NIST Center for Neutron Research

A Liquid Deuterium Cold Source at NIST ?

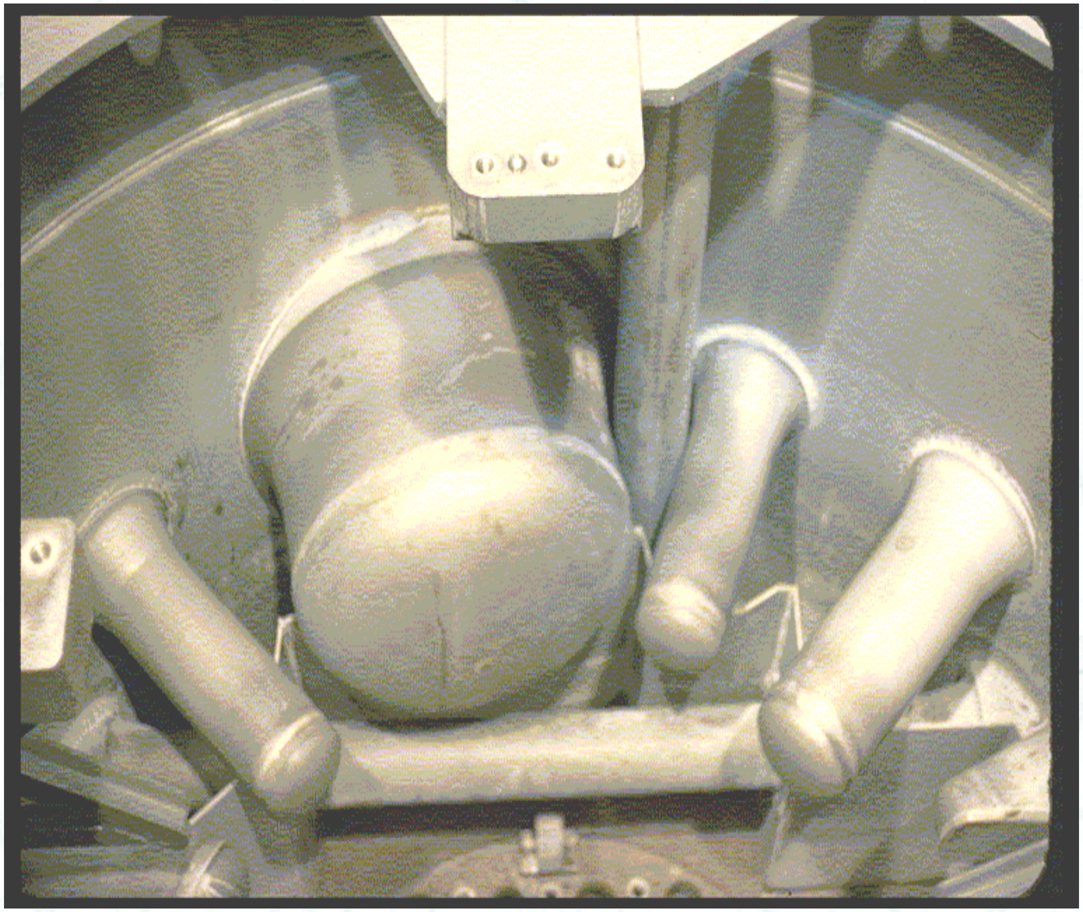
Robert Williams, Paul Kopetka, Mike Middleton
and Mike Rowe (Consultant)

IGORR/TRTR Joint Meeting
Knoxville, Tennessee
September 19-23, 2010

NIST

Outline:

1. Cold Source Development at NIST
2. Feasibility of a Liquid Deuterium Source
3. Optimization and Heat Load Calculations
4. Work Required for a LD_2 Source
5. Conclusion



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

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.

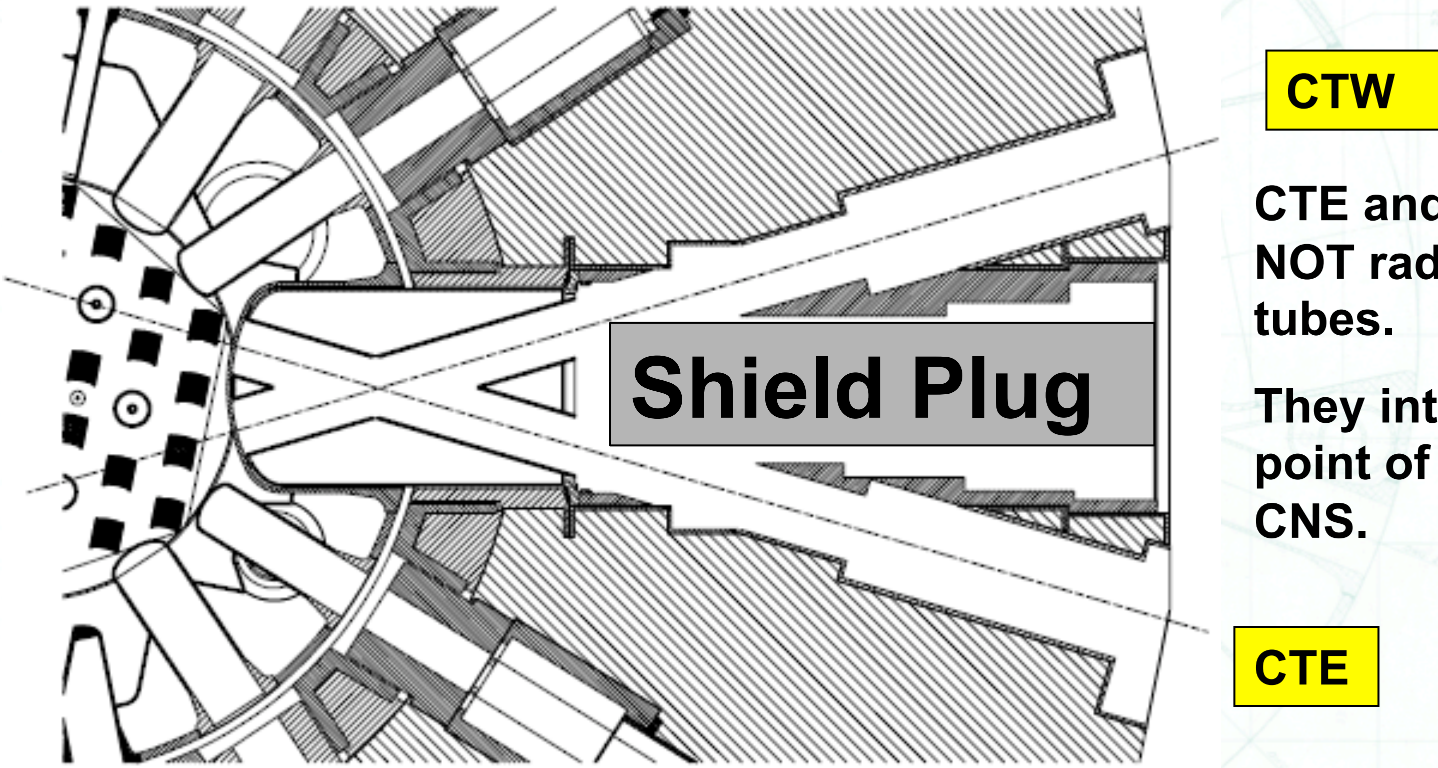


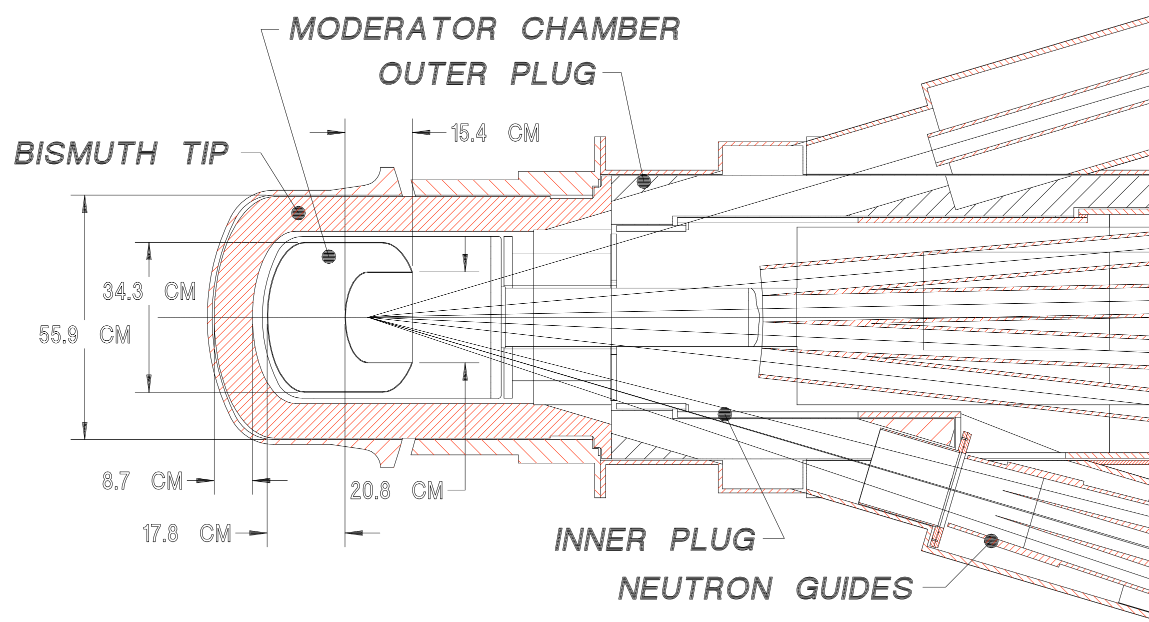
Figure 2.2. Original layout of the cold neutron port.

CTE and CTW are NOT radial beam tubes.

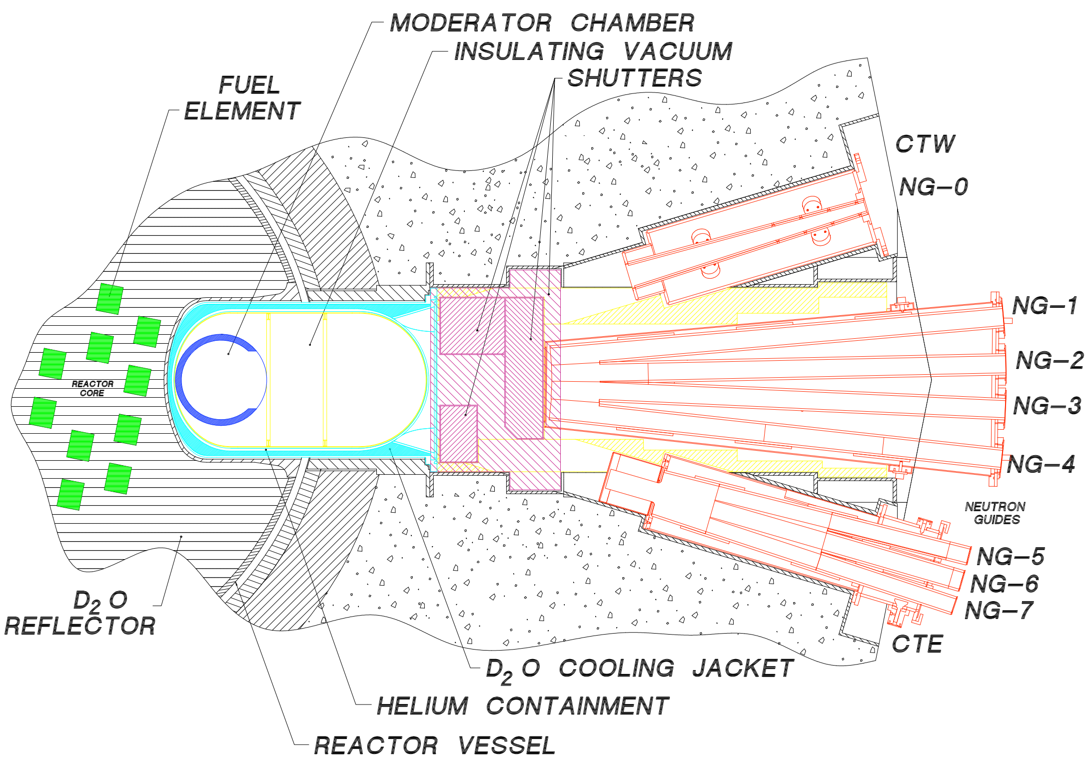
They intersect at the point of the planned CNS.

NBSR Designed for a D_2O Ice Source

- 16 liters of ice at 35 K
- A Lead/bismuth shield (water cooled) required to reduce nuclear heating
- Optimum source contained 8% H_2O
- Operated from 1987 to 1994



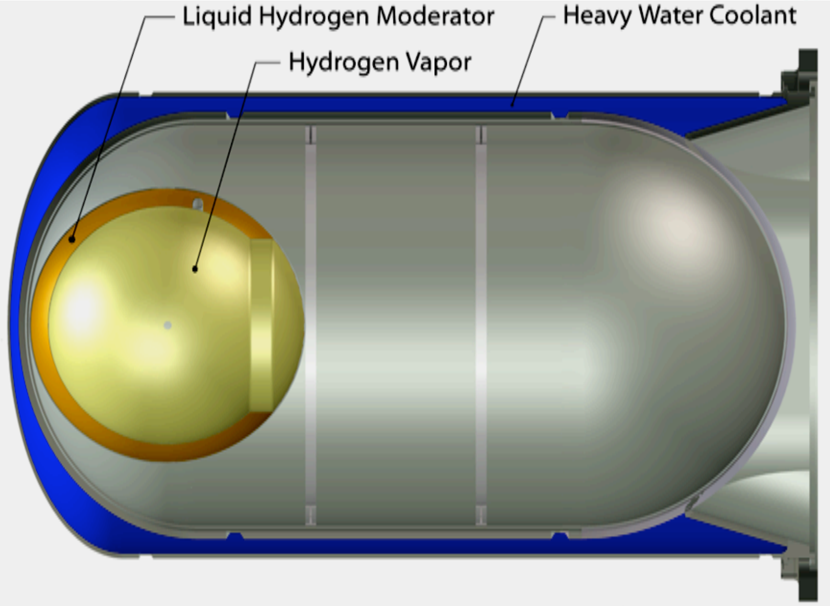
The LH_2 CNS, Unit 1, installed in 1995, had a gain of 6 times the D_2O source



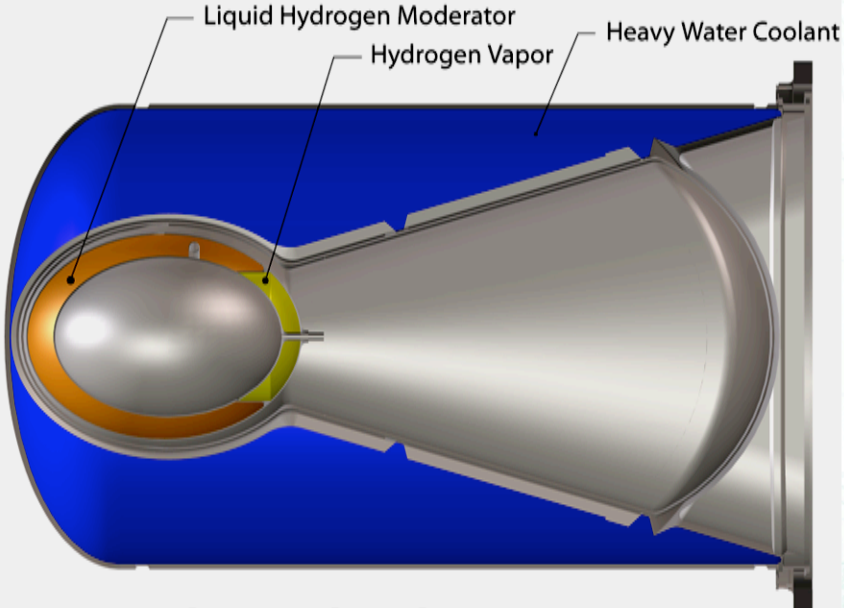
To fully illuminate the beam ports, the source had to have a very large area.

A 320-mm spherical annulus, 20 mm thick, with a 200-mm diameter exit hole was chosen:

- Low heat load (850 W)
- 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.

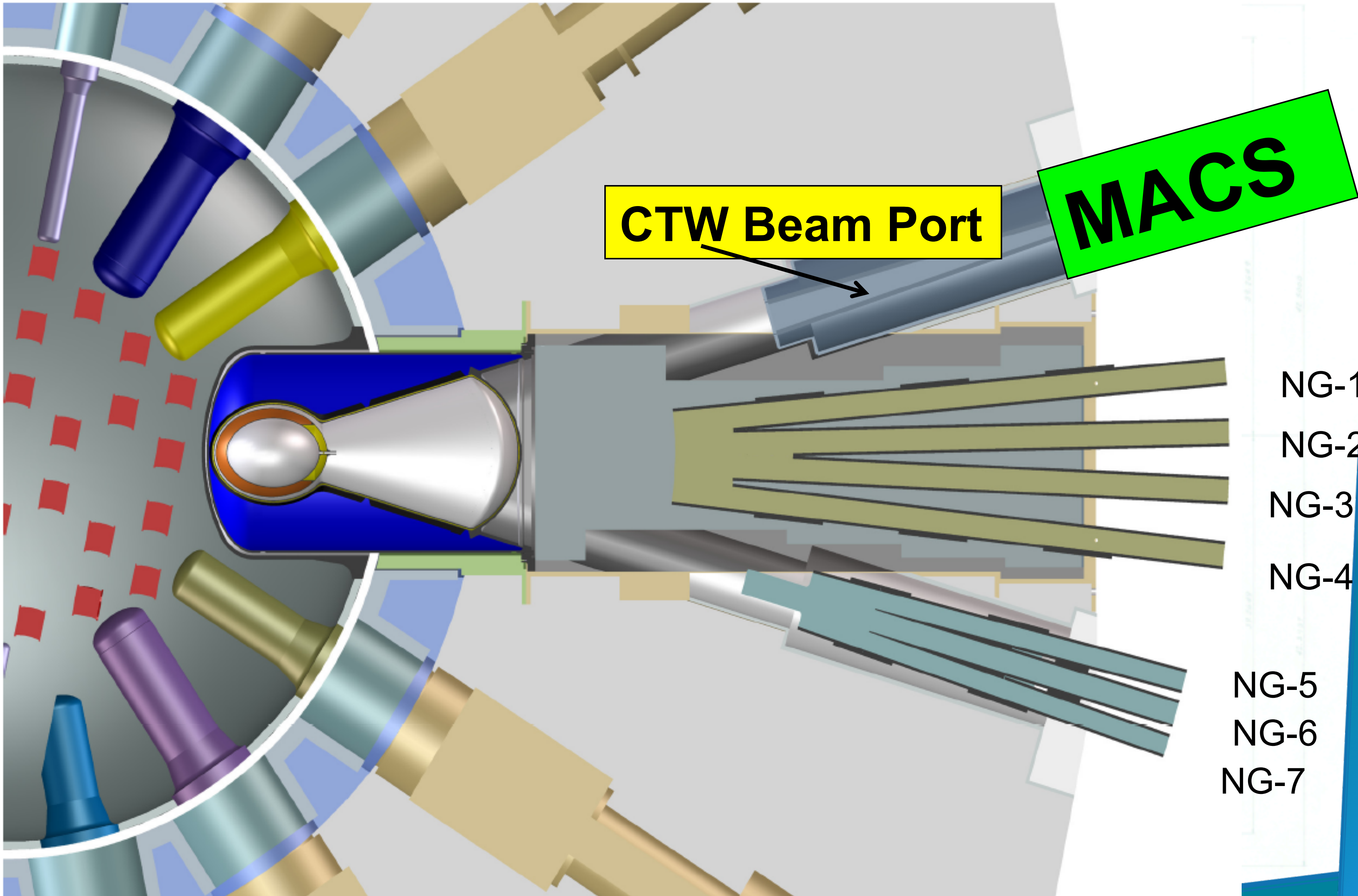
Much more D_2O in Unit 2 results in a higher neutron flux in the CNS region and the adjacent fuel elements.

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

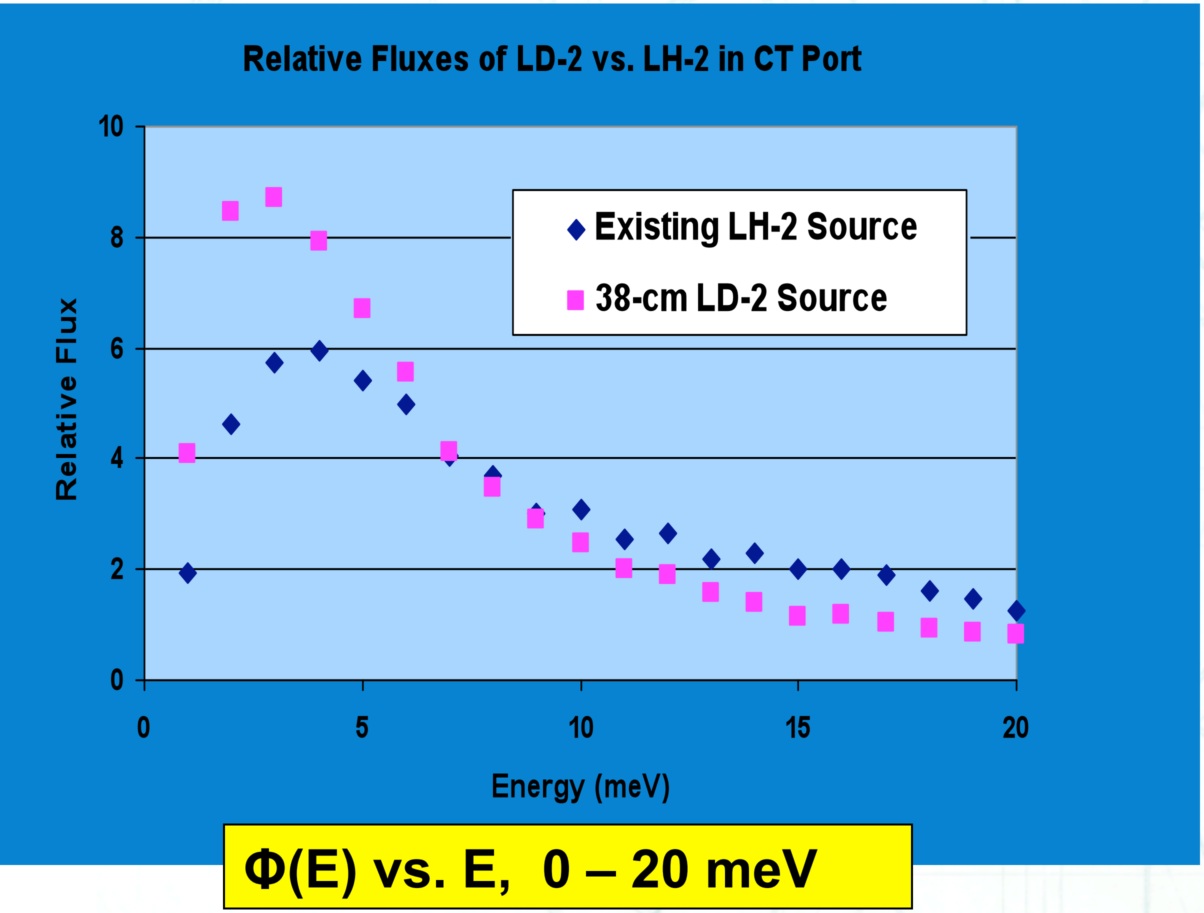
Vacuum filled inner ellipsoid.

NIST

Existing LH_2 Cold Source, In-pile Neutron Guides



What is to be gained with deuterium?



- Spectrum shifts to lower energies.
- Gain of 2 for the longest wavelengths.
- Maxwell–Boltzmann temperature drops from 38 K to 28 K
- Large volume, low absorption.
- Small loss of intensity for 5 – 10 meV.
- Up to 50% loss at 15 meV (2.5 Angstroms).

NIST Center for Neutron Research

NIST

Feasibility of a LD_2 Source (I)

- A LD_2 source requires a large volume compared to LH_2.
- The CT thimble in the NBSR has ample room for a very large LD_2 moderator vessel (30–50 liters).
- Calculations have shown that a gain of 1.6 may be realized for cold neutrons, $E < 5$ meV ($\lambda > 4$ Å).
- The nuclear heat load could be 3–4 kW, however, depending on the volume and vessel wall thickness.

Feasibility of a LD_2 Source (II)

- NEED MORE REFRIGERATOR CAPACITY !
- A 7-kW refrigerator procurement was *cancelled* in August.
- We are still looking for a few million dollars.
- *Alternatively*…
- Can our existing, nominally 3.5-kW refrigerator be upgraded (bigger compressor, new turbine expander) to a larger capacity at a higher temperature?
  - (LD_2 boils at ~3 K higher than LH_2)
  - Existing refrigerator insufficient for LD_2 source, as is.
  - Must cool small LH_2 source, too!

Example of a "small" deuterium source

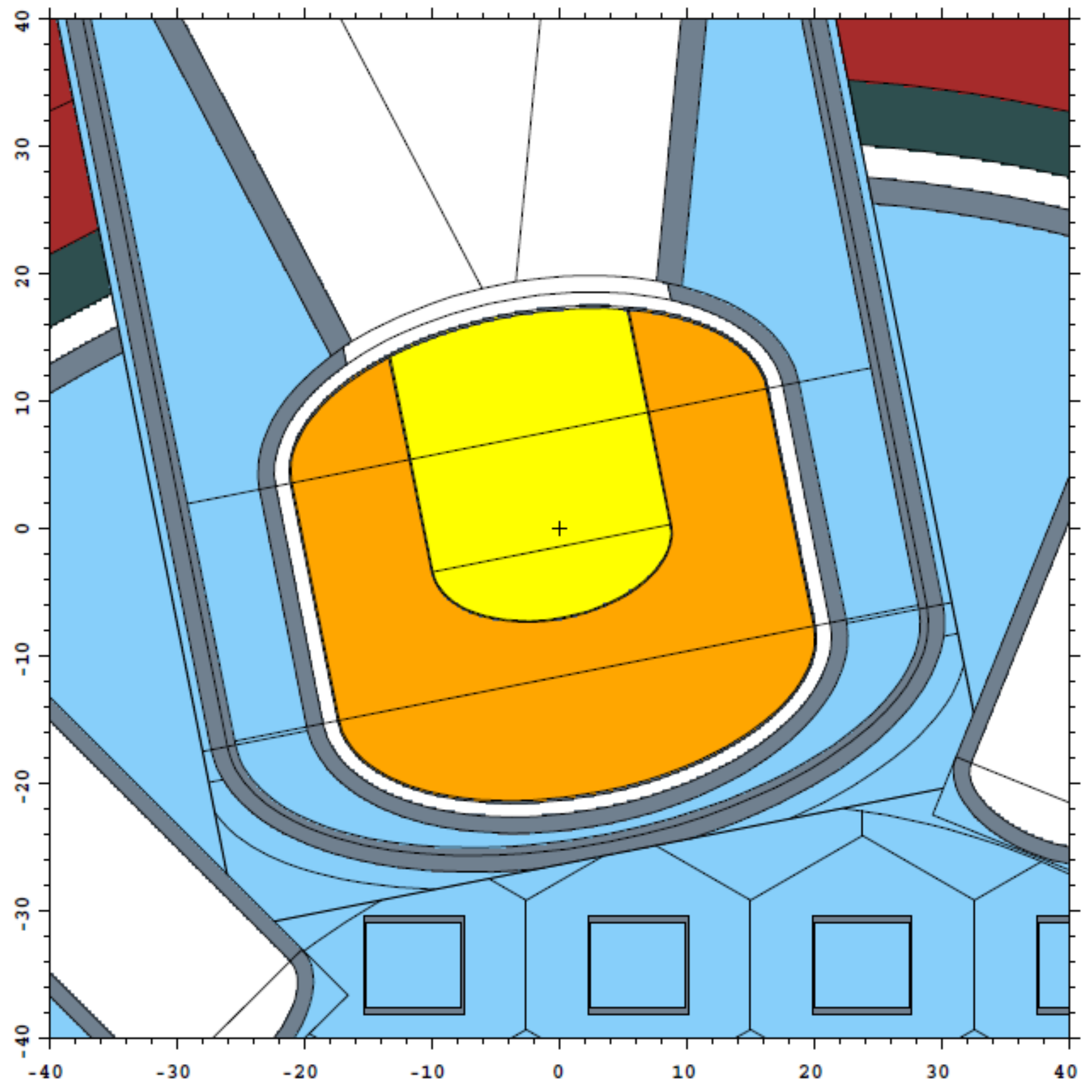
A 38x38 cm LD_2 vessel:

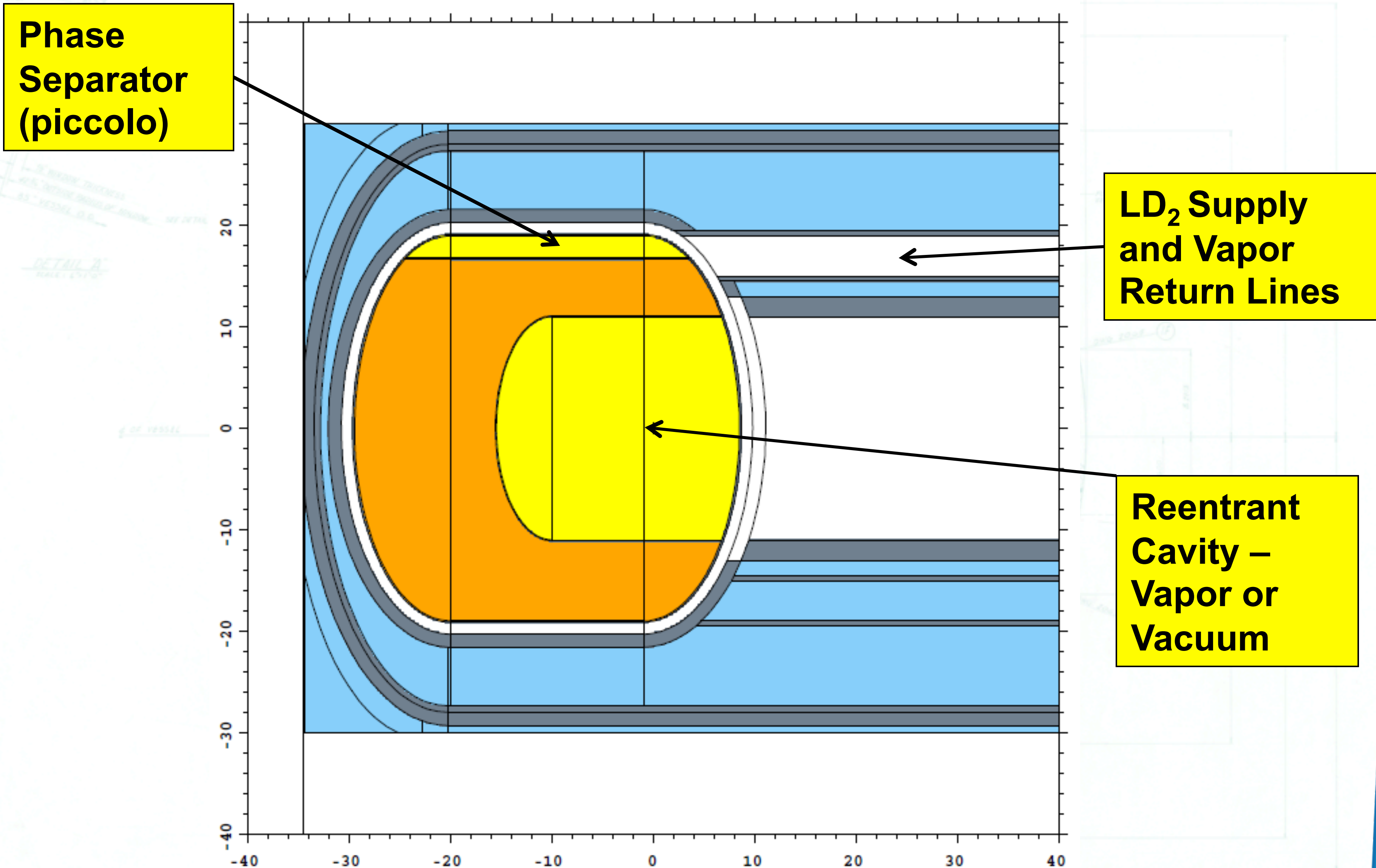
- 26 liters
- 24-cm reentrant cavity

It must be surrounded by:

- Insulating vacuum
- He containment
- D_2O coolant

~2 kW with 1.3 mm walls




Phase Separator (piccolo)
LD$_2$ Supply and Vapor Return Lines
Reentrant Cavity – Vapor or Vacuum
-40
-30
-20
-10
0
10
20
30
40

Factors Affecting CNS Performance (I)

1. **Volume:** Gain increases with vessel size.
2. **Reentrant Hole Depth:** Can be used to “tune” the gains somewhat.
3. **Hydrogen Content:** The addition of a small quantity may increase gain a bit (need HD scattering kernel).
4. **Ortho/Para Content:** PSI measured the ortho-LD_2 fraction at 76%, which is less than the equilibrium value of 96% (we assume 67%).

NIST Center for Neutron Research

NIST

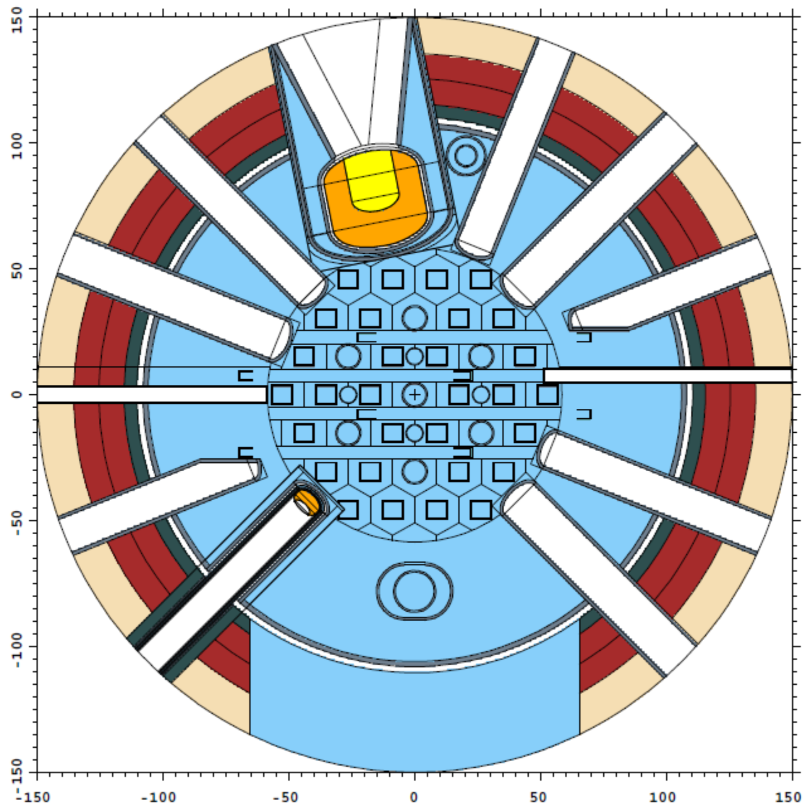
Factors Affecting CNS Performance (II)

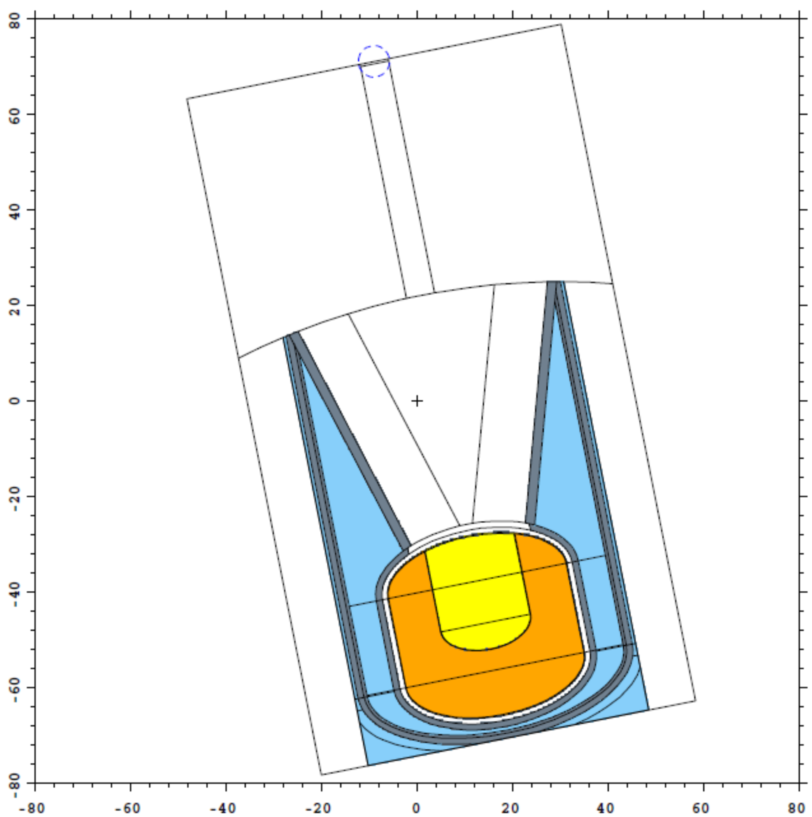
5. **Void Fraction (depends on heat load):** We assume a void fraction of 10% (about half of Kazimi Correlation for pool boiling) based on LH_2 and R-134a measurements.
6. **Exotic Materials for "focusing" (maybe):**
   - Diamond nano-particles may be used at ILL to enhance long-wavelengths from vertical LD_2 CNS.
   - Would add to heat load.

Many parameters to vary for optimization.

MCNP is used to optimize CNS performance in a 2 step process.

The code has generalized geometry and *scattering kernels for cold moderators*, and powerful *variance reduction techniques* to tally low-probability events.

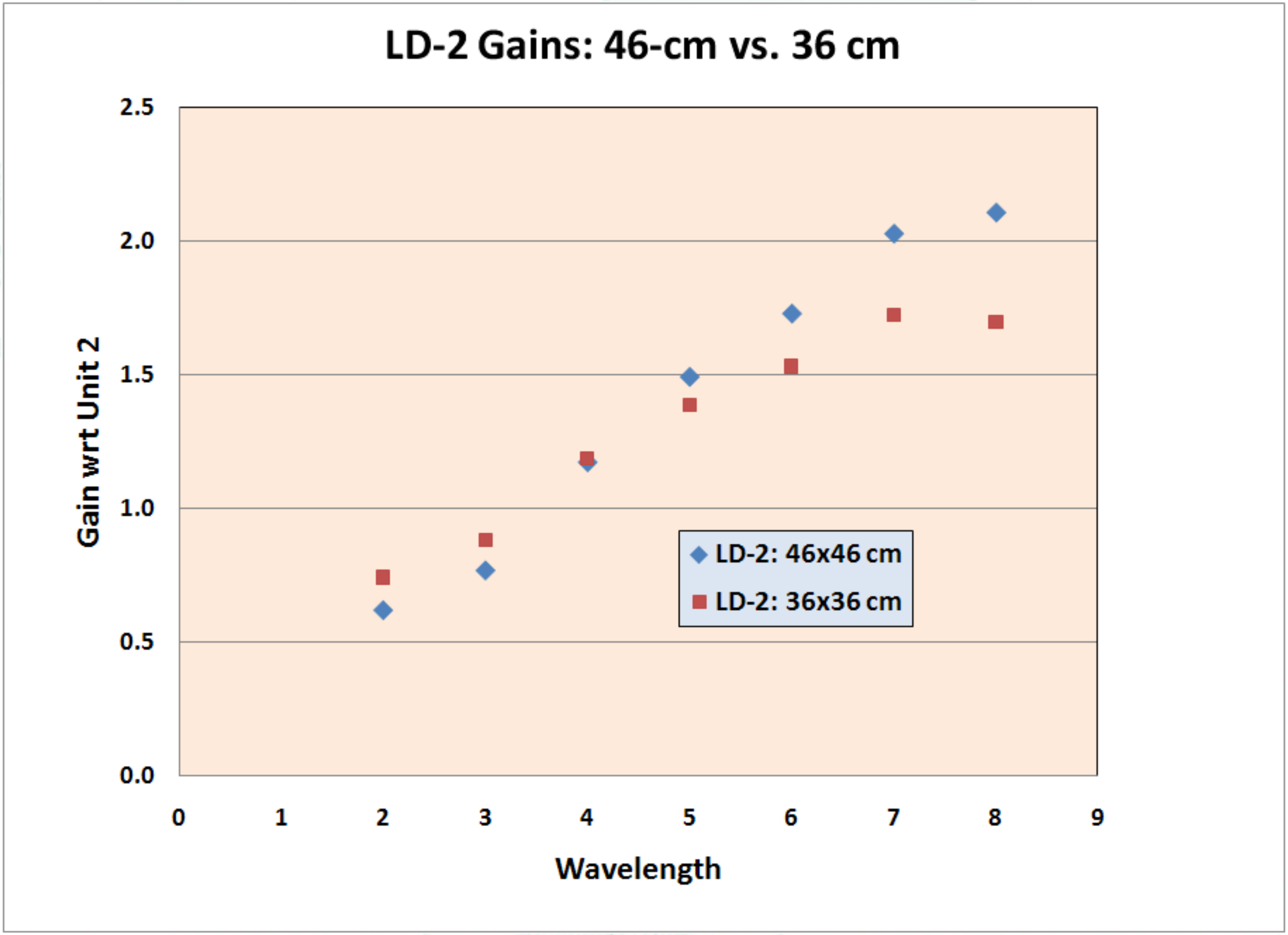


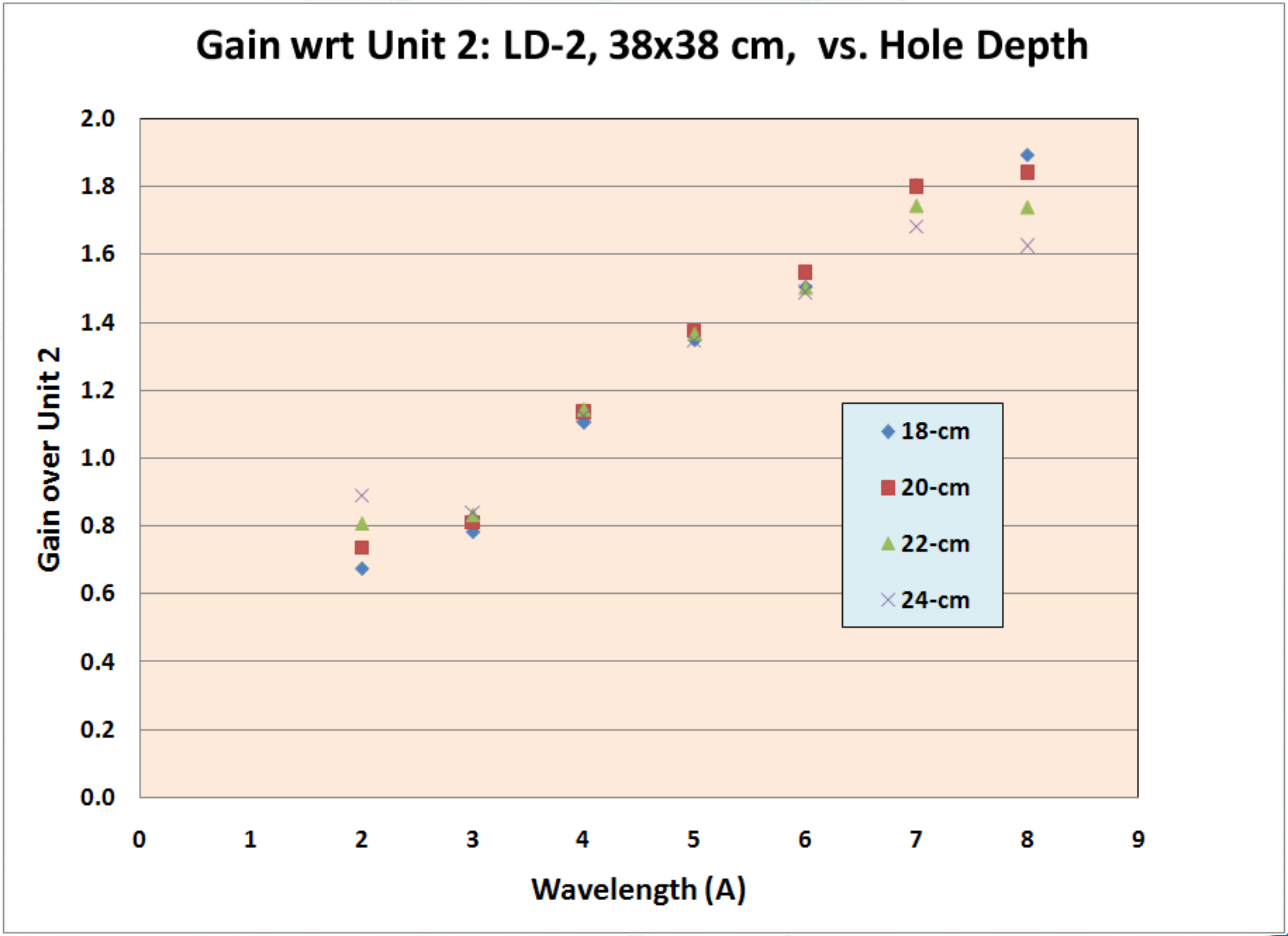


1.) A surface source was generated from the whole-core criticality calculation for CNS performance calculations.

This source preserves the normalization.

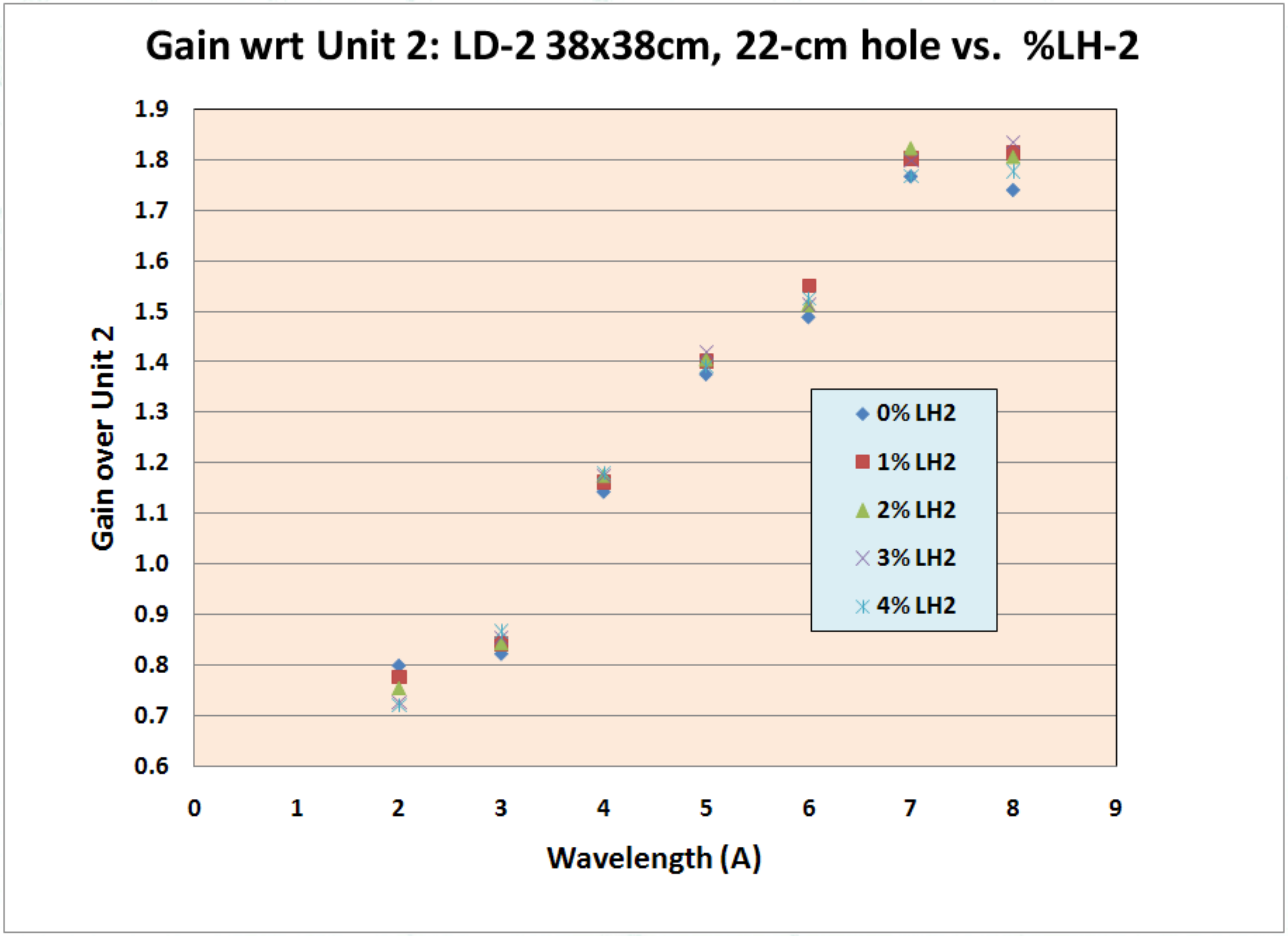
2.) The DXTRAN feature was used to force "***pseudo***" particles to a current tally plane at the neutron guide entrance.


LD-2 Gains: 46-cm vs. 36 cm
Gain wrt Unit 2
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
Wavelength
LD-2: 46x46 cm
LD-2: 36x36 cm



NIST Center for Neutron Research

NIST


Gain wrt Unit 2: LD-2 38x38cm, 22-cm hole vs. %LH-2
Gain over Unit 2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0
1
2
3
4
5
6
7
8
9
Wavelength (A)
0% LH2
1% LH2
2% LH2
3% LH2
4% LH2

Nuclear Heat Load Calculations

- Energy deposited by neutrons and prompt photons directly tallied by MCNP.
- Delayed gamma rays from modified ^{235}U cross section file.
- Energy from beta particles obtained from tally of the $^{27}Al(n,\gamma)^{28}Al$ reaction rate (1.25 MeV per β).
- Average heating rates:
  - 0.26 – 0.31 W/g in LD_2
  - 0.30 – 0.34 W/g in Al

Expected Gains and Heat Loads for Possible LD_2 Sources

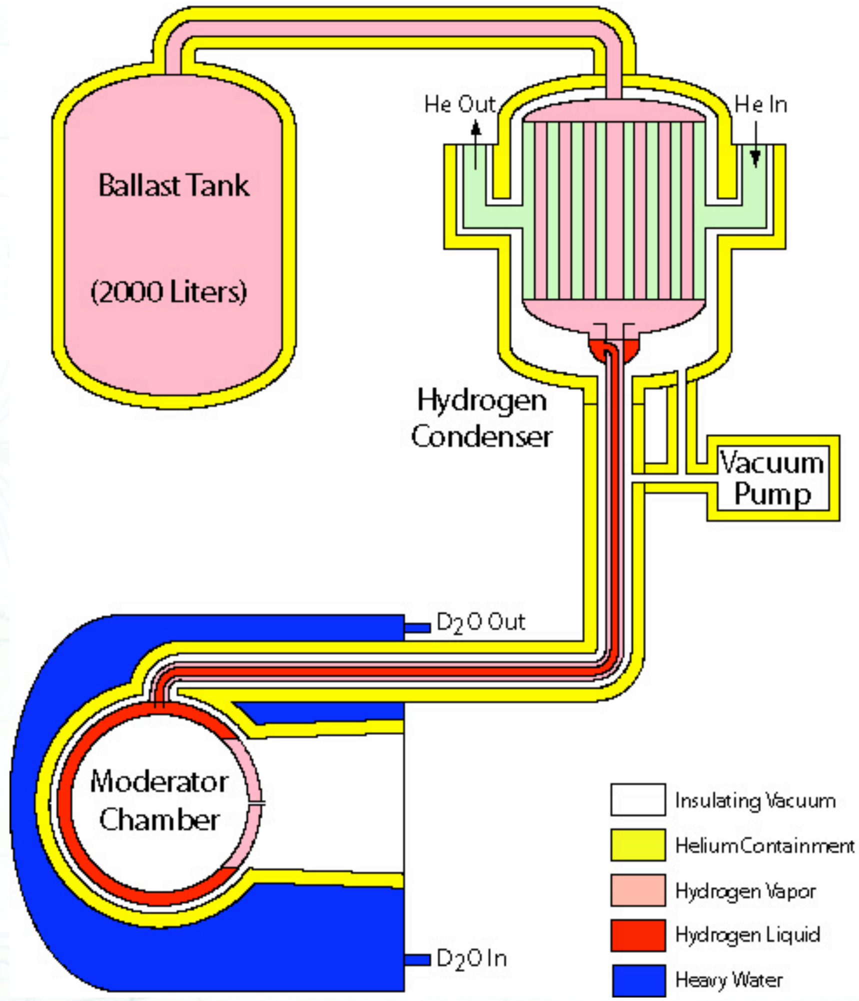
Diameter/Depth (cm)	46/28	42/24	38/22
Volume (liters)	55	41	26
Deuterium (kg)	8.1	6.1	3.9
Aluminum (kg)	4.0	2.7	2.0
Heat Load * (W)	3260	2700	2030
Gain (λ > 4 Å)	1.63	1.59	1.47
Gain (λ > 9 Å)	2.22	2.14	1.91

*** May be higher – depends on wall thickness, working pressure.**

The LD_2 source must also be passively safe, simple and reliable

- A thermosiphon is the simplest way to supply the source with LD_2.
  - Cold helium gas cools the condenser below 23 K.
  - Deuterium 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 gas handling (No vents or pressure relief).
- Low pressures: 4-5 bar warm, 1 bar operating
- All system components are surrounded by He containments.

Liquid Hydrogen Thermosiphon



(Unit 2 CNS)

Required Work:

- **Get a refrigerator!**
- Finalize performance and heat load calculations incorporating "engineering constraints", such as the minimum wall thickness, and the actual dimensions of the vacuum and He jackets.
- Build and test prototype vessels to check FEA stress analysis.
- Thermal-hydraulic tests of the thermosiphon (*may not be needed if system is like the horizontal source at ILL*).
- Install a BIG ballast tank.
- Amend the cold source SAR for a higher inventory.
- Control tritium with hydride storage or recombiner.

Conclusion

- **The cryogenic beam port of the NBSR is a perfect location for a large-volume LD_2 source.**
- ***It would allow us to do what we do best*** **: provide an intense source of long-wavelength neutrons.**
- **This is our goal, but…**
- **WE NEED A REFRIGERATOR!!**