Optimization of a Cold Neutron Source for a Proposed LEU Reactor at NIST

RYAN BONK
SURF STUDENT COLLOQUIUM
NIST CENTER FOR NEUTRON RESEARCH
GAITHERSBURG, MD
The lifetime of the National Bureau of Standards Reactor (NBSR) will be coming to an end sometime in the middle of this century.

- NCNR hosts over 2,000 researchers annually
- 70% use cold neutrons in their experiments.
- Feasibility study for a Low-Enriched Uranium (LEU) reactor underway
Cold Neutrons

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy Range</th>
<th>Wavelength Range (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast</td>
<td>1 MeV – 20 MeV</td>
<td>.0003 - .0001</td>
</tr>
<tr>
<td>Thermal</td>
<td>.025 eV – .625 eV</td>
<td>1.8 - .04</td>
</tr>
<tr>
<td>Cold</td>
<td>&lt; .005 eV</td>
<td>&gt; 4</td>
</tr>
</tbody>
</table>

Note: 1 Å = 1 x 10^{-10} m

- Materials with structural spacings on the order of 100 Å have become more prominent in science and technology (Ex. Polymers).
- With their low energy and long wavelength, cold neutrons are better suited for probing these materials.
Producing Cold Neutrons

- To increase the production of cold neutrons from a reactor core, a cold neutron source (CNS) is used.
- Cryogenically cooled to around 20 K to shift the spectrum of neutrons to lower energies.
- Atoms with low Z (Example: hydrogen or deuterium) make ideal moderators.
- The new CNS design will be filled with liquid Deuterium (2021).
Neutron Moderation

- Neutrons collide with the atoms of the medium they reside in much like air molecules colliding in the room around us.

- Their kinetic energies depend only on the temperature of the surroundings according to the **Maxwell-Boltzmann Distribution**.
  - $D_2O$ Moderator $\approx 300 \, K$
  - LD$_2$ Moderator $\approx 20 \, K$

Why Switch to Deuterium?

- Spectrum shifts to lower energies.
- Gains of up to 2 for the longest wavelengths.
- Up to a 50% loss at 15 meV (2.5 Å).
- Conversion of NBSR to LEU will result in 10% reduction in thermal and cold neutron beams.
- New CNS/guides intended to make up for this reduction.
Deuterium Cold Neutron Source for Replacement Reactor

- CNS
- Thermal Beams
- Heavy Water
- Light Water

- Neutron Beam Guide
- Gaseous Deuterium Re-entrant Cavity
- Liquid Deuterium Moderator

Plane View (Top)
Plane View (Side)
Optimizing the Cold Source Location

• Monte Carlo N-Particle (MCNP) computer simulations were used previously to perform flux calculations on the new reactor design.
The quantity used to measure the performance of the cold neutron source is the **Brightness**.

- Units: $n/cm^2\cdot s\cdot meV\cdot ster$ or $n/cm^2\cdot s\cdot Å\cdot ster$

A surface source is generated around the CNS using a whole-core criticality calculation.

The **DXTRAN** feature is used to force “pseudo” particles to a tally plane at the neutron guide entrance.

This surface source is used to perform surface current calculations on the CNS.
Optimizing the Cold Source Geometry

The effects of changing the size and shape of the re-entrant cavity were investigated using MCNP.

<table>
<thead>
<tr>
<th>#</th>
<th>Geometry (X x Y x Z) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Original (Trapezoid)</td>
</tr>
<tr>
<td>2</td>
<td>16 x 12 x 20 Box</td>
</tr>
<tr>
<td>3</td>
<td>Cylinder: d = 15, h = 20</td>
</tr>
<tr>
<td>4</td>
<td>38° Cone (vertex @ center)</td>
</tr>
<tr>
<td>5</td>
<td>8 x 12 x 8 Ellipsoid</td>
</tr>
<tr>
<td>6</td>
<td>No Re-entrant Cavity</td>
</tr>
</tbody>
</table>
Brightness Gain Compared to the Original Deuterium CNS Design

NEUTRON BRIGHTNESS GAIN FOR VARYING ELLIPSOID CAVITY DEPTH (WIDTH = 8 CM, HEIGHT = 8 CM)

- Depth = 12 cm
- Depth = 10 cm
- Depth = 8 cm
- Depth = 6 cm
- Depth = 16 cm
- No Re-entrant Cavity
- Unit 2

WAVELENGTH (Å)
Brightness Gain Compared to the Original Deuterium CNS Design

**NEUTRON BRIGHTNESS GAIN FOR VARYING ELLIPSOID CAVITY WIDTH (DEPTH = 12 cm, HEIGHT = 8 cm)**

- **Width = 8 cm**
- **Width = 4 cm**
- **Width = 12 cm**
- **Width = 16 cm**
- **Width = 20 cm**
- **No Re-entrant Cavity**

**WAVELENGTH (Å)**

- 1.5
- 2.5
- 3.5
- 4.5
- 5.5
- 6.5
- 7.5
- 8.5
- 9.5

Gain values range from approximately 0.2 to 1.8.
Brightness Gain Compared to the Original Deuterium CNS Design

NEUTRON BRIGHTNESS GAIN FOR VARYING ELLIPSOID CAVITY HEIGHT (DEPTH = 12 CM, WIDTH = 8 CM)

- Height = 4 cm
- Height = 8 cm
- Height = 12 cm
- Height = 16 cm
- Height = 20 cm
- No Re-entrant Cavity
Nuclear Heat Load

- The Deuterium Cold Source is more massive than the existing Hydrogen cold source, meaning it will take on a greater nuclear heat load.

- MCNP used to calculate expected heat deposition rate in the LD$_2$ and moderator chamber with an (8 x 12 x 8) cm ellipsoid re-entrant cavity.

- A new 7 kW cryogenic helium refrigerator is being installed to account for this threefold increase in heat load.

<table>
<thead>
<tr>
<th>Radiation Source</th>
<th>Deuterium (3806 g)</th>
<th>Aluminum (2280 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate (W/g)</td>
<td>Heat (W)</td>
</tr>
<tr>
<td>Neutrons</td>
<td>0.0716</td>
<td>777</td>
</tr>
<tr>
<td>Beta Particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma Rays</td>
<td>1.53</td>
<td>1465</td>
</tr>
<tr>
<td>Subtotal</td>
<td></td>
<td>2242</td>
</tr>
</tbody>
</table>

**Total Cryogenic Heat Load = 3666 W**
Conclusion

• An optimized LD$_2$ cold source is needed to recover the 10% loss in neutron flux due to the switch to LEU fuel.

• The position and re-entrant cavity geometry were optimized to produce brightness gains between 1.3 - 1.5 for the desired range of 4 - 9 Å.

• (8 x 12 x 8) cm Ellipsoid re-entrant cavity consistently performs the best in terms of brightness in the 4 - 9 Å range.
Future Research

• Cold Source re-entrant cavity has been optimized to within a few minor geometrical variations.
• The size and shape of the moderator chamber warrants further optimization research.
• This model must be adapted to the actual beam guide geometry.
Acknowledgements

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