How Neutrons Are Produced: The NIST Research Reactor and Cold Neutron Sources

Dagistan Sahin
NIST Center for Neutron Research

February 3, 2022

Dagistan.sahin@nist.gov
Outline:

- Basics
- NBSR History, Description
- Cold Source Development
- Conclusion

Informal History on the NCNR Web Site under About NCNR:
NIST Research Reactor History

- Designed in the 1960’s and included a beam port for a cold neutron source.
- **NBSR First Critical, December 7, 1967.**
- 10 MW until 1985, 20 MW since.

Cold Neutron Facility Development:
- First neutrons in the guide hall in 1990.
- LH$_2$ Source installed September 1995.
- Advanced LH$_2$ CNS, Unit 2, installed 2002.
- NCNR Expansion Project – 5 more guides.
Thermal Reactor Components

1. **Fissile fuel** material, such as $^{235}$U, only 0.7% abundant, or $^{239}$Pu.
2. **Moderator** to slow neutrons ($D_2O$, $H_2O$, Graphite)
3. **Control Elements** (Cd, B)
4. **Other Stuff:**
   - Shielding
   - Coolant
   - Neutron Source
   - Neutron Detectors
NBSR Core Characteristics

- **HEU** Fuel: 93% $^{235}\text{U}_3\text{O}_8 + \text{Al}$
  - 350 g $^{235}\text{U}$ per Fuel Element
  - 34 plates: 11 in x 2.5 in x .02 in
  - Heavy water coolant ($\text{D}_2\text{O}$)

- 30 Fuel Elements
  - Fuel cycle ~38 days @ 20 MW
  - Load 4 fresh elements, reposition the others
  - About 960 g $^{235}\text{U}$ consumed per cycle

- Split Core – No Fuel at Mid-plane
  - The BTs and CNS are at this elevation.
  - Thermal neutron “flux trap”.
  - BT fluxes $\sim 1.5 \times 10^{14} \text{ n/cm}^2\text{-s}$

** Need to convert to LEU (U-10Mo) when fuel is qualified.**
Shim Arm

Cold Source

20 MW
D₂O, HEU

~ 1 - 3.5 x 10¹⁴ W/m²/s
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
The NBSR was designed with a 55-cm diameter cryogenic beam port for a D$_2$O-ice CNS.

**History:**

1. D$_2$O Tank (1967)
2. D$_2$O Ice (1987) with gain 3-5
3. Unit 1 LH$_2$ (1995), gain ~ 6
4. Unit 2 LH$_2$ (2002), gain ~ 2

*Reference:* Kopetka et. al., NISTIR 7352
The neutrons born in fission have an average kinetic energy of about 2 \textit{Mega–}electron volts, 2 MeV.

They are slowed to thermal energies (20 – 400 milli–eV) by scattering from the molecules of the heavy water (D\textsubscript{2}O) moderator in the reactor. The D\textsubscript{2}O is about 115 °F, or 320 Kelvin.

\textit{In thermal equilibrium, the neutron energy spectrum is determined solely by the temperature of the moderator} (a Maxwell–Boltzmann distribution), analogous to the motion of atoms in an ideal gas.

\textit{To reach lower energies, therefore, we introduce a cold moderator, such as liquid hydrogen at 20 K.}
The LH$_2$ CNS, Unit 1, installed in 1995, had a **gain of 6** times the D$_2$O source.

- To fully illuminate the beam ports, the source had to have a very large area.
- A 320-mm spherical annulus, 20 mm thick, with a 200-mm diameter exit hole was chosen:
  - Low heat load (850 W)
  - Ease of fabrication. Material: Al 6061–T6
  - Composed of concentric Al spheres (5 liters of LH$_2$)
  - Hydrogen vapor filled the inner sphere, which was open at the bottom.

Thermal-hydraulic tests with LH$_2$ conducted at NIST Boulder.
Unit 1 had too much empty space next to the reactor core.

Vapor in the inner sphere scattered cold neutrons from the beam.

Much more \( D_2O \) in Unit 2 results in a higher neutron flux in the CNS region and the adjacent fuel elements.

32 x 24 cm ellipsoid allowed more \( D_2O \) and a thicker \( LH_2 \) annulus.

Gain \(~2\) (2002)
The liquid hydrogen cold source is passively safe, simple to operate, and very reliable

Liquid Hydrogen Thermosiphon

- A thermosiphon is the simplest way to supply the source with LH$_2$.
  - Cold helium gas cools the condenser below 20 K.
  - Hydrogen liquefies and flows by gravity to the moderator chamber.
  - Vapor rises to the condenser and a naturally circulating system is established.

- The system is closed to minimize hydrogen gas handling.
- All system components are surrounded by He containments.
Insertion of Unit 2 Cold source – November 2001
Existing LH$_2$ CNS, In-pile Guides as of April 2011

CTW Beam Port (now has inpile piece for new guides)

MACS

NG-1
NG-2
NG-3
NG-4
NG-5
NG-6
NG-7

CTE
A second LH$_2$ source was installed in BT–9 (2012) as part of the NCNR Expansion Initiative

- 5 new guides have been installed for the guide hall expansion.
- MACS has moved to BT–9 and has its own small LH$_2$ source.
- “Peewee”: 11–cm ID, and a 0.5–l volume.
- It has a gain of about 1.7 over Unit 2.
- MCNP code used to estimate performance and heat load.
Peewee:
14.6-cm OD water jacket
It has its own H$_2$ tank, but the condenser is cooled in parallel with Unit 2.

Piccolo “phase separator”
Operating successfully since April 2012.

Reference: IGORR 2009

Thermal-hydraulic tests of thermosiphon used R-134.
The plug provides shielding and supports the cryostat assembly.

A diverging beam of cold neutrons is provided for MACS.
CNS Team installed Peewee in BT-9 in September 2011.
Conclusion

- The LH\textsubscript{2} cold sources at NIST have made NCNR a world class cold neutron facility.
- About 70% of experiments use cold neutrons.
- LD\textsubscript{2} source planned for 2023(?), to replace Unit 2 (reference: IGORR 2016, Berlin).
- Relicensed in 2009 for 20 more years!!
- Plan to relicense again in 2029.
- Studies have been initiated for a new reactor optimized for cold neutron production.
NCNR Expansion – Fall 2010

Original Building 1963-1967

Guide Hall Addition

Technical Support Building
Xenon Poisoning

- The A=135 fission product decay chain:
  - \( ^{135}\text{Te} \rightarrow ^{135}\text{I} \rightarrow ^{135}\text{Xe} \rightarrow ^{135}\text{Cs} \rightarrow ^{135}\text{Ba} \)
  - \( T_{1/2} \) 19 sec 6.57 hr 9.10 hr (stable)
  - Fission yield (\( \gamma \)) 6.39% 0.23%

\[
\frac{\delta Xe}{\delta t} = \gamma_{Xe} \Sigma_f \varphi(r, t) + \lambda_I I(r, t) - \lambda_{Xe} Xe(r, t) - \sigma_{a}^X \varphi(r, t) Xe(r, t)
\]

(fission) \(^{135}\text{I decay} \) \(^{135}\text{Xe decay} \) (Burnup)

At 20 MW, XE burnup ~ 5 times its radioactive decay!

Immediately after a shutdown, Xe concentration grows to a maximum before decaying with a 9–hr half life.
The buildup of $^{135}\text{Xe}$ can overwhelm the available excess reactivity and keep the NBSR shutdown 30 – 40 hours.

- reactor start-up at time = 0 after a shutdown of one month
- reactor trip at $t = 50$ hours

After an unplanned shutdown the operators are very busy:
- Find the cause, fix it
- Reduce cooling flow
- Commence restart

**The Xe clock is ticking, so please refrain from calling the control room!**
Existing Instrument Layout – Nov 2014

New Guide Hall