The Water Ingress Effects on the Reactivity Change of the Conceptual Designed Reactor at NIST

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NIST Center For Neutron Research

www.ncnr.nist.gov

Gaithersburg, MD
NCNR has 28 instruments for various scientific experiments, 21 of them use cold neutrons (as of Dec. 2015), and hosts over 2,000 guest researchers annually, 70-80% of them are using cold neutrons.
Cut-away View of the NBSR Core

- Cd Shim Safety Arms (4)
- Reactor Vessel
- Radial Beam Tubes (9)
- Split Core: 18-cm Unfueled Gap – Flux Trap
- Primary Outlet (2)
- Top Grid Plate
- Fuel Elements (30)
- Fuel Plates
- Liquid Hydrogen Cold Neutron Source
- Bottom Grid Plate
- D₂O Primary Inlet Plenums
- Thermal Shield
Cross-sectional View of the Mid-plane of the NBSR

**BT**: Beam Tube

**CT**: Cryogenic Tube

**CNS**: Cold Neutron Source
Status of the Present NBSR

- First critical on Dec. 7th, 1967
- Current operating license will go through 2029
- One additional extension may be achievable
- Most likely reach retirement in 2050s

Challenges for Conversion of NBSR to LEU

- LEU $U_3Si_2/Al$ dispersion fuel is not workable
- LEU U–10Mo monolithic fuel is feasible but not manufactured yet – may be 10 years off
- 30% more increase on fuel costs
- 10% reduction on neutron performance
Main Design Parameters of New Reactor

<table>
<thead>
<tr>
<th></th>
<th>New Reactor</th>
<th>NBSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power (MW)</td>
<td>20 - 30</td>
<td>20</td>
</tr>
<tr>
<td>Fuel cycle length (days)</td>
<td>30</td>
<td>38.5</td>
</tr>
<tr>
<td>Fuel material</td>
<td>U$_3$Si$_2$/Al</td>
<td>U$_3$O$_8$/Al</td>
</tr>
<tr>
<td>Fuel enrichment (%)</td>
<td>19.75 (LEU)</td>
<td>93 (HEU)</td>
</tr>
</tbody>
</table>

Other Important Considerations:

- **Compact core** concept is employed in the design
- Principle objective is to provide cold neutron source (**CNS**)
- At least **TWO** CNSs are targeted in the new design
- Significantly utilize existing facilities and resources
- Combine latest proven research reactor design features
A Compact Core and ‘Tank-in-Pool’ Concept

(a) Elevation view
A schematic view of the side-plane (left) and mid-plane (right) of the reactor.

(b) Plan view

The compact core exploits inverse flux trap (i.e., the thermal flux peaks outside of the core).
The mid-plane of the split core reactor. Two cold neutron sources are placed in the north and south side of the core, and four thermal beam tubes are located in the east and west side of the core at different elevations.
Horizontally Split Core With 18 Fuel Elements

A close view of the horizontally split-core. The core consists of total 18 fuel elements which are evenly distributed into two horizontal split regions.

Core Design Information

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power rate (MW)</td>
<td>20</td>
</tr>
<tr>
<td>Fuel cycle length (days)</td>
<td>30</td>
</tr>
<tr>
<td>Active fuel height (cm)</td>
<td>60.0</td>
</tr>
<tr>
<td>Fuel material</td>
<td>$\text{U}_3\text{Si}_2/\text{Al}$</td>
</tr>
<tr>
<td>U-235 enrichment in the fuel (wt. %)</td>
<td>19.75</td>
</tr>
<tr>
<td>Fuel mixture density (g/cc)</td>
<td>6.52</td>
</tr>
<tr>
<td>Uranium density (g/cc)</td>
<td>4.8</td>
</tr>
<tr>
<td>U-235 mass per fuel element (gram)</td>
<td>399</td>
</tr>
<tr>
<td>Number of fuel elements in the core</td>
<td>18</td>
</tr>
</tbody>
</table>
A 3–D View of the Split–Core Design

- H₂O Flow
- D₂O Tank
- H₂O Pool
Comparison of Unperturbed Radial Flux at EOC

Along N-S axis only

16 FE Core

20 FE Core
# Neutronics Performance Characteristics of the New Reactor

<table>
<thead>
<tr>
<th>Reactor</th>
<th>NBSR</th>
<th>HFIR</th>
<th>BR-2</th>
<th>OPAL</th>
<th>CARR</th>
<th>FRM-II</th>
<th>NBSR-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Country</strong></td>
<td>U.S.</td>
<td>U.S.</td>
<td>Belgium</td>
<td>Australia</td>
<td>China</td>
<td>Germany</td>
<td>U.S.</td>
</tr>
<tr>
<td><strong>Power (MW$_{th}$)</strong></td>
<td>20</td>
<td>85</td>
<td>60</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>HEU</td>
<td>HEU</td>
<td>HEU</td>
<td>LEU</td>
<td>LEU</td>
<td>HEU</td>
<td>LEU</td>
</tr>
<tr>
<td><strong>Max $\Phi_{th}$ ($\times 10^{14}$ n/cm$^2$-s)</strong></td>
<td>3.5</td>
<td>10</td>
<td>12</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td><strong>Quality factor ($\times 10^{13}$ MTF/MW$_{th}$)</strong></td>
<td>1.8</td>
<td>1.2</td>
<td>2.0</td>
<td>1.5</td>
<td>1.3</td>
<td>4.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The **Quality factor** is defined as the ratio of maximum thermal flux (MTF) to the total thermal power of the reactor.
Water at Difference Locations of the Reactor

- The reactor core is slightly pressurized and surrounded by the heavy water reflector.
- The core is cooled and moderated by light water, which is separated from heavy water with a core box made of Zircaloy.
- Neutronics calculations was performed to determine the effect and trend of the reactivity changes due to water ingress in different scenarios by purposely mixing the waters at three representative places in the reactor.
## Neutron Moderating Characteristics of H$_2$O and D$_2$O

<table>
<thead>
<tr>
<th>Moderator</th>
<th>H$_2$O</th>
<th>D$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (g/cc)</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>$\sigma_a$ (barn)</td>
<td>0.66</td>
<td>0.001</td>
</tr>
<tr>
<td>$\sigma_s$ (barn)</td>
<td>103</td>
<td>13.6</td>
</tr>
<tr>
<td>$\Sigma_a$ (cm$^{-1}$)</td>
<td>0.0221</td>
<td>3.31E–5</td>
</tr>
<tr>
<td>$\Sigma_s$ (cm$^{-1}$)</td>
<td>3.4429</td>
<td>0.4498</td>
</tr>
<tr>
<td>$\xi$</td>
<td>0.948</td>
<td>0.57</td>
</tr>
<tr>
<td>$\xi\Sigma_s$ (cm$^{-1}$)</td>
<td>3.264</td>
<td>0.256</td>
</tr>
<tr>
<td>$\xi\Sigma_s/\Sigma_a$</td>
<td>148</td>
<td>7752</td>
</tr>
</tbody>
</table>

- $\xi$ – Neutron average lethargy gain (or average logarithmic energy loss) per collision.
- $\xi\Sigma_s$ – Neutron moderating power or slowing down power
- $\xi\Sigma_s/\Sigma_a$ – Neutron moderating ratio
Light Water Ingress in the Heavy Water Tank

- The reflector tank is filled with D$_2$O that is assumed to be volumetrically 99.97% pure.
- In the perturbations, the volumetric fraction of the D$_2$O is reduced in several cases: each case has 2% less D$_2$O, while the H$_2$O fraction for each case is increased accordingly to preserve the total volume of water.
- Any amount of light water contamination in the reflector would have a negative effect on the reactivity to the reactor. A nearly linear decreasing trend on reactivity change is observed.
Heavy Water Ingress in the Light Water Region

- Focus on those cases for which heavy water leaks into the core regions.
- Examine the water mixing at two different locations in the core: the flowing coolant region (fuel center) and the stationary coolant region between fuel elements (fuel periphery).
- Water mixing in the fuel center provides a negative effect on the reactivity change, whereas water mixing at fuel periphery renders a positive effect.
- The combined effect of water mixing in the light water coolant has slightly positive effect.
Neutron Flux Spectrum at Different Locations

Entire energy range.

Thermal energy range.
The split core design employs a ‘tank-in-pool’ design pattern, in which the core is immersed in a cylindrical heavy water tank and the tank is surrounded by a light water pool.

The effect on reactivity due to the water mixing in either direction is studied in this paper.

The results show that light water ingress in the heavy water tank would always cause negative reactivity.

Heavy water ingress in the coolant at the fuel center provides negative effects, whereas heavy water ingress in the coolant at the fuel periphery renders positive effects, which results a slightly positive effect on the reactivity in the combined case.

These reactivity effects will be taken into account when designing the primary and reflector cooling systems.

Thank you!