Progress towards Operation of a Deuterium Cold Neutron Source at the NCNR

J Jurns[1], M Middleton[1] and R Williams[1]

[1]NIST Center for Neutron Research, Gaithersburg MD 20899, USA

Abstract

The NIST Center for Neutron Research (NCNR) operates a 20 MW research reactor that produces neutrons for a suite of 30 neutron scattering instruments. 70% of these instruments use cold neutrons (E<5 meV), which are moderated by two separate cold neutron sources. The cold moderator for both sources is liquid hydrogen (LH_2), which is in turn cooled by a recently commissioned 7 kW, 14K helium refrigerator.

NCNR plans to *replace the larger cold source with a new one operating with liquid deuterium (LD_2)*. This report focuses on progress towards the upgrade to liquid deuterium, and options to address the particular *challenges of designing and operating a cooling system that simultaneously supports operation with both LH_2 and LD_2*

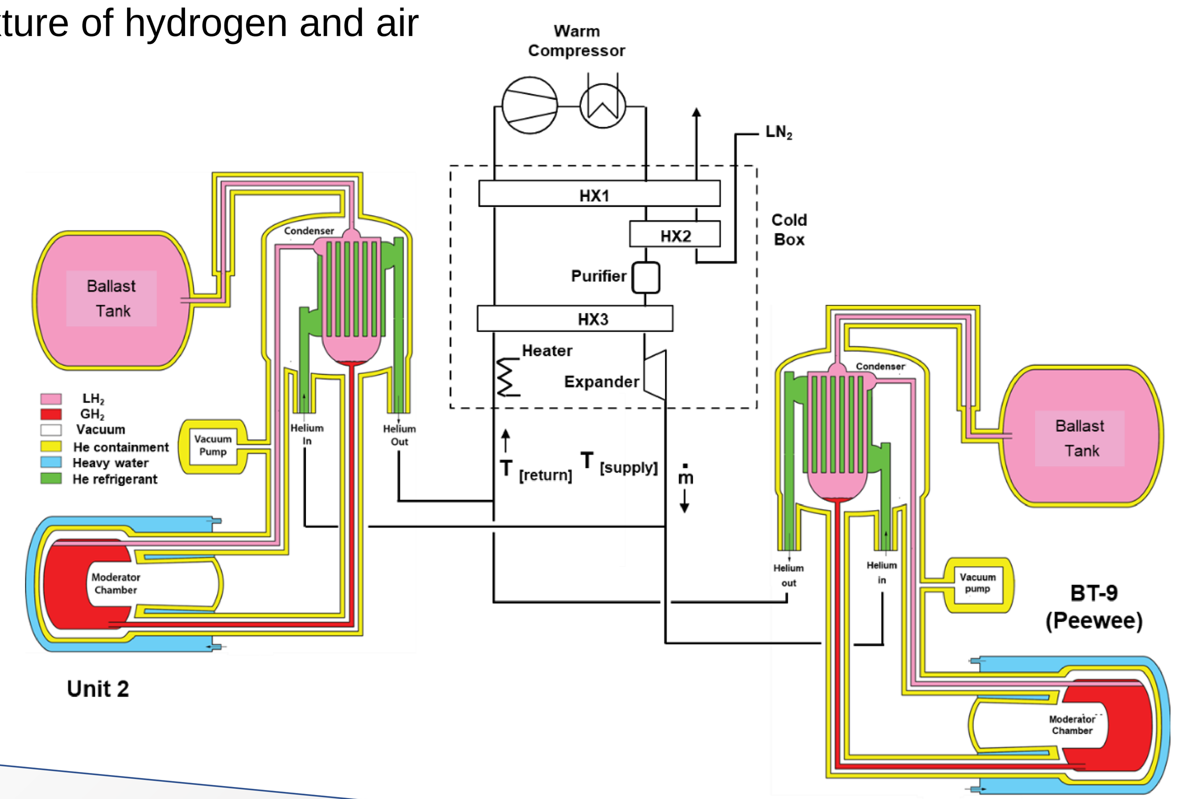
Future plans for NCNR include changing from Highly Enriched Uranium (HEU) fuel in reactor to Low Enriched Uranium (LEU) fuel. *Conversion to LD_2 will compensate for anticipated 10% loss in neutron flux*

Background

- First liquid hydrogen (LH_2) cold neutron source (CNS) installed at NBSR in 1995 (Unit 1), with a neutron flux gain of ~ 6 compared to previous heavy ice cold source
- Unit 1 LH_2 source replaced with the Advanced LH_2 Cold Source (Unit 2) in 2002, doubling the flux of cold neutrons to all the instruments
- Second LH_2 source ("Peewee") installed in thermal neutron beam port BT-9 in 2012, solely for the Multi-Axis Crystal Spectrometer (MACS II)
- Unit 2 to be replaced with new LD_2 cold source (planned 2023). LD_2 source will provides average gain in brightness of 1.5 between 4 Å and 9 Å with respect to the existing liquid hydrogen cold source, and a gain in brightness of 2 at the longest wavelengths

Current configuration

- Two LH_2 cold sources cooled with 7 kW helium refrigerator
- Hydrogen liquefied in a condenser heat exchanger located approximately 2 m above the cryostat (target) and gravity fed to the cryostat where neutrons are slowed as they pass through the LH_2
- Heat transferred to LH_2 by the neutrons vaporizes a portion, which returns to the condenser to be re-liquefied
- Circulation accomplished by a thermosiphon design that operates completely passively. Operator intervention not required for safety. Should cooling fail (refrigerator failure) hydrogen simply boils off and is safely stored in the buffer tank
- System includes the cryostat, condenser heat exchanger, interconnecting piping and a warm gas buffer tank
- The system is hermetically sealed. No pressure relief devices of any kind
- All components are surrounded by helium blanket to prevent the possibility of creating a mixture of hydrogen and air



Planned change from LH_2 to LD_2

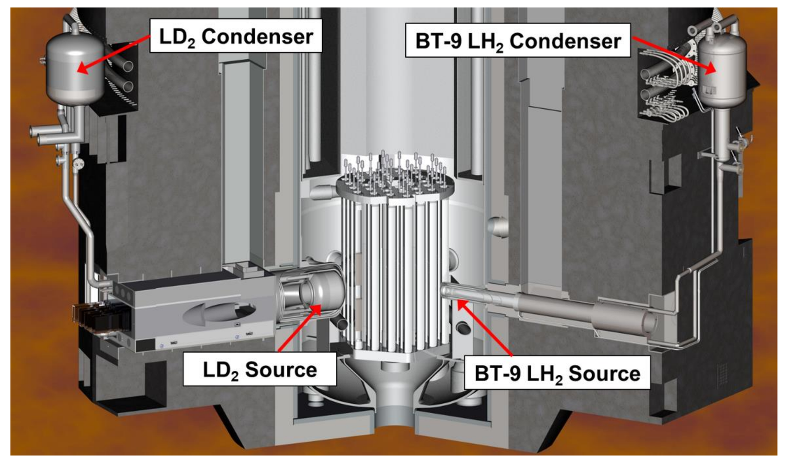
- 35 liters of LD_2 required to achieve gains anticipated by converting to LD_2
- Expected nuclear heat load in LD_2 cryostat and vessel is 4 kW
- New 7 kW helium refrigerator installed and commissioned in 2018 to provide the necessary cooling capacity

Cryoplant specifications

- Cooling capacity 7 kW at 14 K
- Nitrogen precool
- 80 K adsorber
- Air Liquide expansion turbine
- (2) Compressor skids, 600 kW Sullair 25 LA
- (3) Oil coalescers, final oil removal

7 kW He refrigerator Cold box

- Unit 2 LH_2 cold source will be removed, and the new LD_2 cold source installed in its place. Cyostat designed to same overall dimensions as Unit 2 and will fit in the existing reactor beam port
- Peewee cold source will remain and continue to operate with hydrogen
  - LD_2 not an option as neutron beam intensity would be reduced by at least a factor of two unless Peewee cryostat geometry changed. Geometry change is not possible as reactor BT-9 geometry is fixed
- LD_2 cold source will operate as a naturally circulating thermosiphon



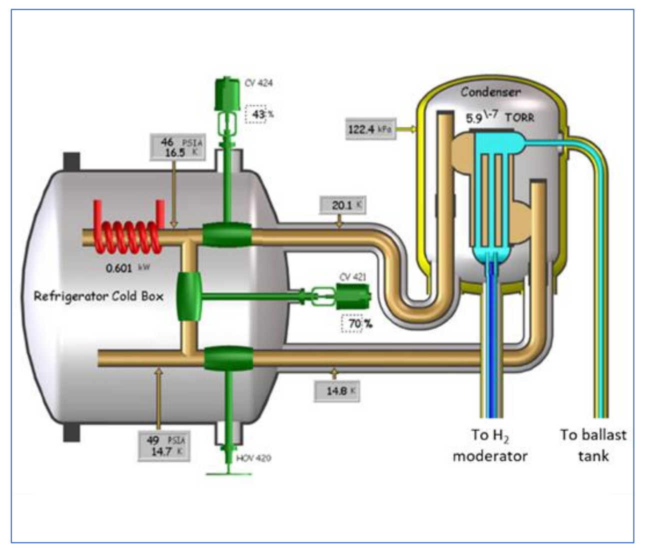
Cutaway view of LD_2 and Peewee cold sources in NBSR reactor

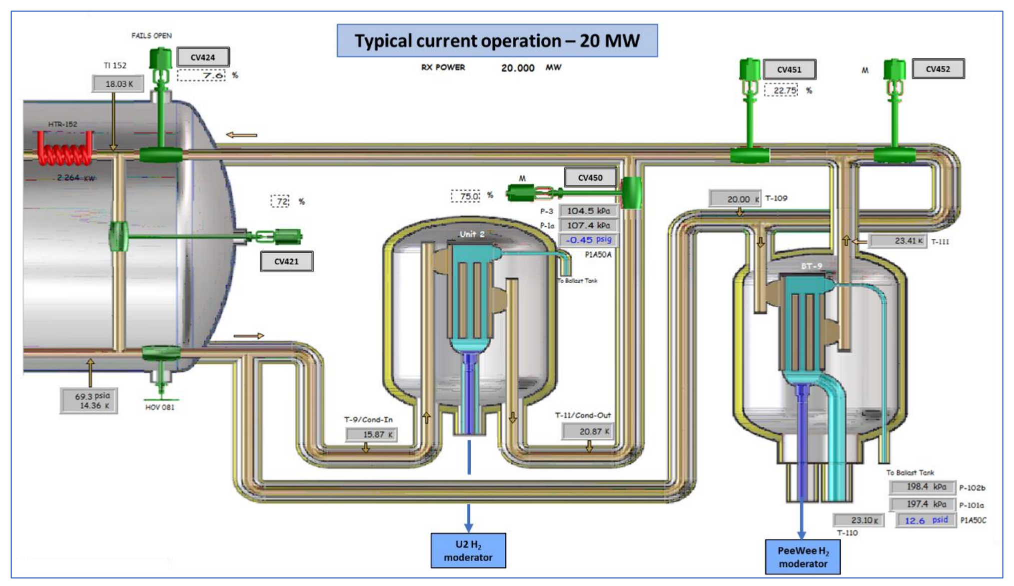
Neutronic cryogenic heat loads – current for LH_2 and planned for LD_2

	Unit 2		Peewee		LD_2	
Radiation Source	H_2	Al	H_2	Al	H_2	Al
Neutrons	104	3	33	1	440	6
Beta particles		308		29		657
Gamma rays	185	815	25	74	1053	1538
Subtotal	289	1126	58	104	1493	2111
Total cryogenic heat load (watt)	**1415**		**162**		**3604**	

Design challenges – current operation with LH_2

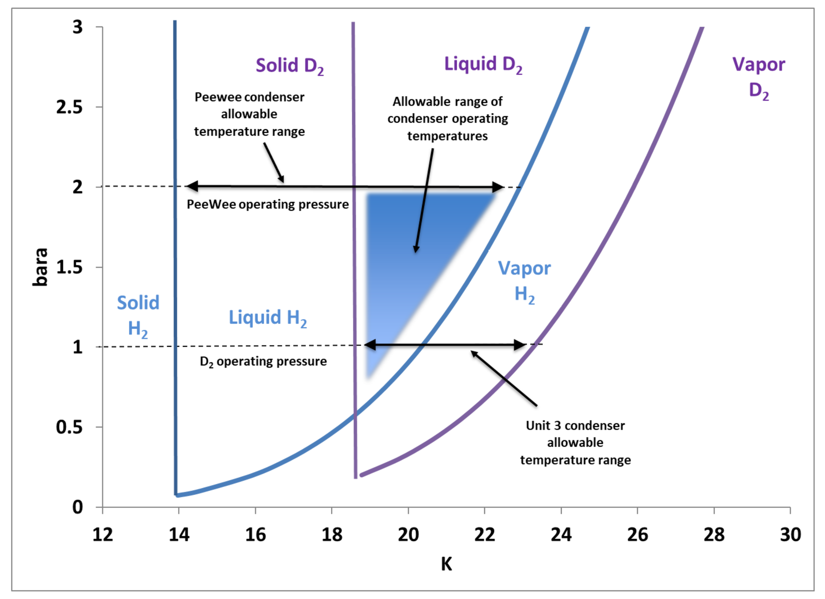
- The Unit 2 cold source hydrogen pressure initially controlled with CV424
- Helium refrigerator capacity greater than the Unit 2 heat load, a portion of cold helium bypassed through CV421
- Return temperature to the refrigerator maintained at constant 18 K, heater making up the balance of heat load to maintain a constant 2.2 kW load on the refrigerator.
- Installation and operation of Peewee caused control problems with Unit 2
- New control algorithm for control valves provides much more stable operation





Design challenges – future operation with LD_2/LH_2

- Deuterium melts and vaporizes at a higher temperature than hydrogen
- Operating the helium cryoplant at the current 14 K supply temperature risks freezing deuterium in the D_2 cold source condenser
- Peewee cold source will continue to operate with hydrogen
- *The challenge is to supply helium to the condensers at a temperature and mass flow rate that will prevent freezing of the deuterium and still provide liquefaction of the hydrogen*



Cold Source	LH_2 (Peewee)	LH_2 (Unit 2)	LD_2 (proposed)
Operating pressure (kPa)	200	100	100-200
Boiling Point (K)	23.0	20.4	23.2-25.9
Melting Point (K)	14	13.8	18.8-19.0
Density (kg/m^3)	67.5	70	164-157

Options to consider for LD_2 upgrade

NIST is evaluating options to address LD_2 and LH_2 temperature mismatch risk

- Additional cooling to Peewee condenser to assure hydrogen condensation
  - Use idle 3.5 kW helium refrigerator, or add small cryocoolers (Stirling or G-M)
- Additional heater at deuterium condenser – Operate refrigerator at a colder temperature to assure hydrogen liquefaction at Peewee condenser, add small heater upstream of the deuterium condenser to assure deuterium does not freeze
- Increase Peewee hydrogen operating pressure to increase liquefaction temperature.
  - H_2 pressure increase to 350 kPa results in operating temperature of 25.4 K
- Replace vacuum jacketed helium flex hose with hard vacuum jacketed piping to decrease heat leak
- Before making any costly hardware changes to the cold sources, tests were performed to better understand system parameters and help in deciding the best design options to pursue. Operational tests were performed with helium refrigerator supplying 17 K to 19 K helium to cold source condensers

He Flow [g/s]	Reactor power [MW]	Turbine Exhaust Pressure [bar]	Turbine Exhaust Temp [K]	Load Return Pressure [bar]	He Return Heater Temp. [K]	Heat Load [kW]	Stable Thermosiphon
200	20	4.7	14.4	4.6	18	4.0	✓
220	0	5.23	16.8	5.14	22.5	6.9	n/a
267	0	5.44	13.6	5.3	18	6.7	n/a
185	1	5.1	17.2	4.78	21.5	4.4	✓
175	20	4.76	17.5	4.63	22	4.3	✓
171	20	5.01	19.1	4.84	24.1	4.6	✓

Tests confirm ability to cool both cold sources with refrigerator operating at 19 K

Progress to date

- Operational tests at higher helium supply temperatures successfully completed
- Preliminary design for LD_2 cryostat assembly complete
- 16 m^3 ballast tank and a pair of condensers (one spare) procured and delivered
- Cold shock to 15 K completed on one of the condenser assemblies
- Contracts for the design of cryostat assembly and prototype vessel awarded 2018
- Expected installation of the LD_2 source initiated in 2023

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