NIST Center for Neutron Research

How Neutrons Are Produced:

The NIST Research Reactor and Cold Neutron Sources

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NIST

Outline:

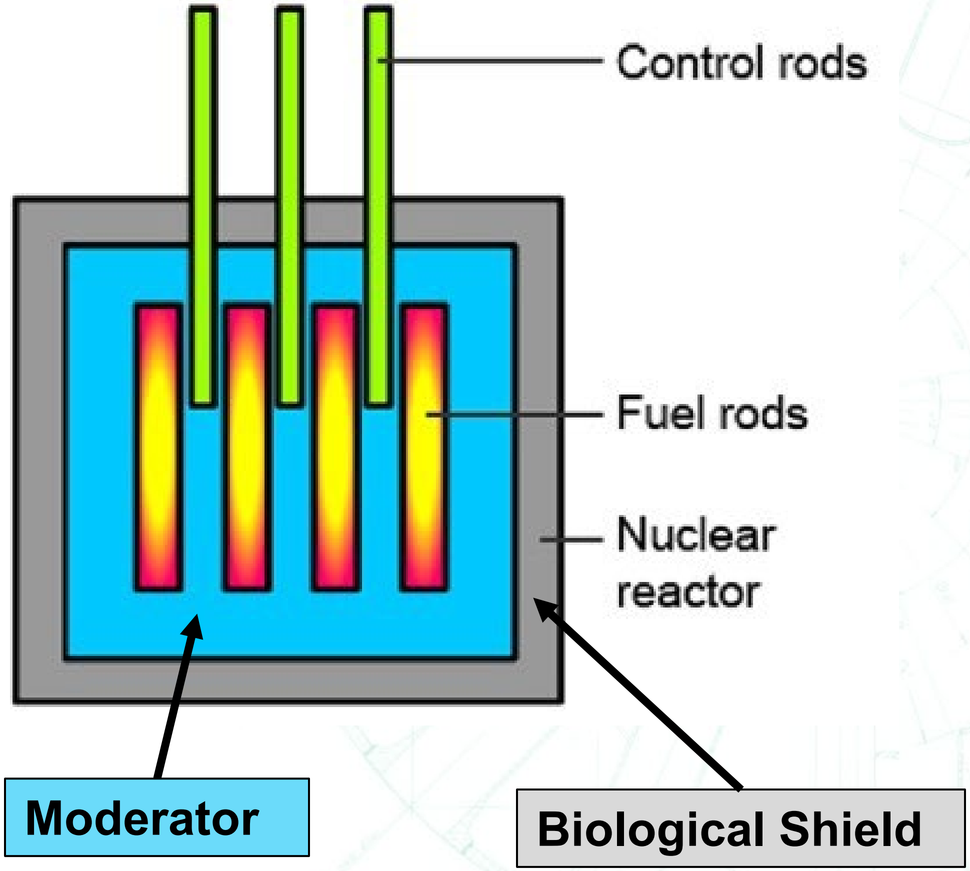
- Basics
- NBSR History, Description
- Cold Source Development
- Conclusion

Informal History on the NCNR Web Site under About NCNR:
https://www.ncnr.nist.gov/NCNRHistory_Rush_Cappelletti.pdf

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:
  - D_2O Cold Neutron Source installed, 1987.
  - 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.
  - "Peewee" CNS installed 2012 in BT-9.

Thermal Reactor Components

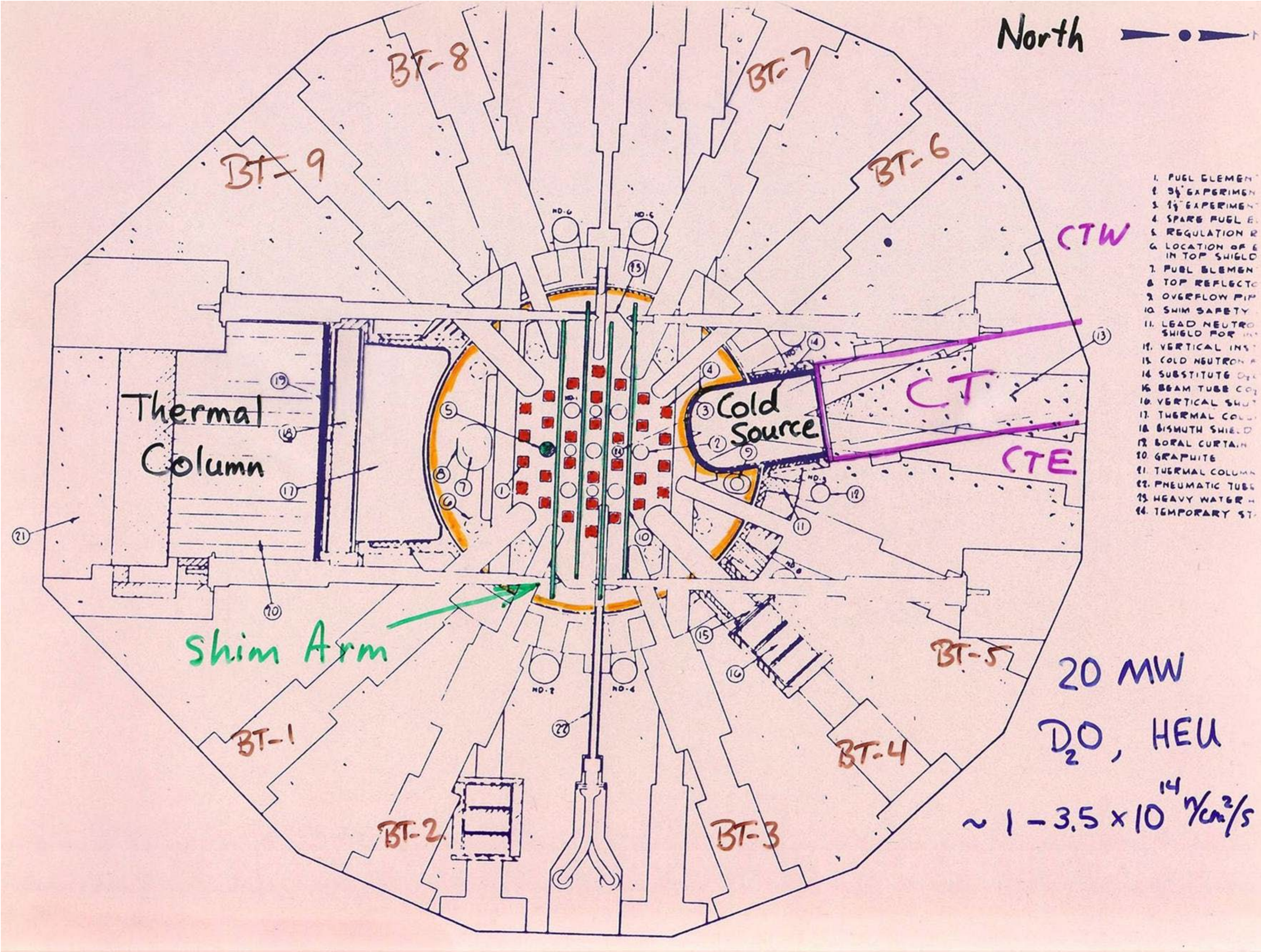


1. ***Fissile fuel*** **material, such as ^{235}U, only 0.7% abundant, or ^{239}Pu.**
2. ***Moderator*** **to slow neutrons (D_2O, H_2O, Graphite)**
3. ***Control Elements*** **(Cd, B)**
4. ***Other Stuff:***
   - **Shielding**
   - **Coolant**
   - **Neutron Source**
   - **Neutron Detectors**

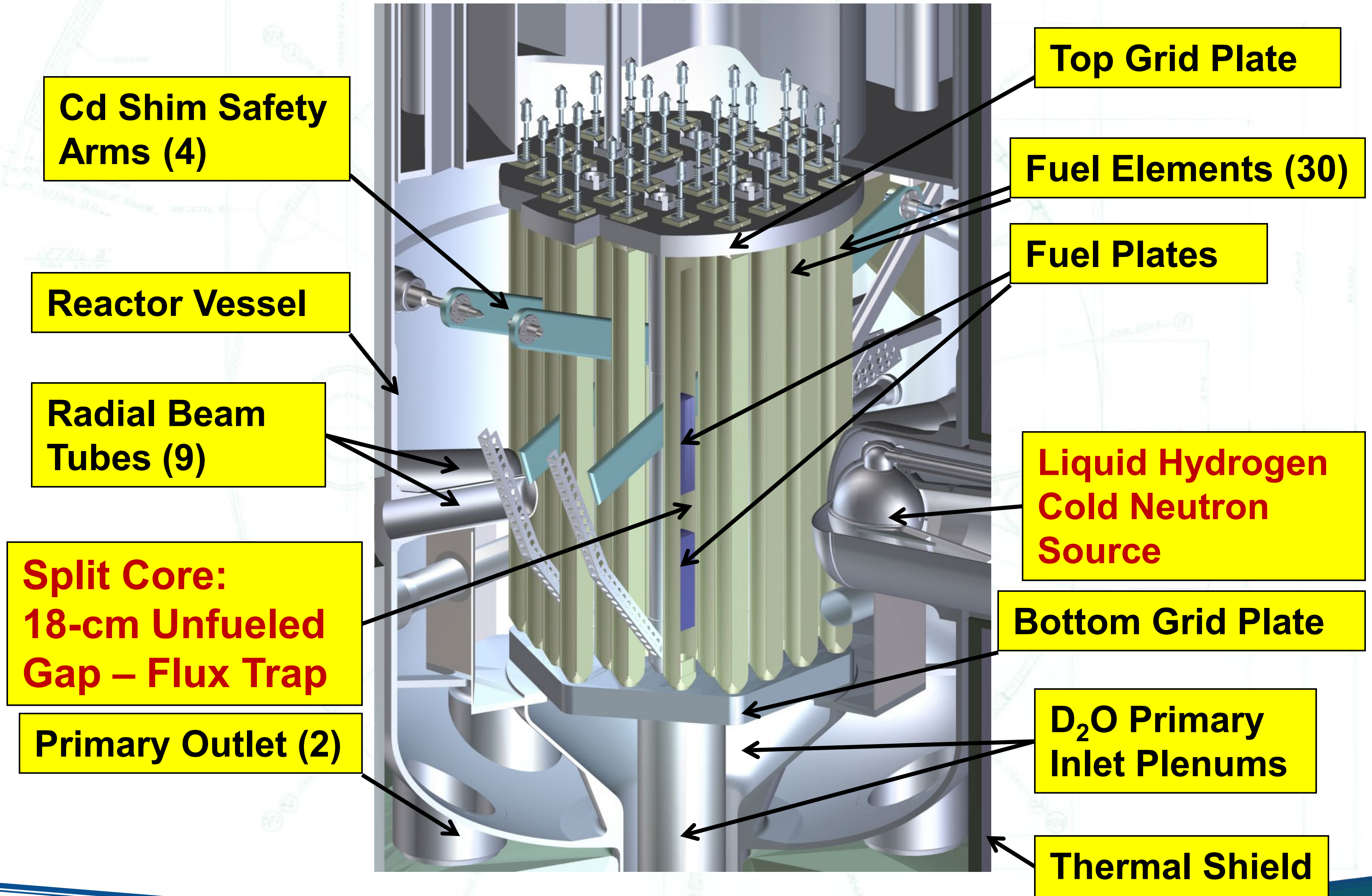
NBSR Core Characteristics

- HEU** Fuel: 93% $^{235}U_3O_8$ + Al
  - 350 g ^{235}U per Fuel Element
  - 34 plates: 11 in x 2.5 in x .02 in
  - Heavy water coolant (D_2O)
- 30 Fuel Elements
  - Fuel cycle ~38 days @ 20 MW
  - Load 4 fresh elements, reposition the others
  - About 960 g ^{235}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 ~ 1.5 x 10^{14} n/cm^2-s

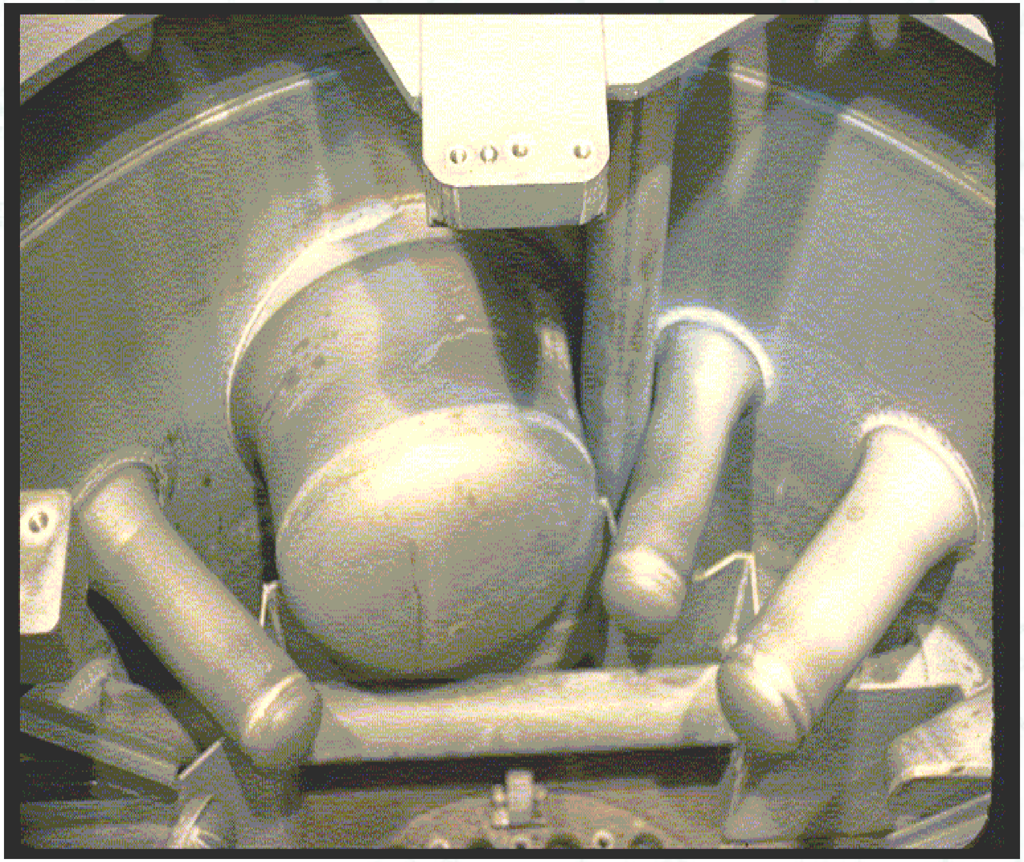
*** Need to convert to LEU (U-10Mo) when fuel is qualified.***


North
BT-8
BT-7
BT-9
BT-6
BT-1
BT-2
BT-3
BT-4
BT-5
Thermal Column
Cold Source
CTW
CT
CTE
Shim Arm
20 MW
D_2O, HEU
$\sim 1 - 3.5 \times 10^{14}$ n/cm²/s
1. FUEL ELEMEN
2. 3½" EXPERIMEN
3. 1½" EXPERIMEN
4. SPARE FUEL E
5. REGULATION R
6. LOCATION OF IN TOP SHIELD
7. FUEL ELEMEN
8. TOP REFLECT
9. OVERFLOW PIP
10. SHIM SAFETY
11. LEAD NEUTRO SHIELD FOR
12. VERTICAL INS
13. COLD NEUTRON
14. SUBSTITUTE
15. BEAM TUBE CO
16. VERTICAL SHU
17. THERMAL CO
18. BISMUTH SHIELD
19. BORAL CURTAIN
20. GRAPHITE
21. THERMAL COLUMN
22. PNEUMATIC TUBE
23. HEAVY WATER
24. TEMPORARY ST

Cut-away View of the NBSR Core



The NBSR was designed with a 55-cm diameter cryogenic beam port for a D_2O-ice CNS.



History:

1. D_2O Tank (1967)
2. D_2O Ice (1987) with gain 3-5
3. Unit 1 LH_2 (1995), gain ~ 6
4. Unit 2 LH_2 (2002), gain ~ 2

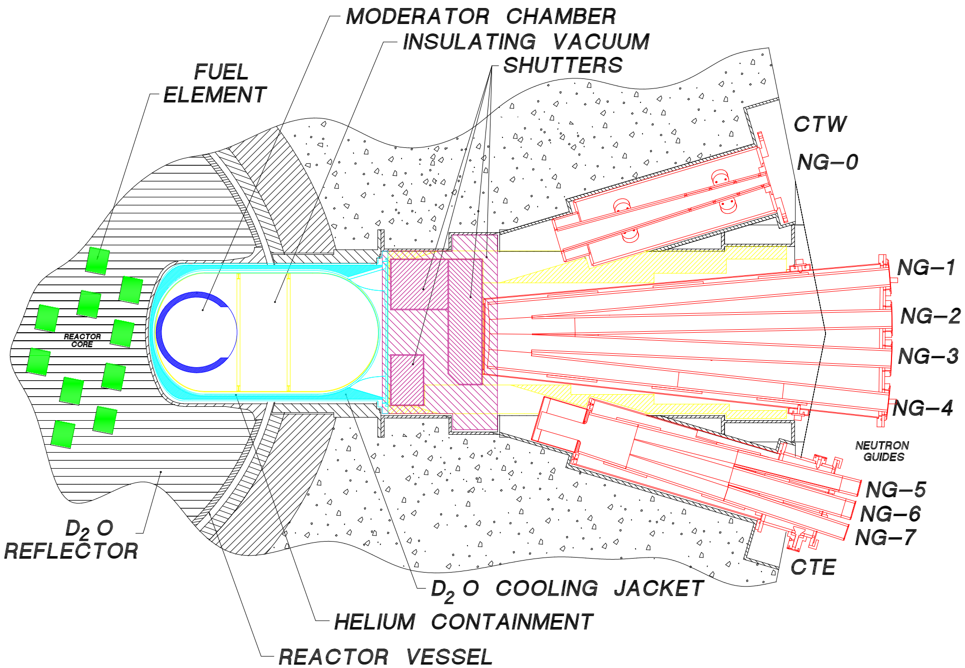
Reference: Kopetka et. al., NISTIR 7352

Production of Cold Neutrons

- The neutrons born in fission have an average kinetic energy of about 2 *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_2O) moderator in the reactor. The D_2O is about 115 °F, or 320 Kelvin.
- *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.

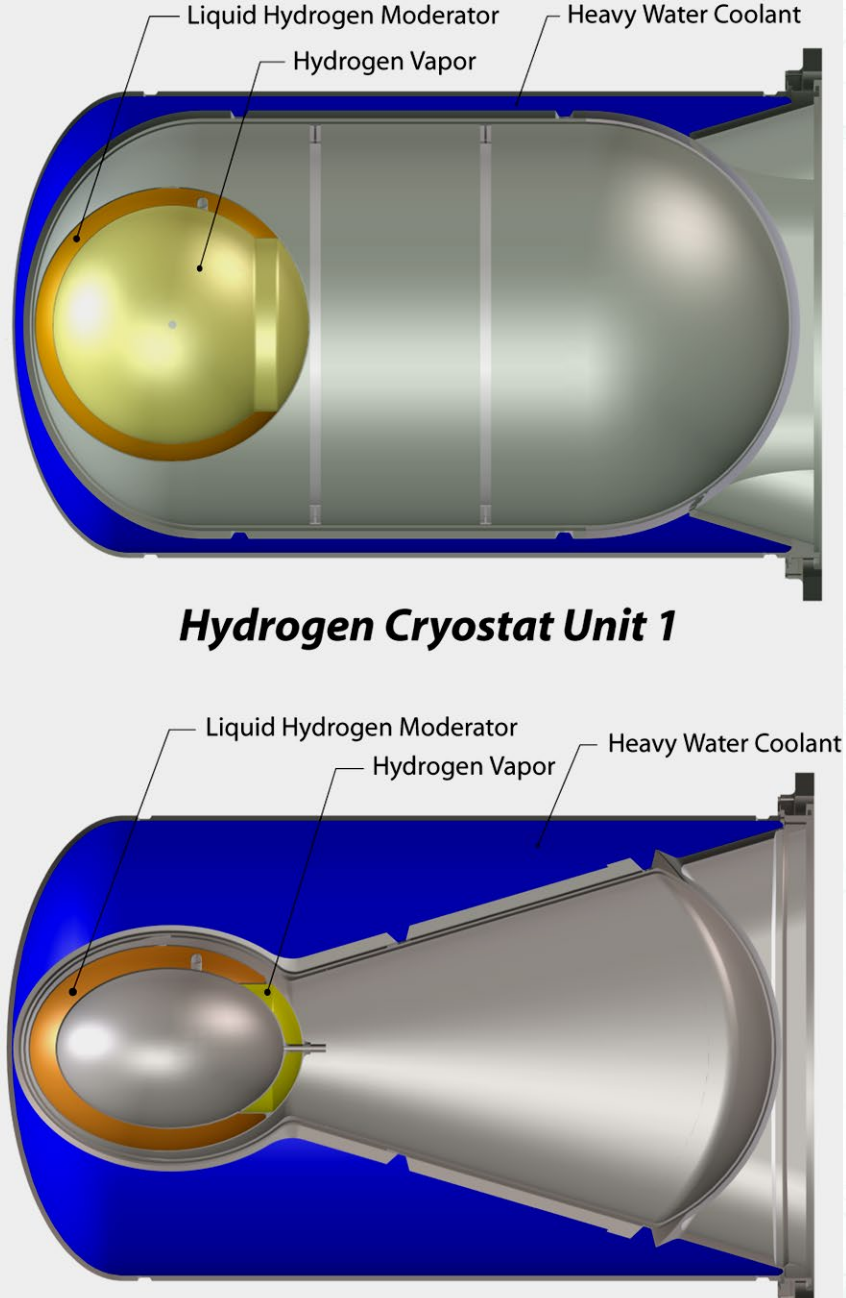
To reach lower energies, therefore, we introduce a cold moderator, such as liquid hydrogen at 20 K.

The LH_2 CNS, Unit 1, installed in 1995, had a ***gain of 6*** times the D_2O source



Thermal-hydraulic tests with LH_2 conducted at NIST Boulder.

- 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.



Hydrogen Cryostat Unit 1

Advanced Hydrogen Cryostat

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.

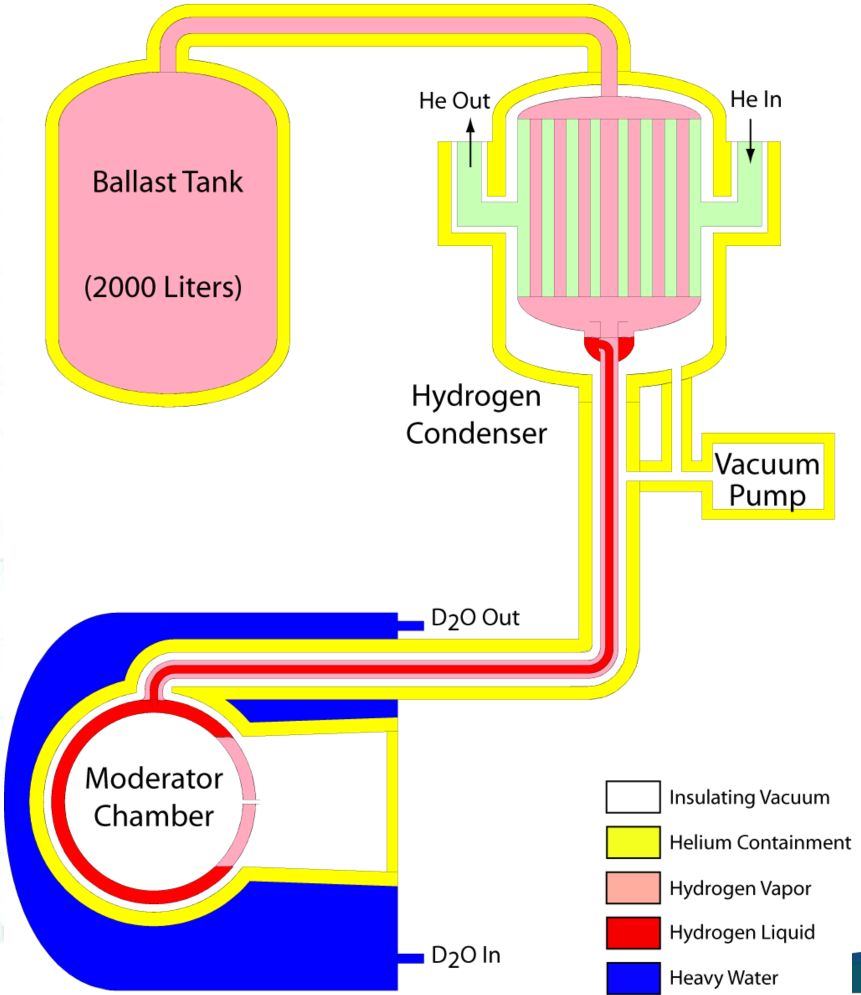
32 x 24 cm ellipsoid allowed more D_2O and a thicker LH_2 annulus.

Gain ~ 2 (2002)

The liquid hydrogen cold source is passively safe, simple to operate, and very reliable

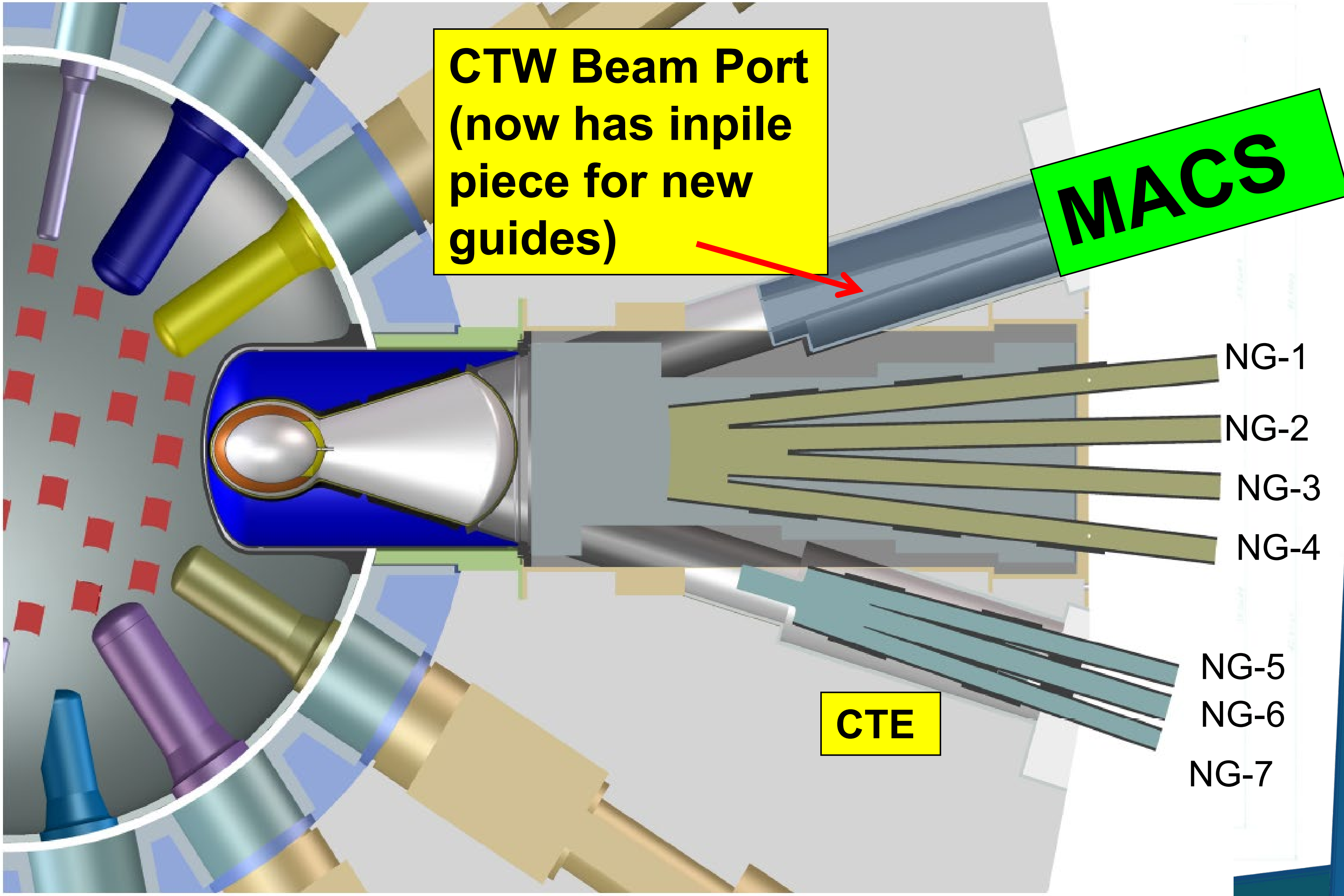
- A *thermosiphon* is the simplest way to supply the source with LH_2.
  - Cold helium gas cools the condenser below 20 K.
  - Hydrogen liquefies and flows by gravity to the moderator chamber.
  - Vapor rises to the condenser and a naturally circulating system is established.
- *The system is closed to minimize hydrogen gas handling.*
- *All system components are surrounded by He containments.*

Liquid Hydrogen Thermosiphon



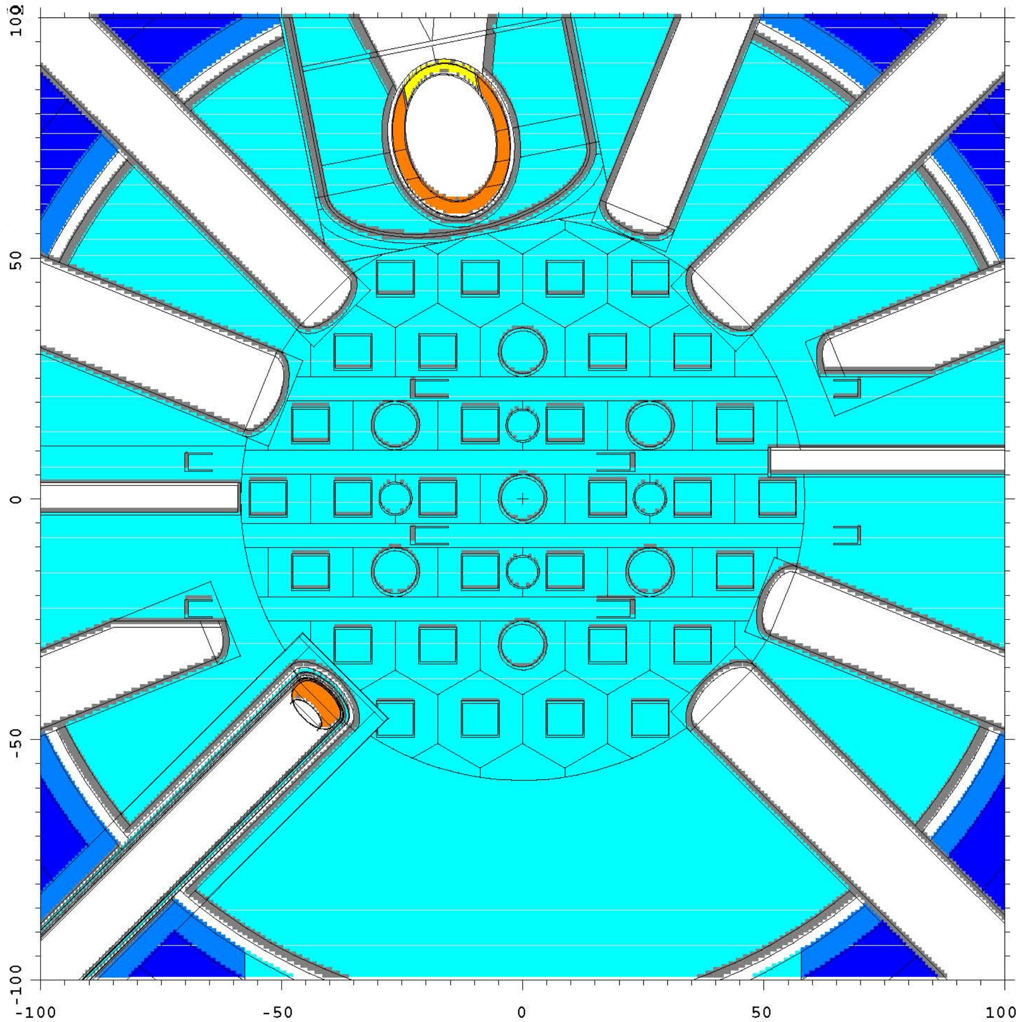
Insertion of Unit 2 Cold source – November 2001

Existing LH_2 CNS, In-pile Guides as of April 2011

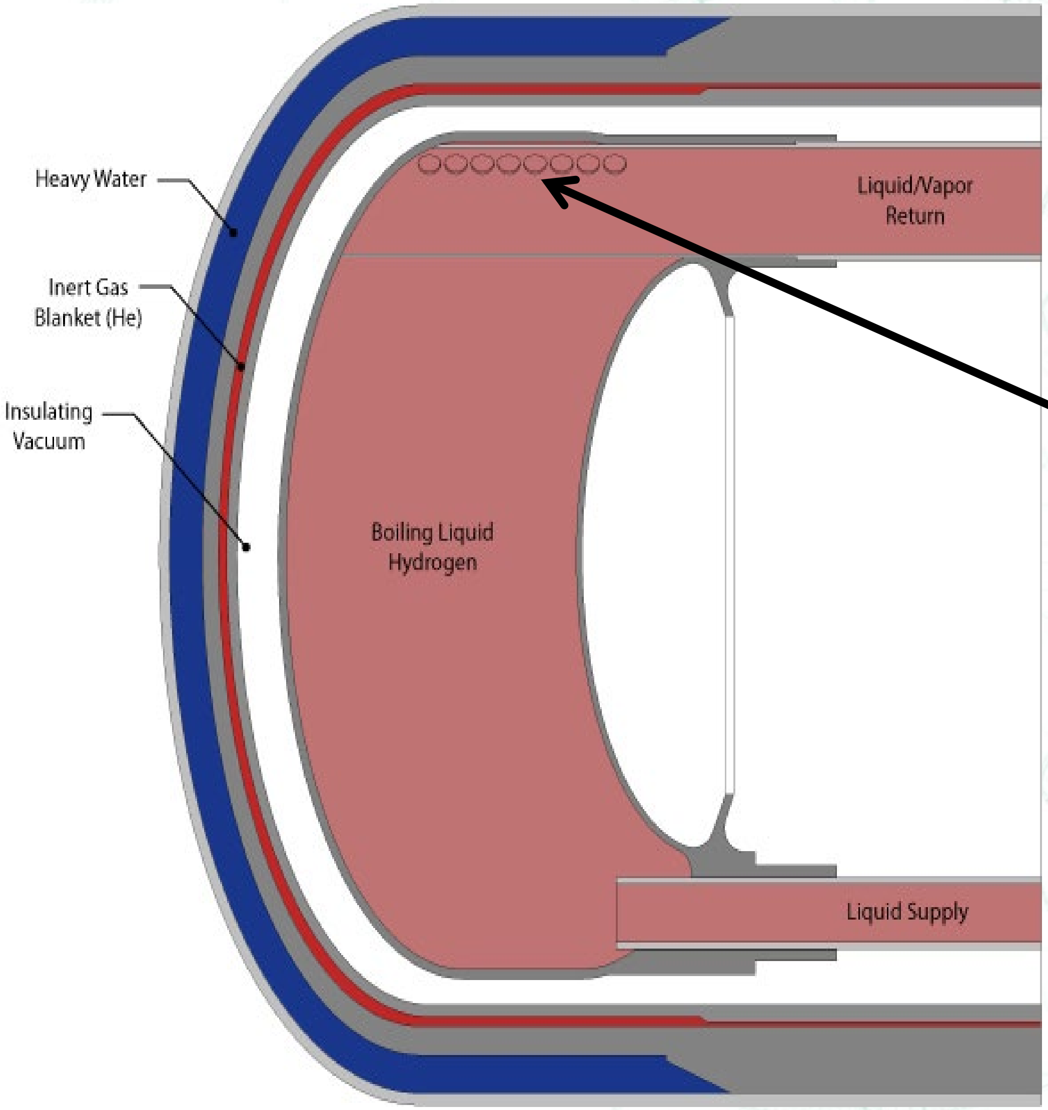


A second LH_2 source was installed in BT-9 (2012) as part of the NCNR Expansion Initiative

- 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.



Side View of BT-9 Cold Source



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.

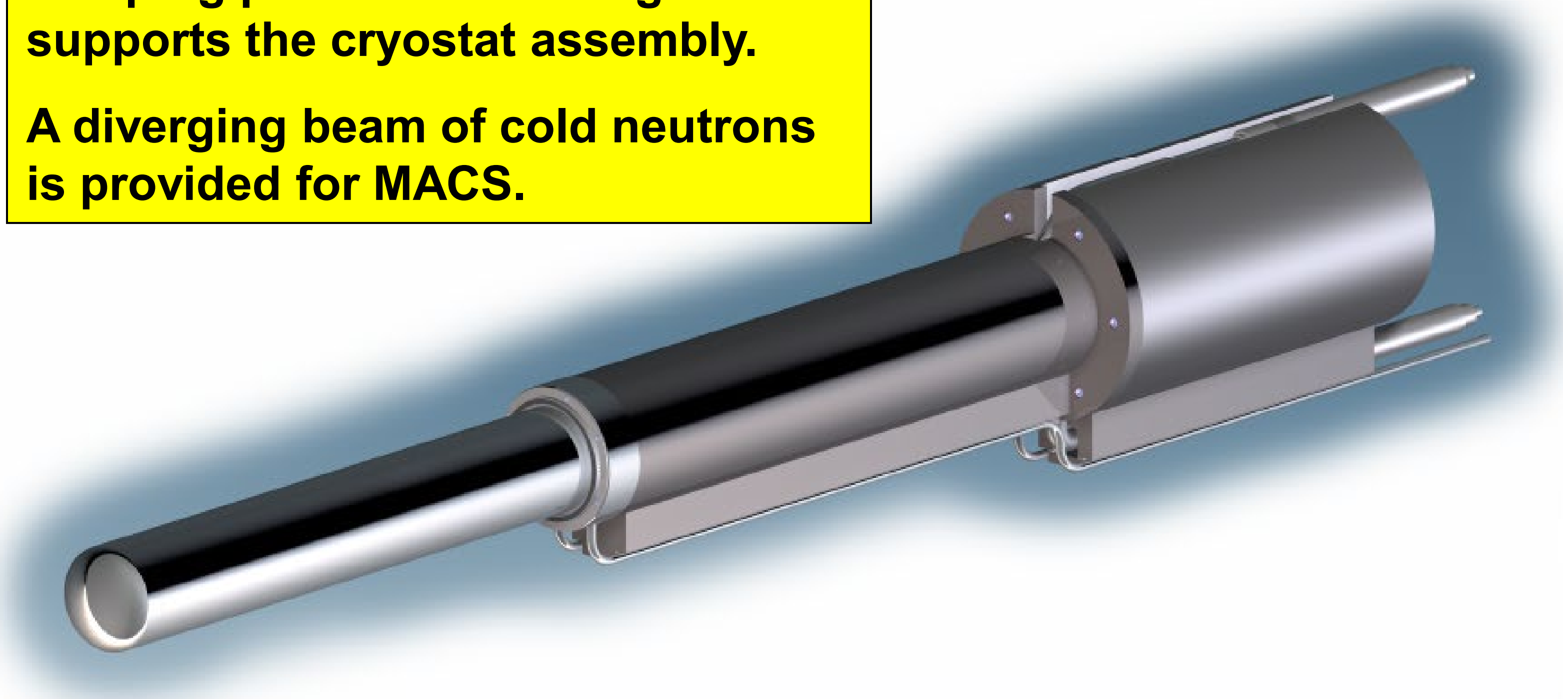
Thermal-hydraulic tests of thermosiphon used R-134.

Reference: IGORR 2009

Inpile Assembly

The plug provides shielding and supports the cryostat assembly.

A diverging beam of cold neutrons is provided for MACS.

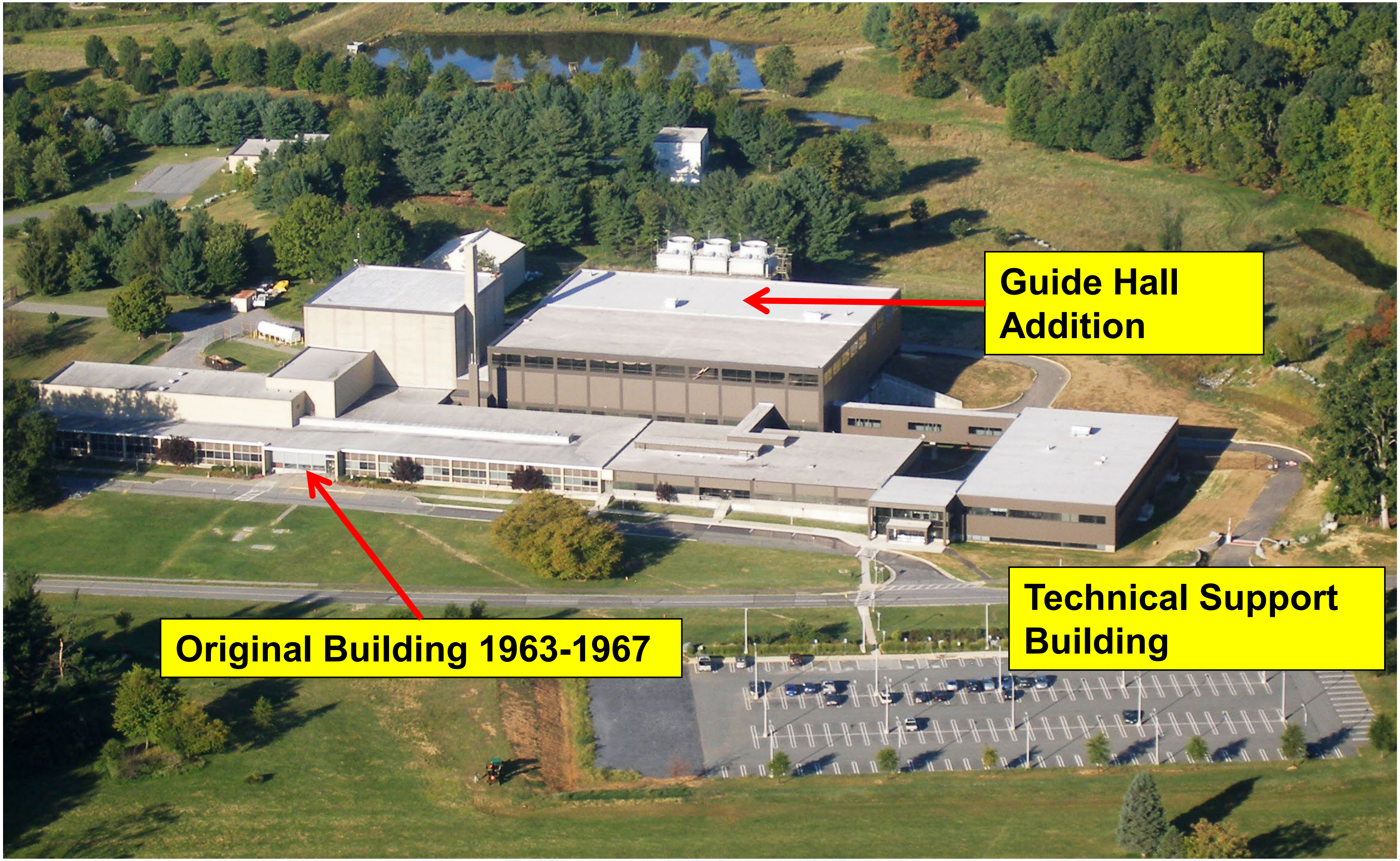


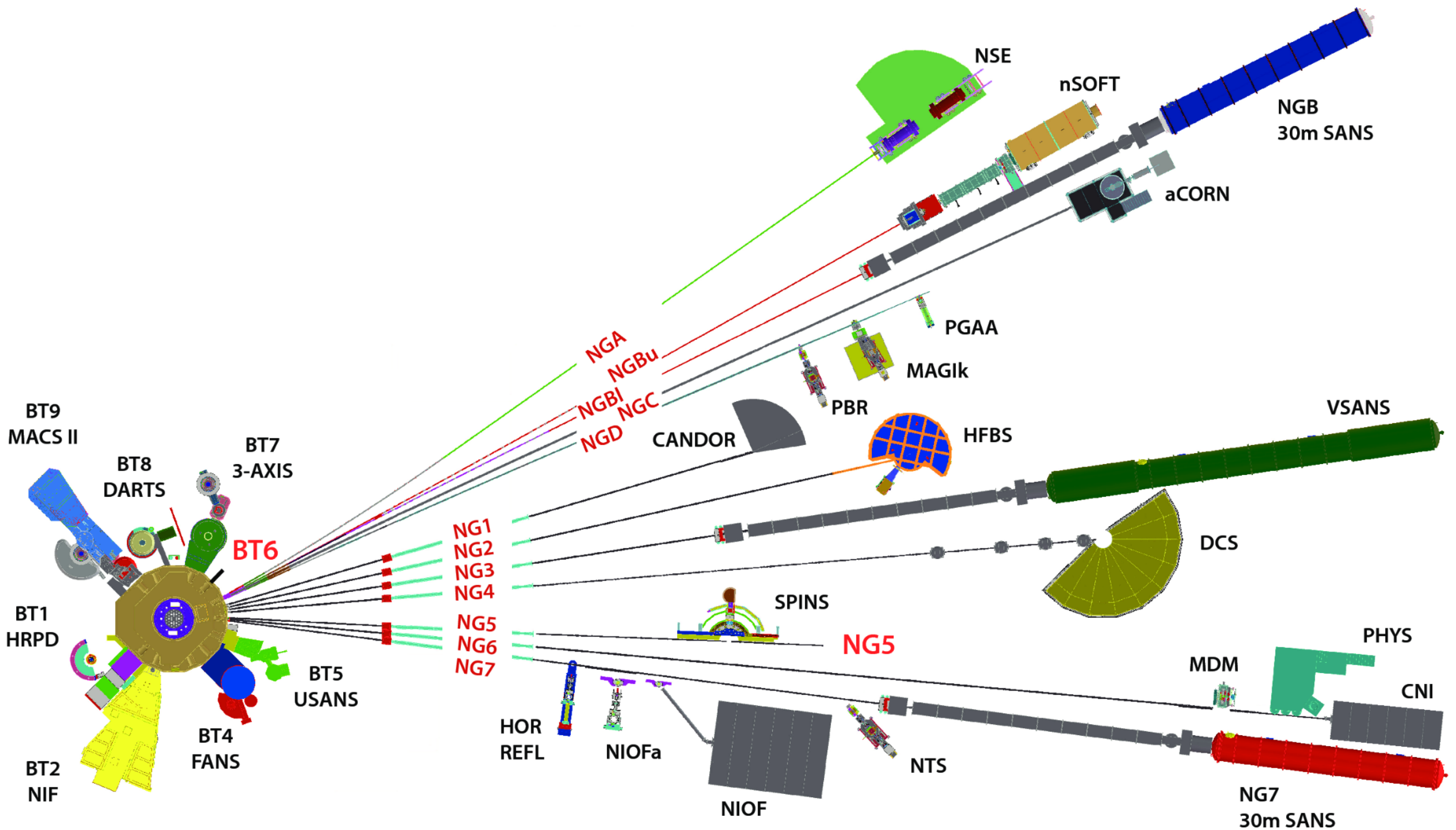
CNS Team installed Peewee in BT-9 in September 2011.

Conclusion

- The LH_2 cold sources at NIST have made NCNR a world class cold neutron facility.
- About 70% of experiments use cold neutrons.
- LD_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




NSE
nSOFT
NGB
30m SANS
aCORN
PGAA
MAGIk
NGA
NGBu
NGBI
NGC
NGD
PBR
CANDOR
HFBS
VSANS
BT9
MACS II
BT8
DARTS
BT7
3-AXIS
BT6
NG1
NG2
NG3
NG4
DCS
SPINS
BT1
HRPD
NG5
NG6
NG7
NG5
PHYS
MDM
CNI
BT5
USANS
HOR
REFL
NIOFa
NTS
BT4
FANS
BT2
NIF
NIOF
NG7
30m SANS

Xenon Poisoning

- The A=135 fission product decay chain:

- … ^{135}Te –> ^{135}I –> ^{135}Xe –> ^{135}Cs –> ^{135}Ba
  - $T_{½}$ 19 sec 6.57 hr 9.10 hr (stable)
  - Fission yield (γ) 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}I decay) (^{135}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}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

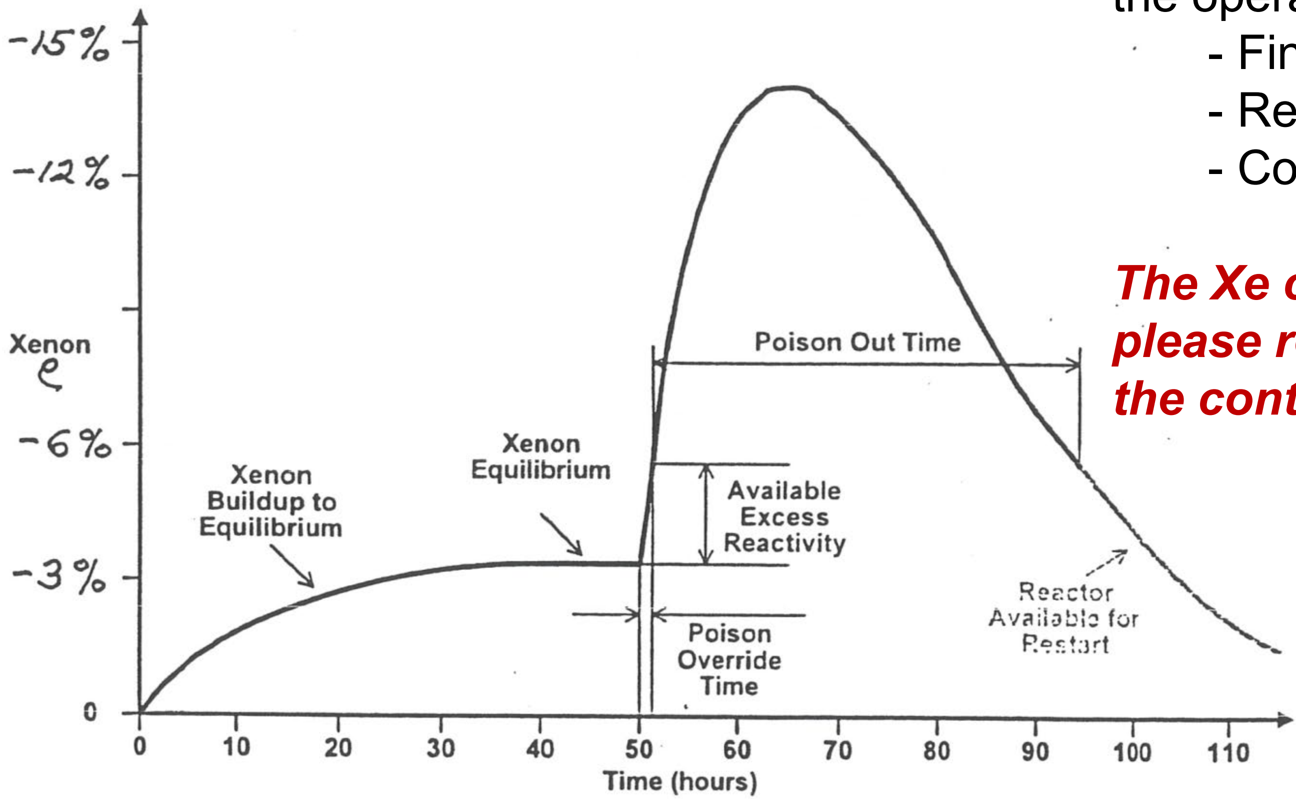


Figure 9
Behavior of Xenon-135

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