NFFFR concept was developed
Overnight Capital Cost
Overview of NFFFR
Nano-particle Fueled Fluid Fast Reactor - NFFFR

- **Goals of NFFFR**
  - Extremely simple core geometry (order of magnitude reduction of capital cost)
  - Recycling actinide without chemical separation targeting high resource utilization
  - Highly improved inherent safety features

- **Concepts (see conceptual schematic draw)**
  - Cost reduction
    - Core is a simple cylindrical pot, which contains mixture of (liquid metal) fluid and nano-size actinide metals
    - Criticality can be determined by controlling particle volume fraction and pot size
  - FP separation without chemical separation of used fuel
    - FPs can escape from nano particles per fission because FP recoil distance is longer than nano-particle size
    - Solid FPs are deposited in fluid and gaseous FPs are collected at gas-plenum
    - Deposited solid FPs can be separated from nano-particles using simple centrifugal separation technology
    - Core may maintain criticality with bred Pu when FPs are removed effectively
  - Potential fluid materials
    - Lead-bismuth-eutectic (LBE), sodium, fluoride salt. etc
Schematic NFFFR Core Configuration

- Fluid pot
- Fluid with nano-fuel particles
- Central hole for fluid overflow
- Control rods
### Schematic Overview of NFFFR Concept

- **Nano particle size** (~100 nm)
- **FP recoil distance** (few μm)

#### Criticality
- Criticality and cycle length are dependent on pot size (diameter and fluid level) and particle volume fraction
  - 10-12% LEU, 20-25% particle volume fraction, 2-meter diameter, and 1-meter long is sufficient
- Excess reactivity is controlled by control rod
- Heat can be removed using surrounding coolant (see heat removal concept)

#### Improved inherent safety feature
- Thermal expansion rates of structure (fluid pot) and fluid are different
- Higher volumetric thermal expansion of fluid results in fluid overflow as temperature rises, which introduces strong negative reactivity feedback
How Big Nano Particle?

<table>
<thead>
<tr>
<th></th>
<th>Values</th>
<th>Relative to neutron size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>~10^-15 m</td>
<td>Golf ball ~4.3x10^-02 m</td>
</tr>
<tr>
<td>Nano particle (100 nano-meter)</td>
<td>~10^-07 m</td>
<td>Moon diameter ~3.5x10^+06 m</td>
</tr>
<tr>
<td>FP recoil distance</td>
<td>~10^-05 m</td>
<td>Moon and earth distance ~4x10^+08 m</td>
</tr>
</tbody>
</table>

- Neutron *(golf ball)* makes a fission in a nano particle *(moon)* and FPs recoil to far outside of nano-particle *(to earth)*
Due to high thermal conductivity of metals (fluid, fuel, and structures are all metals), heat can be transferred to surrounding coolant

Two cooling schemes are considered
- Circular piping or annular cooling schemes
- Cooling capability is dependent on pipe size, thickness of annular coolant blanket, and flow rate, etc.
Comparison between NFFFR vs SFR

<table>
<thead>
<tr>
<th></th>
<th>NFFFR</th>
<th>Conventional SFR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel</strong></td>
<td>Nano-particle uranium</td>
<td>Fuel slug (pellet), cladded and assembled</td>
</tr>
<tr>
<td><strong>Core</strong></td>
<td>Mixture of nano-particle fuel and liquid metal in simple pot (coffee in a cup)</td>
<td>Fuel assemblies are arranged</td>
</tr>
<tr>
<td><strong>Reactor</strong></td>
<td>Control rod and circulation loop</td>
<td>Control rod, fuel handling device, cooling</td>
</tr>
</tbody>
</table>
Feasibility of NFFFR Core Concept
- Power rate of 2000 MWth and power density of ~250 W/cm$^3$
- Pot diameter of ~2.6 m and effective pot height of 1.4 m
- 11% enriched uranium nano particles and particle volume fraction of 25%
- NFFFR core performance was evaluated using equivalent hexagonal core
- Tentatively, feasibility calculations were performed for sodium fluid using ANL fast reactor code system (MC2-3/DIF3D/REBUS3/VARI3D)
NFFFR Core Performance without Recycling

Core performance of once-through option (whole core refueling without used fuel recycling) was assessed. Core k-effective increases initially due to bred Pu, and decreases as FP’s poison effect is accumulated.
Once-through NFFFR Core Performance

<table>
<thead>
<tr>
<th></th>
<th>AFR-100</th>
<th>NFFFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rate, MWth</td>
<td>250</td>
<td>2000</td>
</tr>
<tr>
<td>Fuel volume fraction, %</td>
<td>43.9</td>
<td>25.0</td>
</tr>
<tr>
<td>Fuel form</td>
<td>Metal slug inside cladding</td>
<td>Metal nano particle</td>
</tr>
<tr>
<td>Fresh fuel enrichment</td>
<td>LEU – 13.8%</td>
<td>LEU - 11%</td>
</tr>
<tr>
<td>Cycle length, effective full power year</td>
<td>27</td>
<td>~7</td>
</tr>
<tr>
<td>Eq. core diameter (driver only), m</td>
<td>2.4</td>
<td>2.6</td>
</tr>
<tr>
<td>Active core height, m</td>
<td>1.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Specific power density, MW/t</td>
<td>10.5</td>
<td>55.1</td>
</tr>
<tr>
<td>Overall fissile breeding ratio</td>
<td>0.80</td>
<td>0.88</td>
</tr>
<tr>
<td>Discharge burnup, MWd/kg</td>
<td>101</td>
<td>132</td>
</tr>
<tr>
<td>Peak discharge fast fluence, $10^{23}$/cm$^2$</td>
<td>5.97</td>
<td>a) N/A</td>
</tr>
<tr>
<td>Burnup reactivity loss, %dk</td>
<td>1.1</td>
<td>3.4</td>
</tr>
<tr>
<td>Average linear power, kW/m</td>
<td>15.2</td>
<td>N/A</td>
</tr>
</tbody>
</table>

- **Reference NFFFR can maintain criticality for 7 years**
- **Several conventional physics concepts (power peaking factor, linear power density, etc.) are not applicable to NFFFR**
Reactivity Feedback Characteristics

<table>
<thead>
<tr>
<th></th>
<th>BOC</th>
<th>EOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective delayed neutron fraction</td>
<td>0.0072</td>
<td>0.0043</td>
</tr>
<tr>
<td>Prompt neutron lifetime, μsec</td>
<td>0.35</td>
<td>0.30</td>
</tr>
<tr>
<td>Radial expansion coefficient,  (1/°C)</td>
<td>-0.08</td>
<td>-0.12</td>
</tr>
<tr>
<td>Axial overflow coefficient,  (1/°C)</td>
<td>-0.95</td>
<td>-1.50</td>
</tr>
<tr>
<td>Sodium void worth, $</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doppler coefficient,  (1/°C)</td>
<td>-0.09</td>
<td>-0.09</td>
</tr>
<tr>
<td>Fuel density coefficient,  (1/°C)</td>
<td>-0.19</td>
<td>-0.36</td>
</tr>
</tbody>
</table>

- **Axial overflow is an unique inherent safety feature of NFFFR, which provides strong negative reactivity feedback**
  - Due to higher thermal expansion, fluid along with fuel particles overflows through central hole
  - Volumetric expansion of Na = 2.84E-04 /° C, LBE= 1.35E-04 /° C
  - Nano fuel particle overflow rate = 11.0 kg/° C for Sodium, 5.25 kg/° C for LBE
- **Sodium void may not occur in NFFFR because fluid overflow feedback shutdowns core prior to fluid boiling**
Heat Removal Concept

- Coolant inlet and outlet temperatures were assumed to be 355 and 500°C, arbitrary, and coolant mass flow rate was estimated for circular pipe and annular blanket concepts
  - Circular pipe concept needs thick pipe (~50cm) to have a reasonable coolant velocity of ~10 m/sec
  - Due to higher mass flow rate, annular blanket concept needs lower coolant velocity compared to circular pipe concept.
  - Reference core adopts annular blanket cooling concept with blanket thickness of 15 cm, which can remove heat with coolant velocity less than 10 m/sec

<table>
<thead>
<tr>
<th>Cooling concept</th>
<th>Core (fluid pot) size, m</th>
<th>Pipe radius or annular blanket thickness, m</th>
<th>Average velocity of coolant, m/c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>diameter</td>
<td>height</td>
<td>Sodium</td>
</tr>
<tr>
<td>Circular pipe</td>
<td>3.0 m</td>
<td>1.5 m</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>432</td>
</tr>
<tr>
<td>Annular blanket</td>
<td>3.0 m</td>
<td>1.5 m</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>
Used Fuel Recycling in NFFFR

- After certain burnup, core cannot maintain criticality due to following reasons
  - Accumulated FPs: initially, core k-effective increases initially due to bred Pu, but decreases finally because of the poison effect of accumulated FPs. Thus, FPs should be removed for used fuel recycling
  - HM mass decreases below critical mass. Thus, additional external feed of fresh fuel is needed
- Due to different masses between fission products and nano-particles, FPs can be separated from nano particles by using simple centrifugal separation technology (not chemical separation)
- Criticality of recycled core is dependent on 1) how much fission products are removed, and 2) how much external fresh particles are additionally loaded
Used Fuel Recycling with External Feed

- Core
- Reprocessing
- Fresh Fuel and Liquid Metal
- Fission Products

Fuel Nano-particles and Liquid Metal

- = New Fuel Nano-particle
- = Old Fuel Nano-particle
- = Fission Product

Fuel Nano-particles, Fission Products, and Liquid Metal
Assuming 60% FP removal, used fuel was recycled with external feed of fresh nano particles.

Trends are similar to 100% FP removal case, but required fresh particle mass increases cycle-by-cycle.
Conclusions and Questions
Conclusions

- **Nano-particle Fueled Fluid Fast Reactor (NFFFR) concept was proposed targeting following objectives:**
  - Extremely simple core geometry (order of magnitude reduction of capital cost)
  - Recycling actinide without chemical separation targeting high resource utilization
  - Highly improved inherent safety features

- **2000 MWth NFFFR reference core concept was developed**
  - Reference NFFFR core is a simple cylindrical pot containing LEU nano particles and liquid metal mixture
  - Pot diameter and height are ~2.6m and 1.4 m, respectively
  - With 11% LEU and 25% fuel volume fraction, reference core maintain criticality for 7 years without refueling
  - Overflow concept in an unique inherent safety feature of NFFFR, which provides strong negative feedback

- **Used fuel recycling**
  - FPs are escaped from nano-particles per fission and separated using simple centrifugal separation technology
  - Fuel cycle performance of used fuel recycling core is dependent on FP separation ratio
Future Works Per Questions

- Many Questions and issues for realizing NFFFR concept
  
  Q1. Distribution of nano-particles in fluid?
  Q2. FPs removal rate?
  Q3. Chemistry of FPs in fluid?
  Q4. Is it possible to make LEU nano particles?
  Q5. What happen after fission, nano particle are broken or not?
  Q6. How to provide additional barrier for FPs release (NFFFR does not have cladding. So, one barrier missing)
  
  Q7 ....

- Experiments are essential
  
  - Develop uranium nano particles and irradiate them in a experimental reactor
  - Demonstrate FP recoil separation and measure FP removal rates
Backup
Background of Nano Particles in Nuclear Reactor

- **Fission product recoil separation**
  - In 1950s, FP recoil separation was studied in small particle suspension reactor

- **Enhancement of coolability**
  - Recently, impacts of nano-particles in primary coolant were investigated for improving thermo-physical properties (in particular, thermal conductivity) of primary coolant

- **Other area**
  - Reduction of sodium-water reaction by decreasing chemical reaction activity
The recoil distance of fission fragments in U3O8 is about 8 microns. By using highly diluted suspensions of uranium oxide particles having dimensions much smaller than this figure (mean diameter 0.5 micron), the reabsorption of fission products on uranium oxide was studied. Separation results were studied as a function of the nature of the irradiation medium (solid or liquid) and the separation medium, of particle size and of concentration of particles in the dispersing medium. Decay curves can be used to discriminate between Np-239 and mixed fission products. Most of the Np-239 is found in the U3O8 particles. The location of fission products in solid dispersing media was determined, fission products being found always inside the dispersing medium particles. The results obtained can be applied to the rapid separation of short-lived fission products from a uranium-free starting material. (auth)