How Neutrons Are Produced:

The NIST Research Reactor and Cold Neutron Sources

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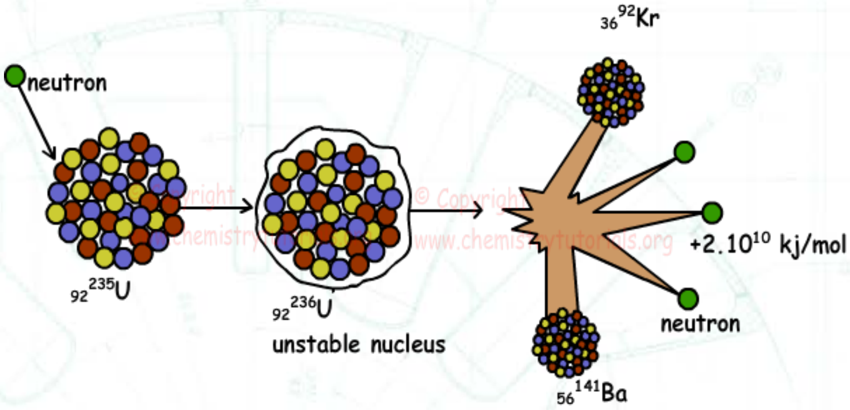
Outline:

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

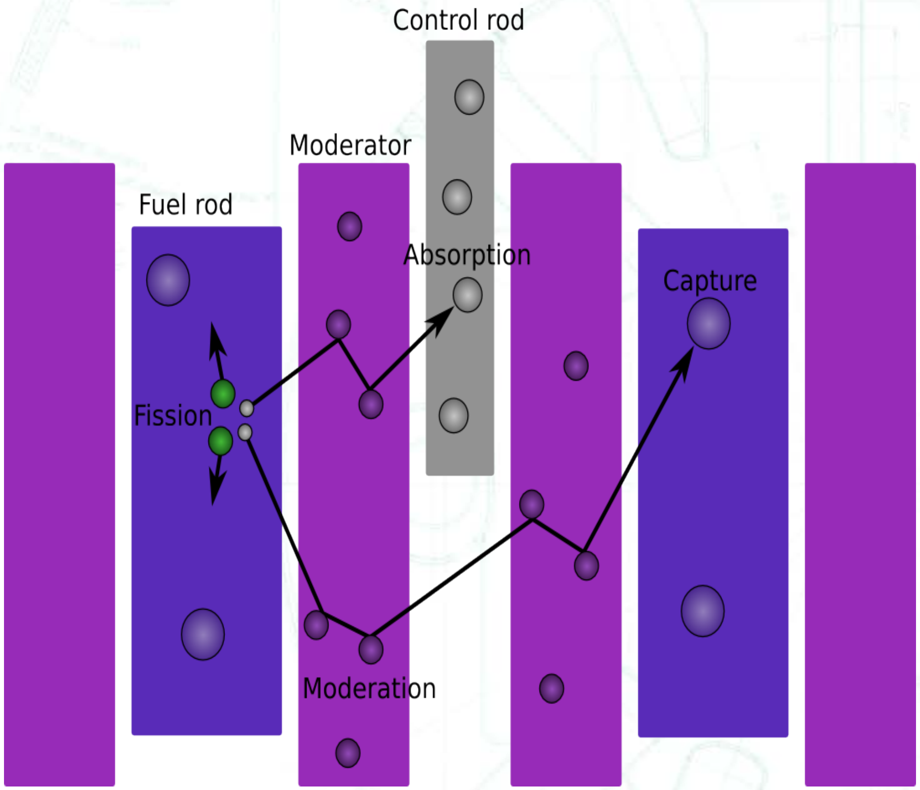
Reference - Informal History on the NCNR Web Site:
https://www.ncnr.nist.gov/NCNRHistory_Rush_Cappelletti.pdf

Thermal Neutron Fission of ^{235}U:



1. **Cross Sections:** ~ 585 barns for fission, ~ 100 b for $^{235}U(n,\gamma)^{236}U$
2. Two or three neutrons are produced at the instant of fission so a chain reaction is possible. ***Critical if exactly one causes fission!***
3. About **200 MeV/fission** is deposited in the reactor, 90% in fuel.
4. Over 1,000 fission fragments identified:
   - All are neutron rich and beta-decay several times.
   - Source of decay heat after shutdown (initially ~ 7%).
   - Some are poisons: ^{135}Xe has a 2 x 10^6 barn capture cross section.
   - A few decay by emitting a (delayed) neutron, enabling reactor control. ***The delayed neutron fraction β = 0.66% for ^{235}U.***

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. Reflector, Shielding, Coolant, Neutron source and detectors

NIST Reactor Facility Milestones

- 10 MW from 1969 until 1985, 20 MW since.
- Cold Neutron Facility Development:
  - First neutrons in guide hall in 1990 (NG5,6,7).
  - NG1-4, 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.
- Relicensed again in 2009 for 20 years
- Plan is to relicense again in 2029.
- Need to convert to LEU fuel when available!

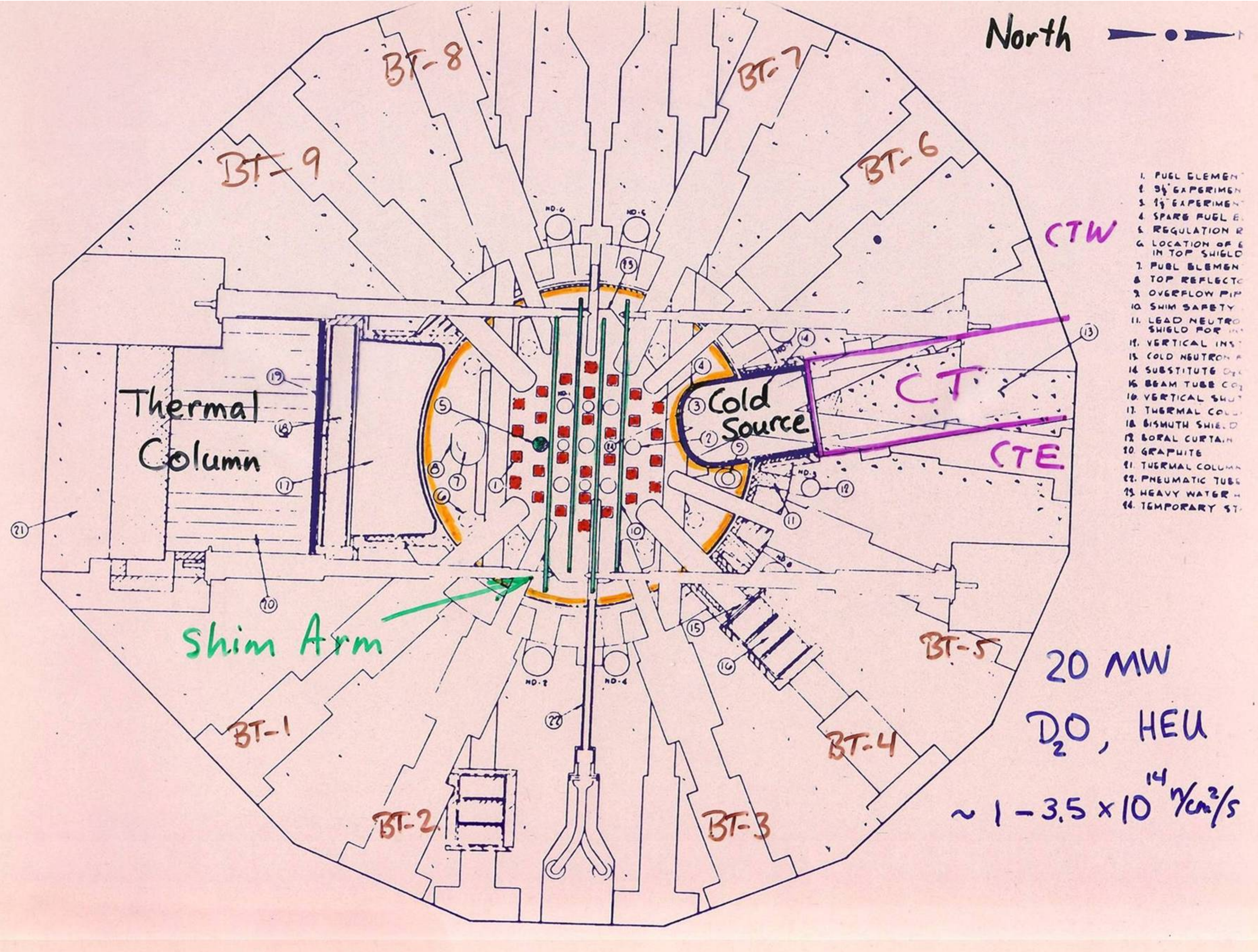
NIST Research Reactor History

- 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.

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
- 30 Fuel Elements
  - Fuel cycle ~38 days @ 20 MW
  - Load 4 fresh elements, reposition the others
  - About 960 g ^{235}U consumed per cycle
- Excellent Fuel Burnup: 64-70%
- 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.***

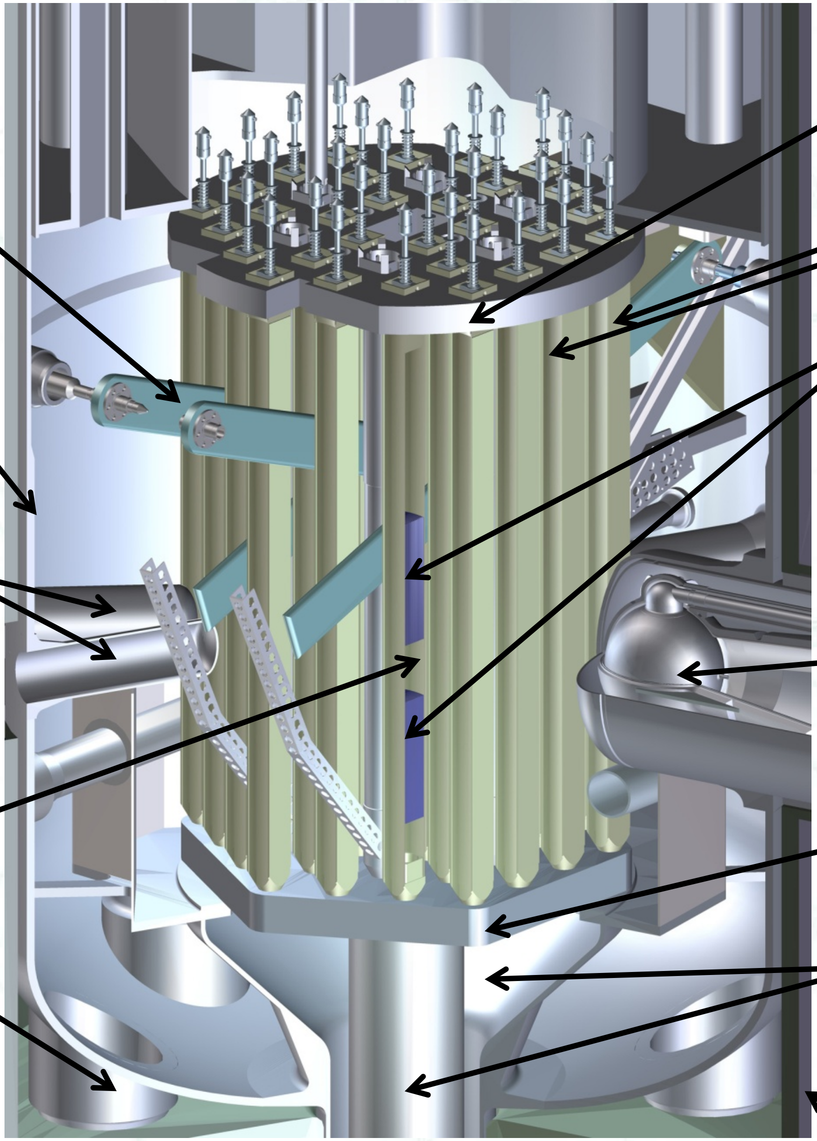


20 MW

D_2O, HEU

~ 1 – 3.5 × 10^{14} n/cm²/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

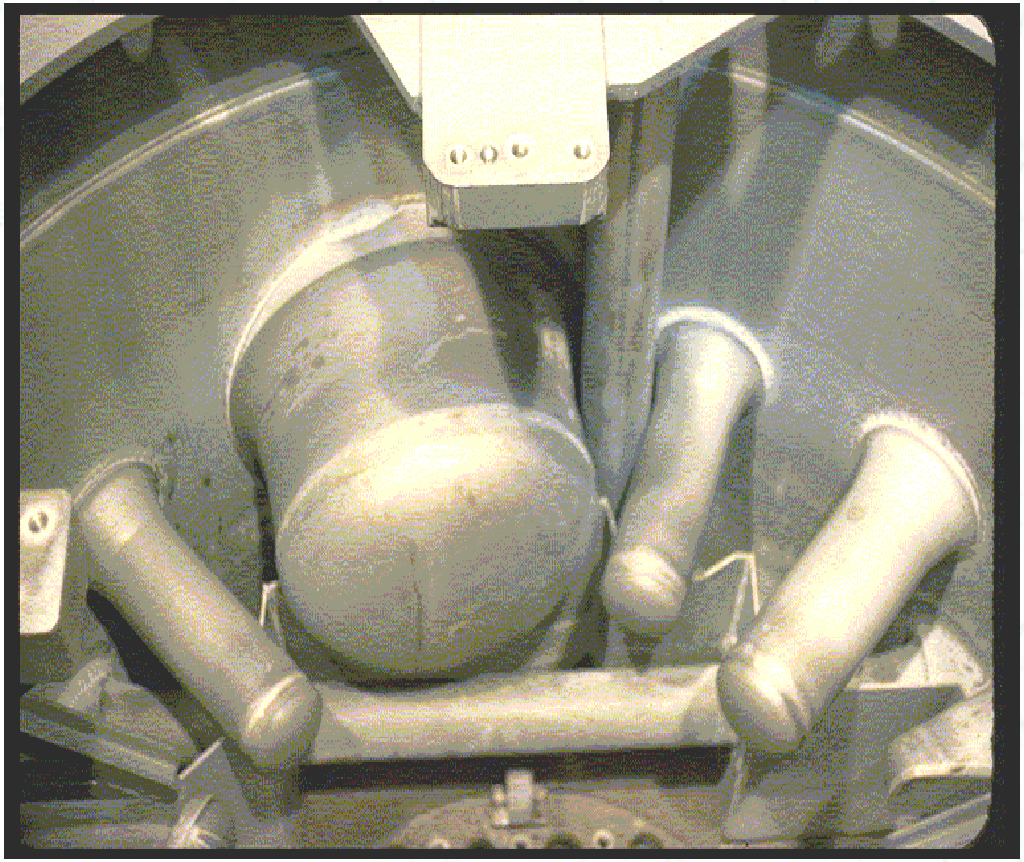
Liquid Hydrogen Cold Neutron Source

Bottom Grid Plate

D_2O Primary Inlet Plenums

Thermal Shield

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

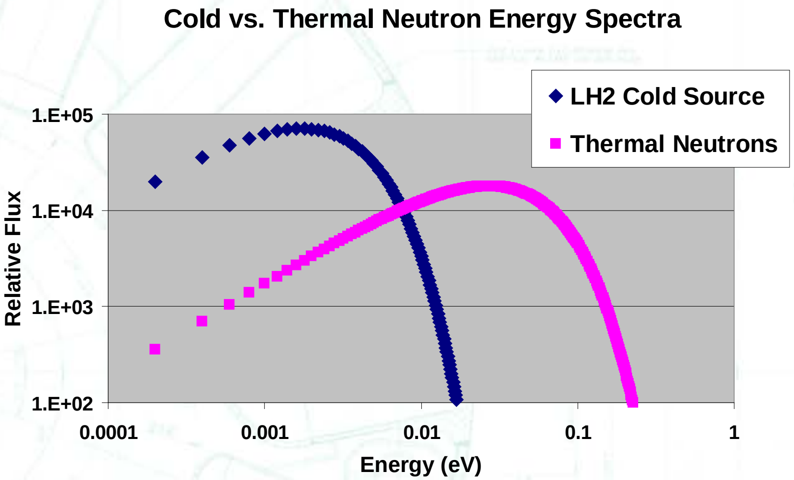
Production of Cold Neutrons

- 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.

Effect of an Ideal Cold Moderator on the Neutron Flux Energy Spectrum

- The Maxwell-Boltzmann energy spectrum is
- $\Phi_{th}(E) = [C\ /T^{3/2}\ ]\ E\ \exp\ (-E/kT)$
- In the limit of E → 0, the maximum theoretical gain of a cold source at 20 K with respect to a thermal spectrum at T_0 = 315 K is:
- $\mathrm{Gain}(E\rightarrow 0) = [T_0/T]^{3/2} = 62.$
  - The LH_2 source had a maximum gain of about 40.
  - "Effective" temperature is about 38 K, limited by neutron capture



Moderator Temperature (K)	Most Probable Energy (meV)	Wavelength (Angstroms)
315	30	1.6
20	2	6.4

Original Plan View of NBSR

For the first 20 years, there was NO cold source!

CT thimble filled by a D_2O tank, with BT's along CTE and CTW.

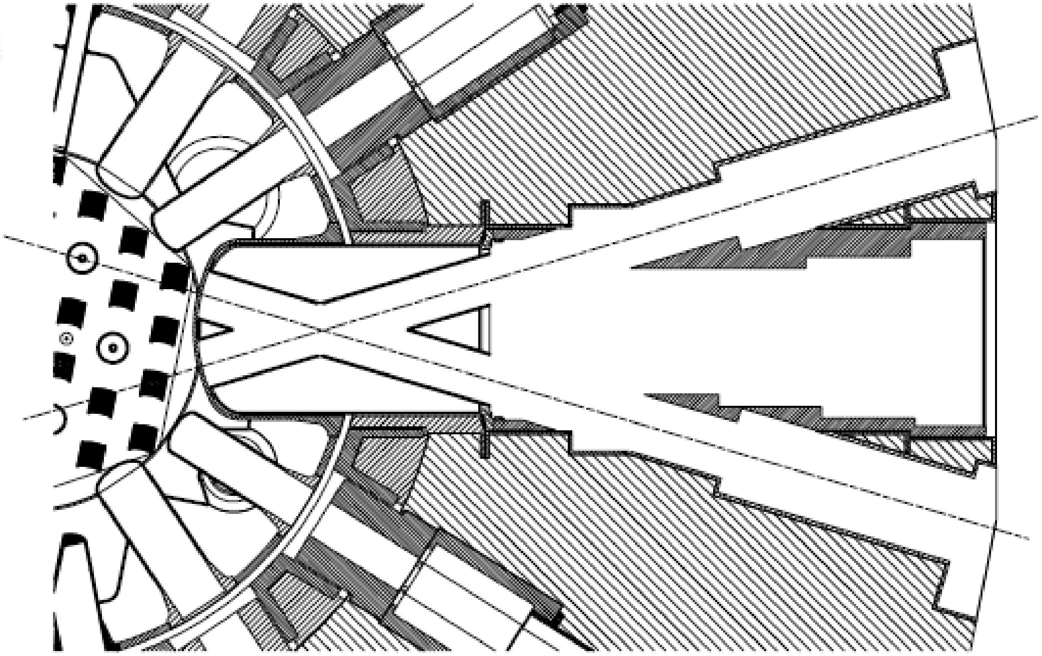


Figure 2.2. Original layout of the cold neutron port.

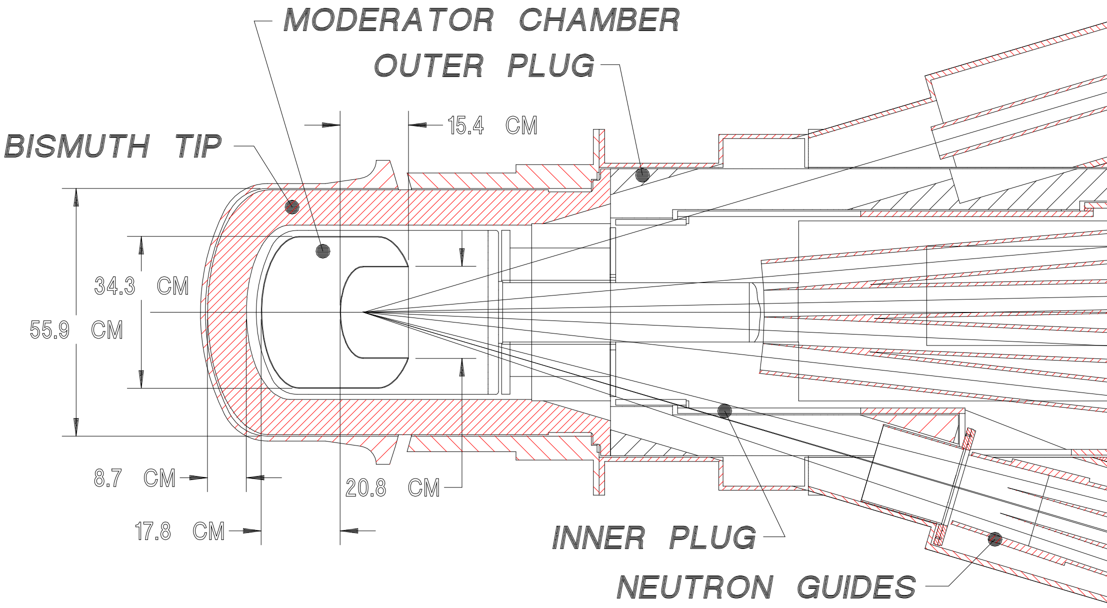
CTE and CTW are NOT radial beam tubes.

They intersect at the point of the planned CNS, far from core.

This geometry imposes CNS design constraints!!

NBSR Designed for a D_2O Ice Source

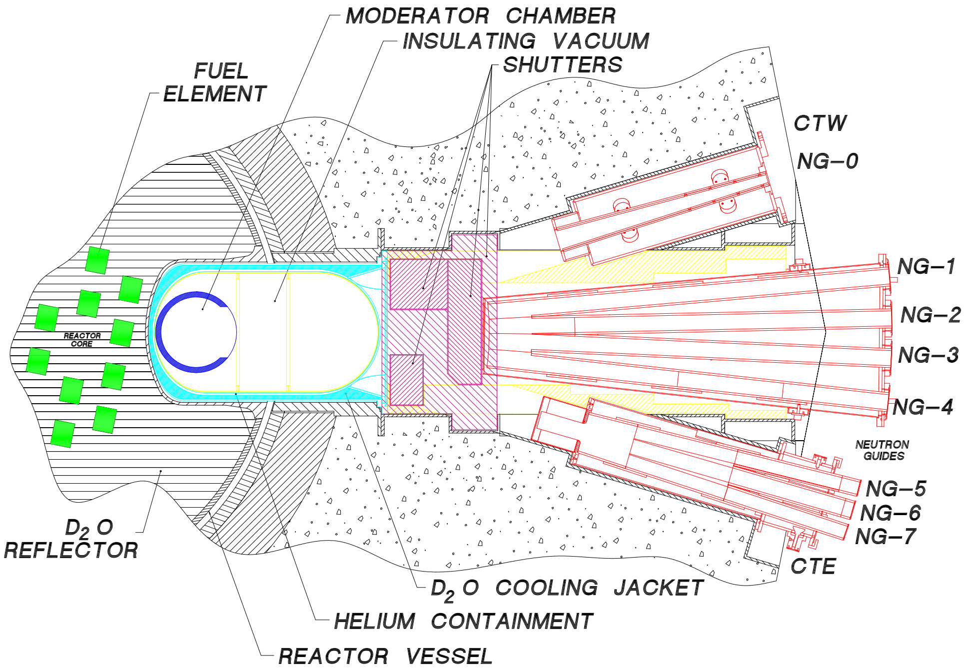
- 16 liters of ice at 30-35 K
- A Lead/bismuth shield (water cooled) required to reduce nuclear heating
- Optimum source contained ~8% H_2O (ice)
- Operated from 1987 to 1994
- Operational difficulties: *Unpredictable stored energy releases from recombination*



Every 2 days, we had to "burp" the cold source!

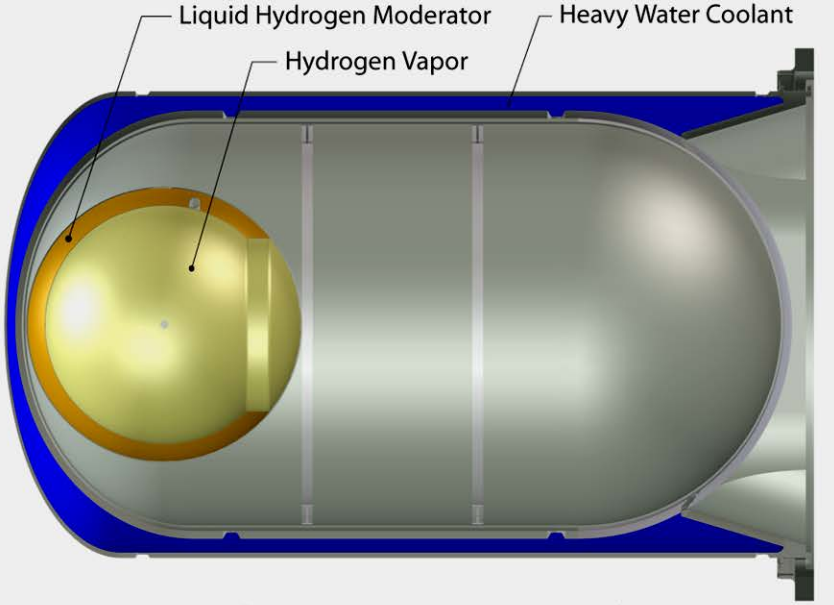
Gain Factor ~ 3

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

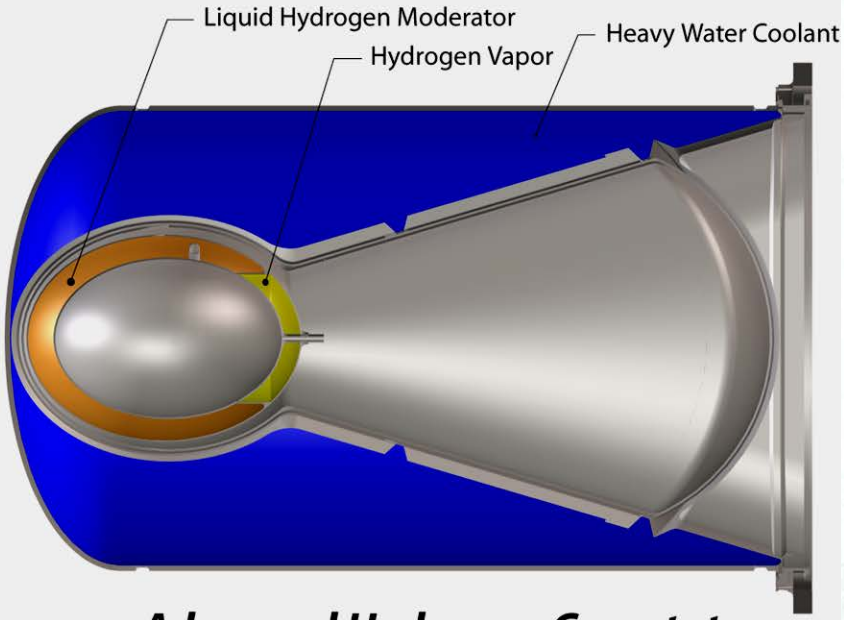


Thermal-hydraulic tests with LH_2 conducted at NIST Boulder.

- New refrigerator – 3.5 kW!
- 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.

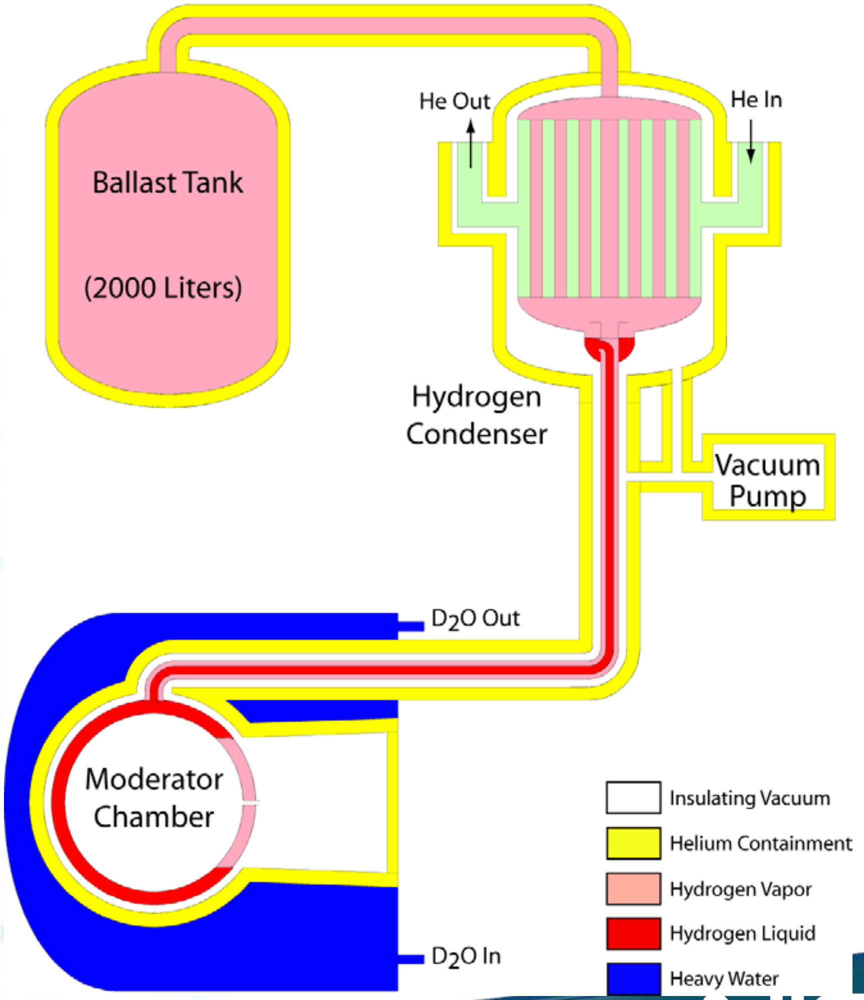
32 x 24 cm ellipsoid allowed more D_2O and a thicker LH_2 annulus.

Gain ~ 2 (2002)

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

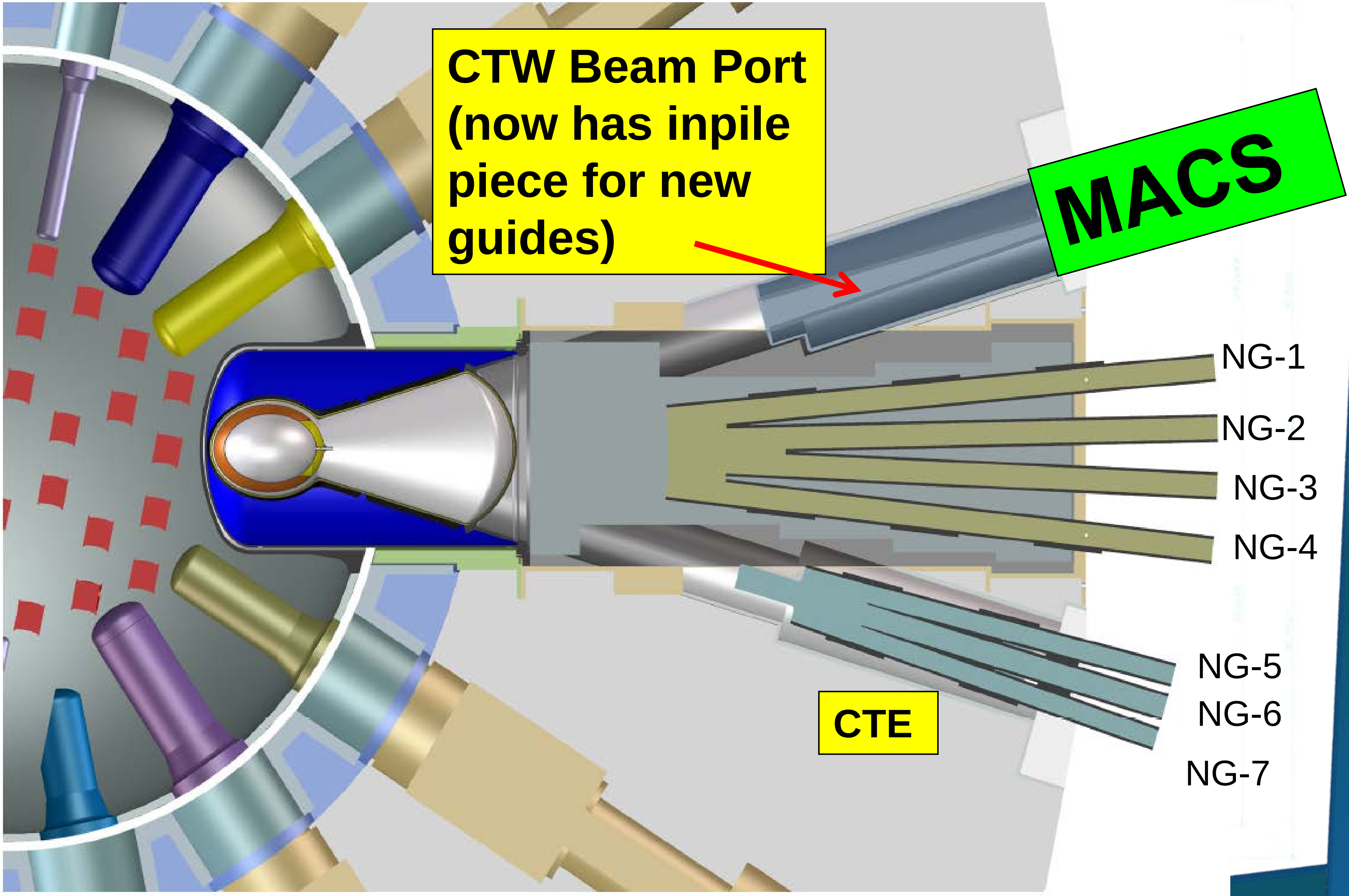
- A *thermosiphon* is the simplest way to supply the source with LH_2.
  - Cold helium gas cools the condenser below 20 K.
  - Hydrogen liquefies and flows by gravity to the moderator chamber.
  - Vapor rises to the condenser and a naturally circulating system is established.
- *The system is closed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



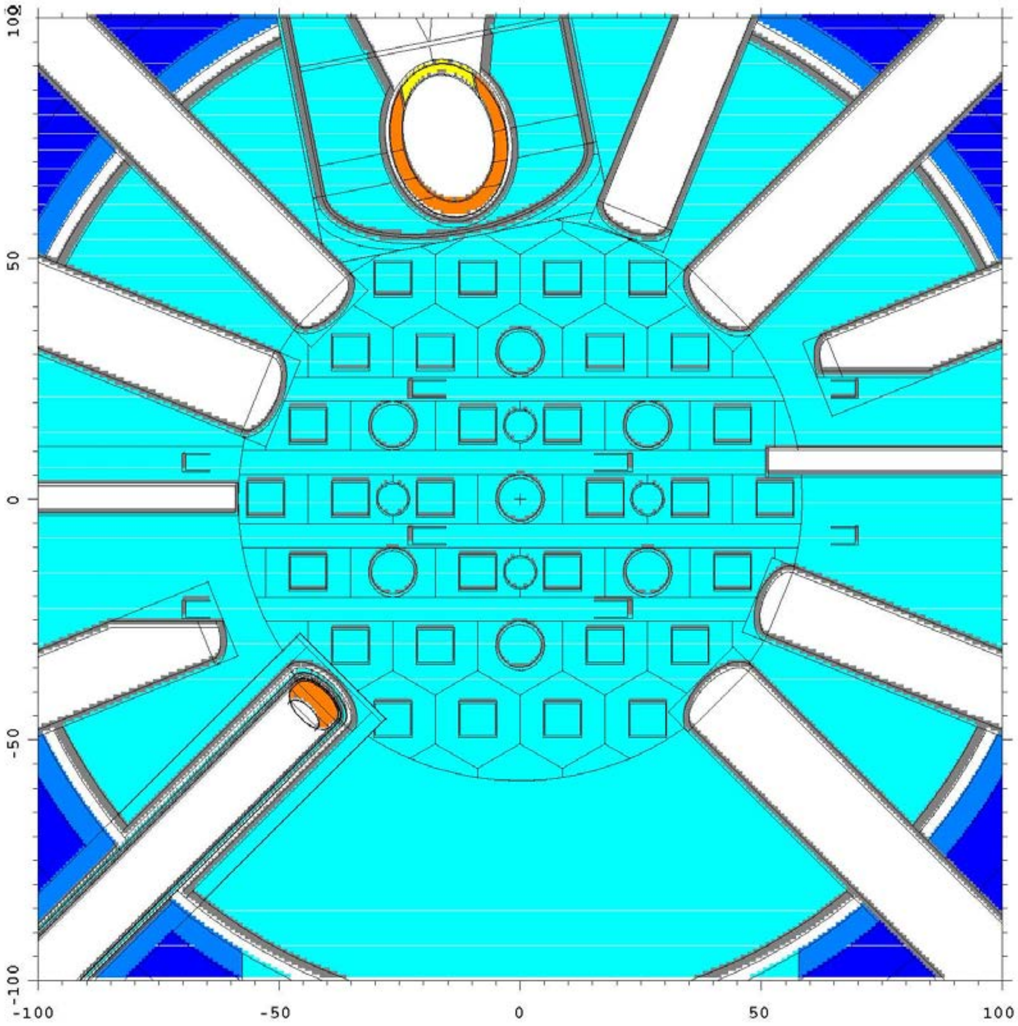
CTW Beam Port (now has inpile piece for new guides)

MACS

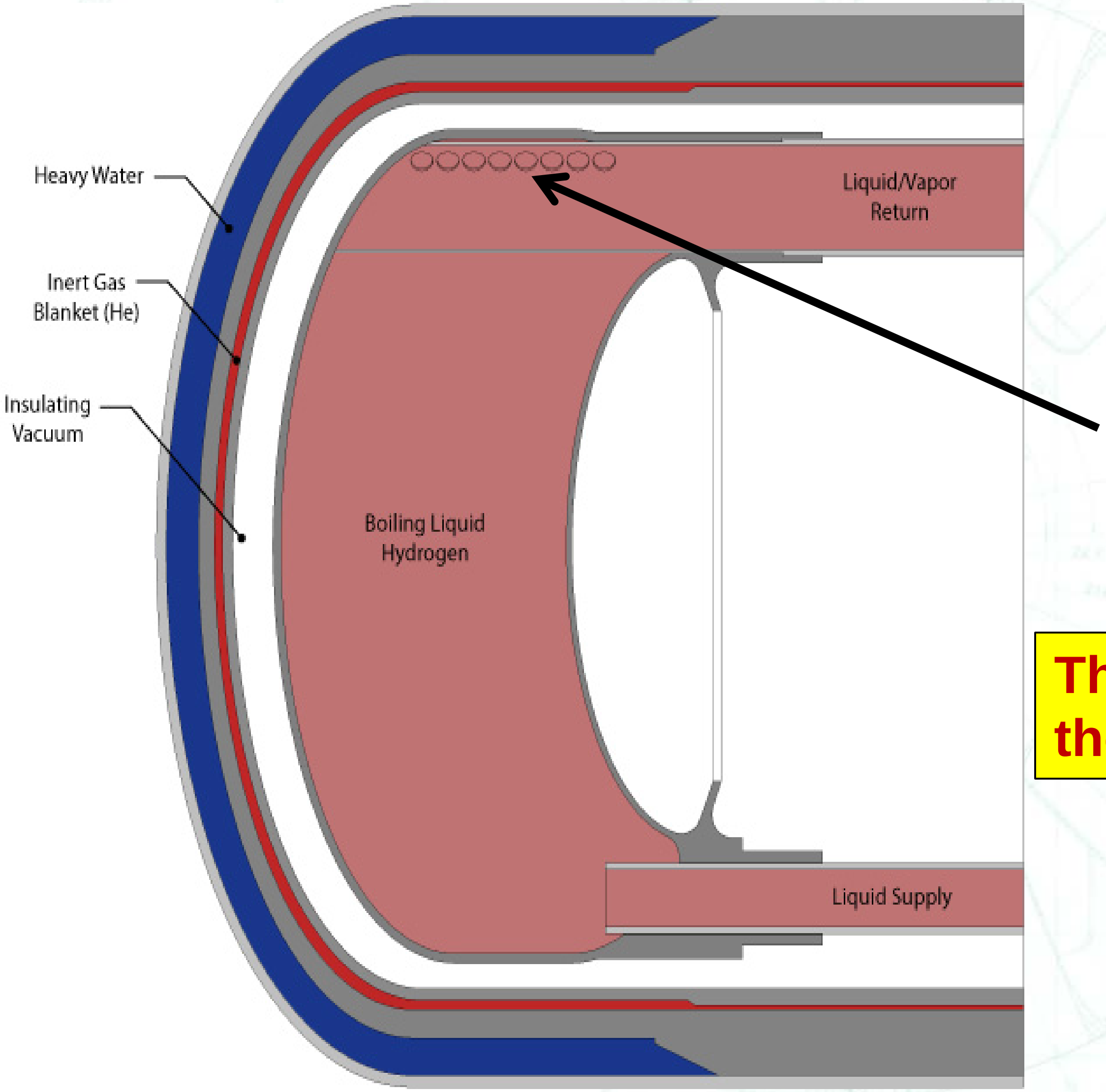
CTE

A second LH_2 source has been installed in BT-9 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.

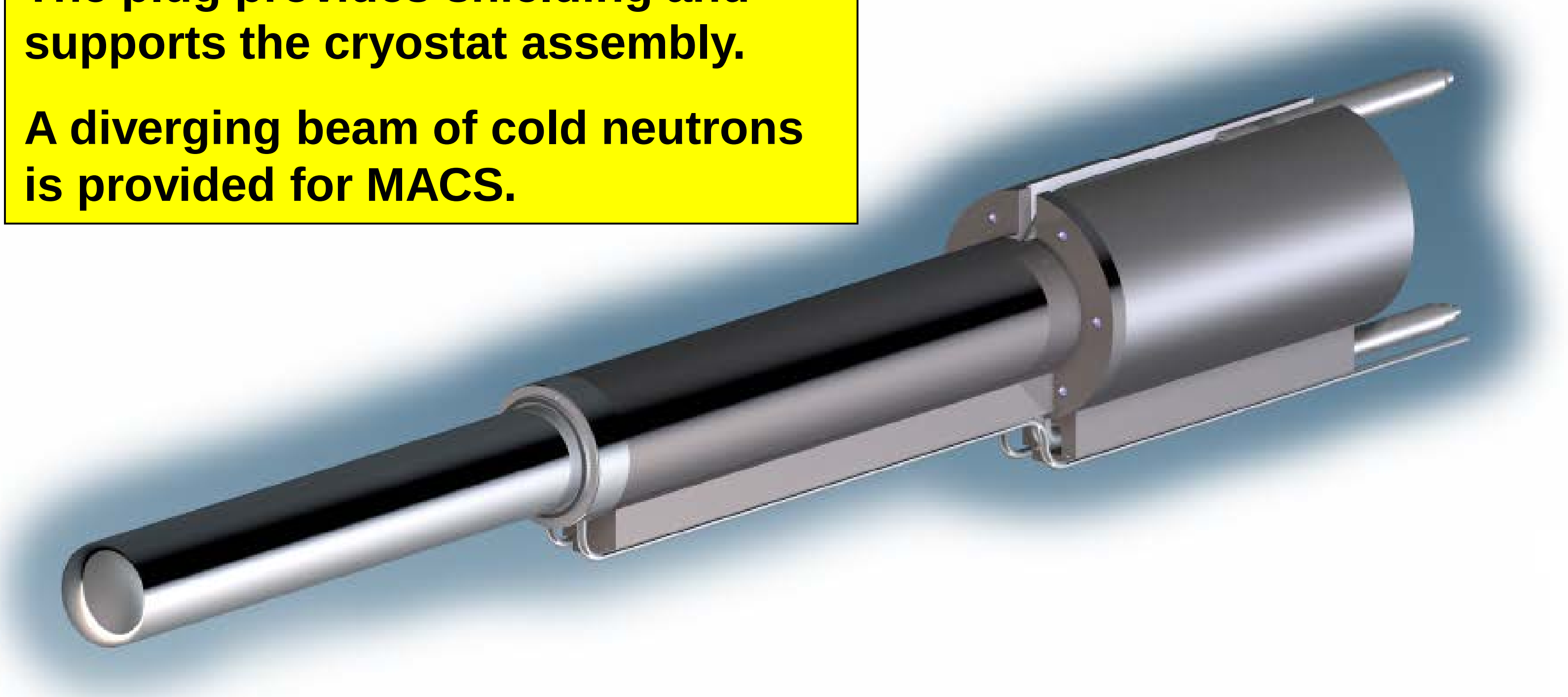
Thermal-hydraulic tests of thermosiphon used R-134.

Reference: IGORR 2009

Inpile Assembly

The plug provides shielding and supports the cryostat assembly.

A diverging beam of cold neutrons is provided for MACS.

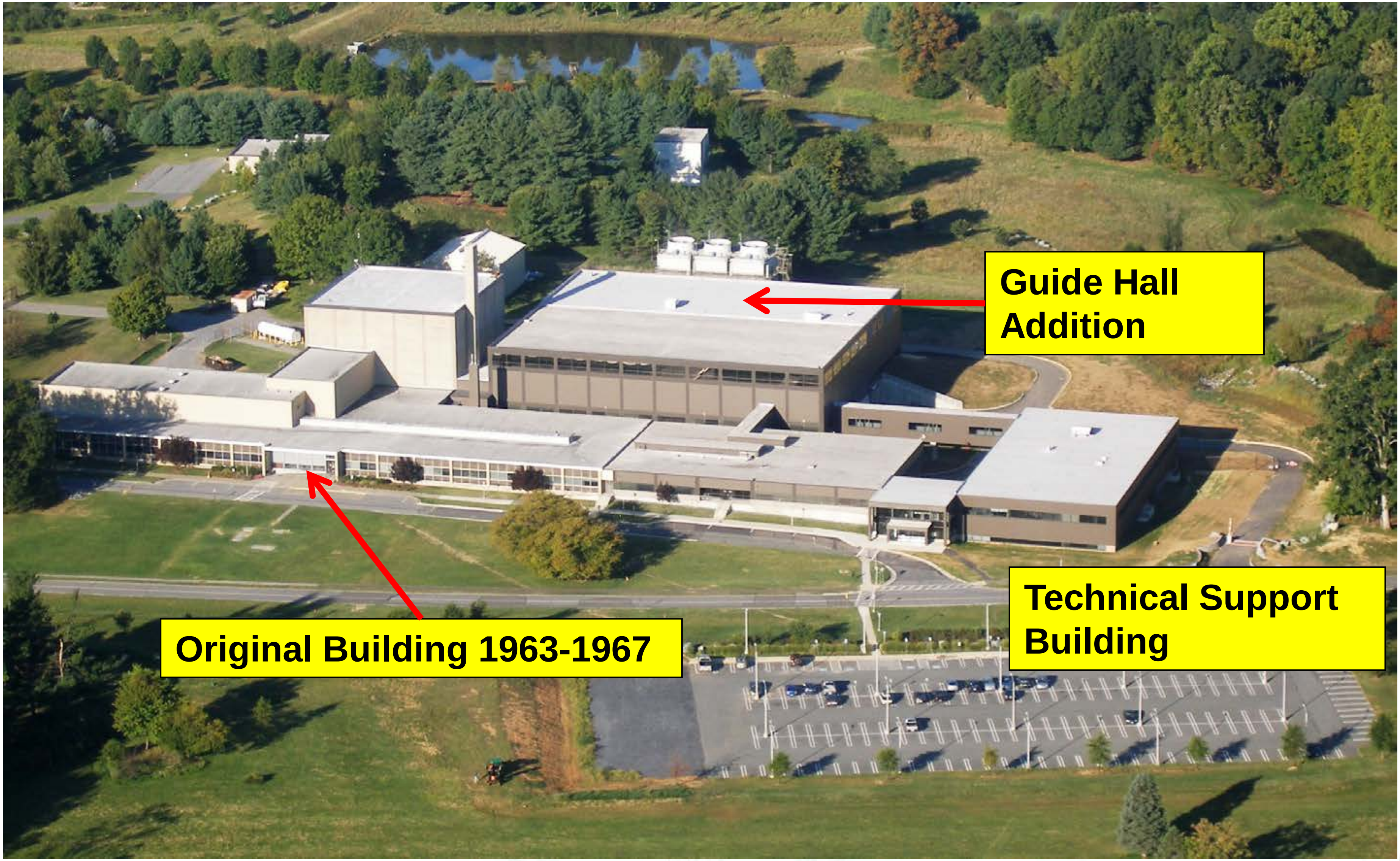


CNS Team installed Peewee in BT-9 in September 2011.

Conclusions

- The LH_2 cold sources at NIST have made NCNR a world class cold neutron facility.
- About 75% of experiments will use cold neutrons.
- LD_2 source planned for 2022(?), to replace Unit 2 (*reference:* IGORR 2013, Daejeon).
- *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 (*reference:* IGORR 2014, Bariloche).

NCNR Expansion – Fall 2010

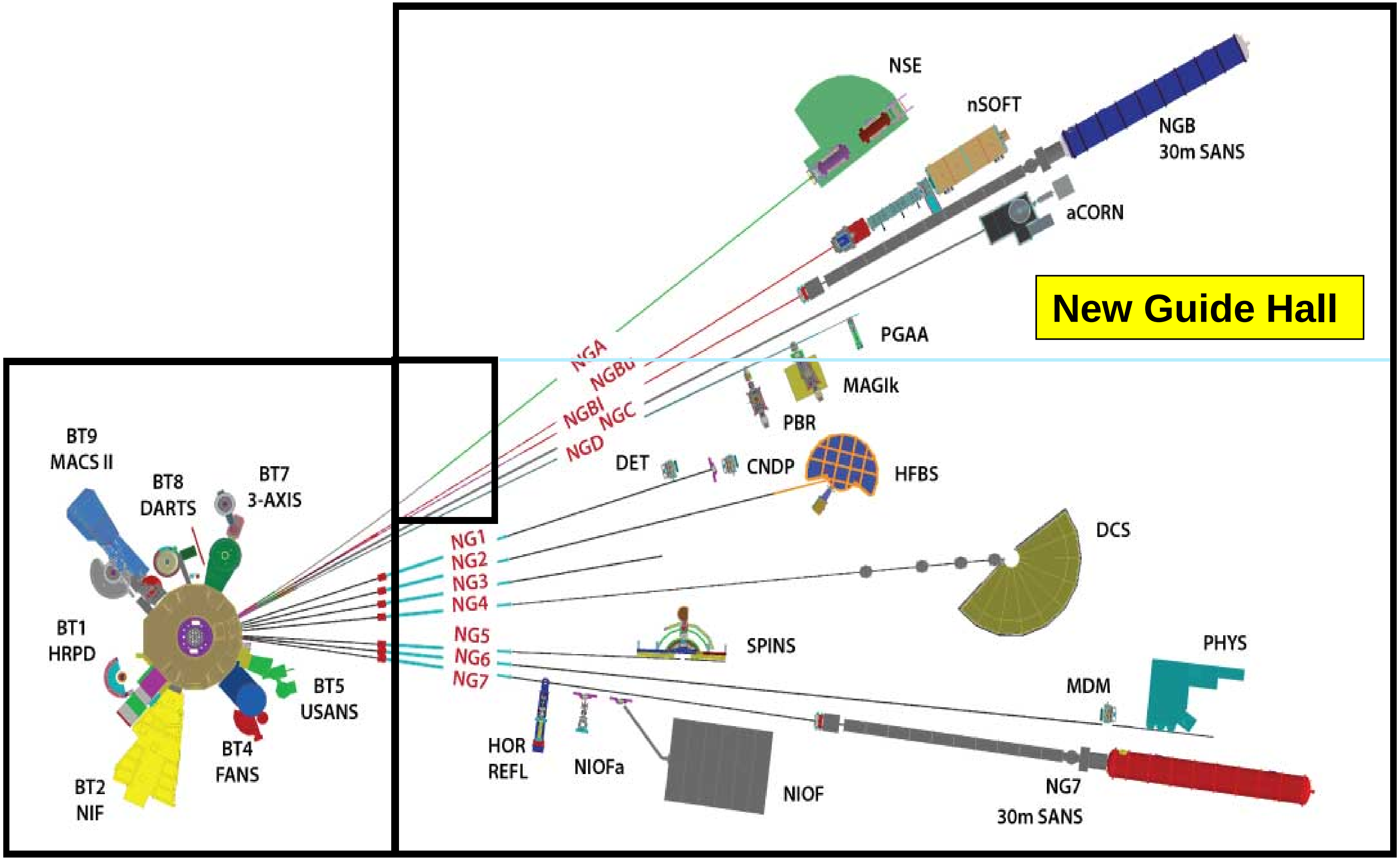


Guide Hall Addition

Original Building 1963-1967

Technical Support Building

Existing Instrument Layout – Nov 2014



Xenon Poisoning

- The A=135 fission product decay chain:
- … $^{135}\mathrm{Te} \rightarrow {}^{135}\mathrm{I} \rightarrow {}^{135}\mathrm{Xe} \rightarrow {}^{135}\mathrm{Cs} \rightarrow {}^{135}\mathrm{Ba}$
  - $T_{½}$ 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

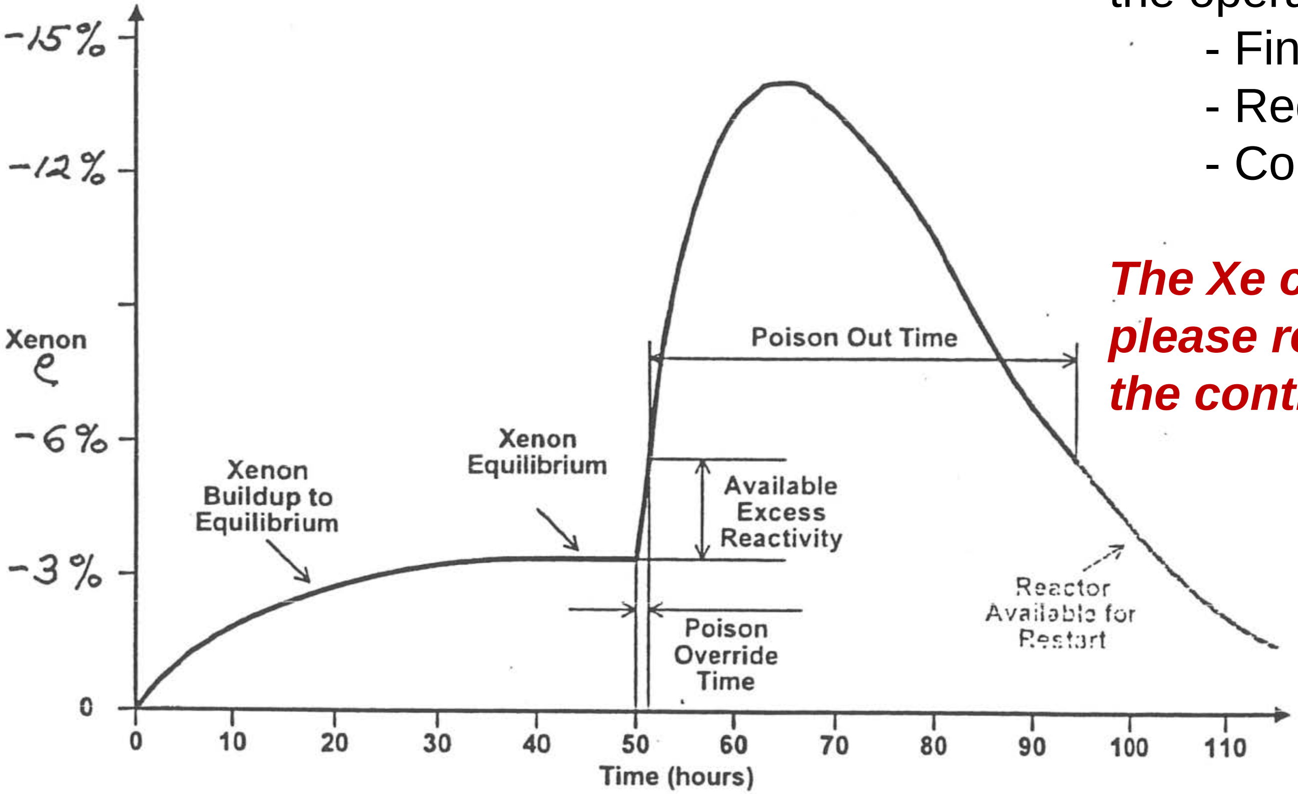


Figure 9
Behavior of Xenon-135

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!