An Advanced Liquid Hydrogen Cold Source For the NIST Research Reactor

Robert E. Williams, Paul Kopetka, and J. Michael Rowe
NIST Center for Neutron Research

Prepared for the Seventh Meeting of the
International Group on Research Reactors, IGORR-7
San Carlos de Bariloche, Patagonia, Argentina
October 26-29, 1999

ABSTRACT

A second-generation liquid hydrogen cold neutron source is currently being fabricated and will be installed in the NIST reactor early next year. The existing source has operated very successfully over the last four years, providing a six-fold increase in the cold neutron yield compared to the previous heavy ice source. The design of the new source is based on our operating experience with the existing LH_2 source and extensive neutron transport calculations using improved MCNP modeling and computational capabilities. Enhanced mechanical design and manufacturing tools are exploited in the fabrication of the advanced source, which is expected to nearly double the yield of the existing LH_2 source.

Presented by
Dr. Robert E. Williams
National Institute of Standards and Technology
100 Bureau Drive
Gaithersburg, MD 20899, USA

Phone: 301-975-6876
Fax: 301-921-9847
E-mail: robert.williams@nist.gov

INTRODUCTION

At the time of this IGORR-7 meeting, the NIST liquid hydrogen cold source will have completed over four years of service. It was installed with three goals: at least double the cold neutron intensity with respect to its predecessor (D_2O ice); operate simply and reliably; and pose no safety threat to the reactor or personnel. It has successfully met or exceeded all these goals[1]. The cold neutron flux increased by a factor of 4 to 6, for wavelengths in the range of 0.2 to 2 nm. A relatively small staff of 2 to 4 engineers and technicians, not necessarily full time, have kept the source in service nearly 99% of the time that the reactor was available (the reactor is shutdown if the source is inoperable). And there have been no hydrogen leaks, nor have any of the insulating vacuums or helium containments been compromised.

Even as the cold source was being installed in 1995, however, improvements in the MCNP[2] model of the NIST reactor were pointing toward a new, but more complicated cryostat assembly, with a possible additional gain of a factor of two. Better coupling between the reactor fuel and the cold source can be achieved by expanding the D_2O cooling jacket into the volume now occupied by the insulating vacuum. The D_2O also serves as an extension of the reactor reflector. This paper describes the evolution of the advanced LH_2 cold source, currently under construction, that will be installed during the next lengthy shutdown, now scheduled for March 2000.

EXPERIENCE WITH EXISTING SOURCE

A description of the LH_2 source was been presented at a previous IGORR[3] meeting, but a brief review is necessary because most of the operational features of the advanced source will be unchanged. The 3.5-kW refrigerator, its instrumentation and PLC controls, the hydrogen condenser and expansion tank, and the insulating vacuum system will be unaffected by the installation of the advanced source. Only the cryostat assembly, located in the cryogenic beam port, will be replaced.

The existing moderator chamber is a 20-mm thick spherical annulus of LH_2, 320 mm in diameter, as shown in Figure 1. The annulus is the 5-liter volume between two concentric spheres of Al-6061. A 200-mm diameter 'bubble' on one side of the inner sphere affords an exit hole for the cold neutrons streaming toward eight neutron guides. The inner sphere is filled with hydrogen vapor because it is open to the annulus only through a small tube at the bottom. Liquid hydrogen from the condenser flows by gravity into the chamber, and mixture of liquid and the vapor produced by the 800-850 W heat load returns to the condenser via a concentric tube. This two-phase return flow results in a very stable thermosiphon, driven by natural circulation with a saturation temperature of 20.4 K at the chosen operating pressure of 105 kPa. Thermal hydraulic tests conducted on a full-scale, glass mockup of the chamber at NIST-Boulder[4] demonstrated convincingly that this thermosiphon could remove a steady heat load of 2200 W without boiling instabilities. Those tests also confirmed that the void fraction in the liquid hydrogen would be between 15% and 10% for operating pressures between 85 kPa and 150 kPa.

In September 1995, the existing cold source, Unit 1, was placed into service. It will have operated successfully for 27 reactor cycles by the time of this IGORR-7 meeting. In general, Unit 1 has operated as expected, based on the MCNP calculations used to predict its performance. Although the calculations overestimated the heat load[5] by about 15 to 20%, the calculated energy spectrum, the cold neutron gain, and the brightness agree within the uncertainty of the measurements[1]. The calculations confirmed another observation made in the early weeks of operation. A reduction in operating pressure from 150 kPa to 105 kPa increases the flux of cold neutrons in the guides by about 5% at the longest wavelengths, even though the density of the boiling liquid hydrogen decreases. The presence of hydrogen vapor degrades the source performance because cold neutrons are scattered out of the beam

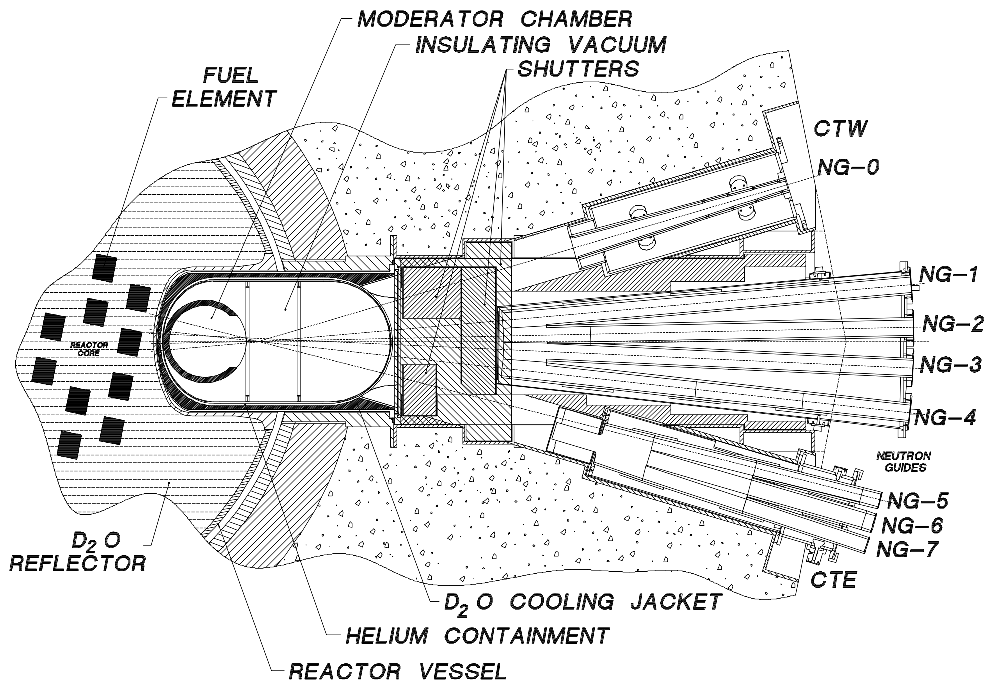

Figure 1. Plan view of the existing liquid hydrogen cold source, installed in 1994. Note that the D_2O cooling jacket is only a few cm thick, and the insulating vacuum is very large, about 120 liters. (The shutters are closed only for maintenance activities.)

as they travel through the 300-mm of vapor in the inner sphere. In one respect, the source has not behaved as we expected; we have never observed a degradation in cold neutron yield due to conversion of the LH_2 from normal hydrogen (75% ortho) to 100% para hydrogen[1]. A catalyst and pump were installed between the ballast tank and condenser to constantly replenish ortho-H_2, which has a much higher cross section than para-H_2 for producing cold neutrons. Operation of the pump, however, made absolutely no measurable difference in the source performance, leading us to conclude that the ortho fraction in the LH_2 remains above 50%, and completely dominates the scattering.

THE ADVANCED COLD SOURCE

Neutron Performance and Nuclear Heat Load Calculations

In the early stages of the design of Unit 1, the cryostat region was modeled for MCNP calculations intended to identify an optimum LH_2 vessel for a given fixed source distribution of reactor neutrons. A source subroutine was generated based on two-group diffusion calculations in the original NBSR safety analysis report, and the same source of neutrons was used to compare various cold moderator configurations. The first MCNP model of the NBSR core was developed in 1993 to calculate the normalized nuclear heat load, and verify the neutron performance estimates. The installation of Unit 1 was nearly complete by the time a sufficiently sophisticated MCNP model of the core was available to study the effect of variations in the cold source geometry on the reactor. It was obvious then, that the addition of more D_2O to the cryostat assembly would improve the coupling between the cold source and the reactor fuel. It was also obvious that a lengthy series of calculations was needed to study and optimize the coupling, that Unit 2 would be more complex and difficult to build, and that it would have to wait a few years.

After the successful operation of Unit 1, the above lessons learned were guiding factors in the calculations that followed. An ideal limiting case, although totally impractical, is a source like Unit 1, with no vapor in the center, nearly surrounded with D_2O, and a very small exit hole, which could provide one small beam with a brightness of 3.4 times that of Unit 1. Since the cold neutron beam ports through the biological shield of the NIST reactor span a range of 17^o on either side of the axis of the center cryogenic port, we needed to balance the conflicting goals of surrounding the source with D_2O and fully illuminating the existing guides. MCNP is ideally suited for this task, but the process required many, lengthy criticality calculations because the addition or subtraction of a few well-positioned liters of D_2O changed k_{eff}, the thermal neutron flux in the region, and even the fuel utilization. These criticality calculations were used to generate MCNP surface sources surrounding the cryostat region for each proposed modification of the D_2O reflector. Minor changes in the moderator chamber that do not affect the reactor, such as the thickness of the LH_2, the presence or absence of vapor, the ortho-para content, etc. were analyzed using these surface sources in much quicker calculations. Separate surface sources with neutrons and gamma rays were also generated to calculate heat loads; these required less statistics than neutron performance calculations.

Engineering constraints must also be considered in the MCNP calculations. The moderator chamber is surrounded by a vacuum vessel, which is surrounded by a helium containment vessel, strong enough to withstand the design basis accidental detonation of liquid hydrogen and solid oxygen. The helium vessel determines the extent of the D_2O volume. Thus, the conceptual design had to be modified as the mechanical design was finalized.

Table 1 is a summary of the results of a series of calculations indicative of the process used to optimize the geometry. The gains listed are the ratios of the cold neutron brightness for each case with respect to the existing source. The modifications represent the “evolution” from Unit 1 to a new geometry similar to Unit 2. As shown in the table, the addition of D_2O surrounding the Unit 1 moderator chamber will increase the brightness by 40%. This is about half of the total gain expected in Unit 2. Further gains of 10-15% each, are due to elimination of the hydrogen vapor, increasing the LH_2 thickness, and reducing the void fraction (Unit 2 will operate at a higher pressure, 1.5 to 1.7 atm). Case 4 does not represent the final geometry of Unit 2, which will be an ellipsoidal shell in which a 20-mm thick layer of vapor in the exit hole is unavoidable. The expected brightness for the advanced source being fabricated is plotted in Figure 2; the cold neutron gain will be a factor of 1.8 over Unit 1. The uncertainties in these MCNP results are all close to 5% standard deviation.

Table 1. Analysis of Cold Neutron Gains

	Modification	Gain over Unit 1
Case 1	Unit 1 chamber with Additional D_2O	1.40
Case 2	Case 1 without vapor	1.50
Case 3	Case 2 with LH_2 thickness Increased to 25 mm	1.65
Case 4	Case 3 at 90% density	1.80

A separate calculation was required to determine the nuclear heat load in the chamber when the reactor is operating at 20 MW. Energy is deposited by prompt neutrons and gamma rays from fission and neutron capture events, and by delayed gamma rays and beta particles from radioisotopes (mainly ^{28}Al and the fission products). MCNP calculated the prompt energy deposition directly. The code can also be used to estimate the delayed radiation using modified cross sections for ^{235}U and Al containing delayed gamma rays, and by calculating beta decay rate (which is the same as the rate of production of ^{28}Al)[5]. For the new moderator chamber described below, the calculated heat load is 1500 W. From our previous attempts at a benchmark for Unit 1, however, we believe that the MCNP result overestimates the heating by 15-20%, and we expect that 1200 to 1300 W will be deposited in Unit 2. In either case, based on our tests at Boulder, the increased heat load over Unit 1 can be easily removed by exploiting our excess refrigerator capacity.

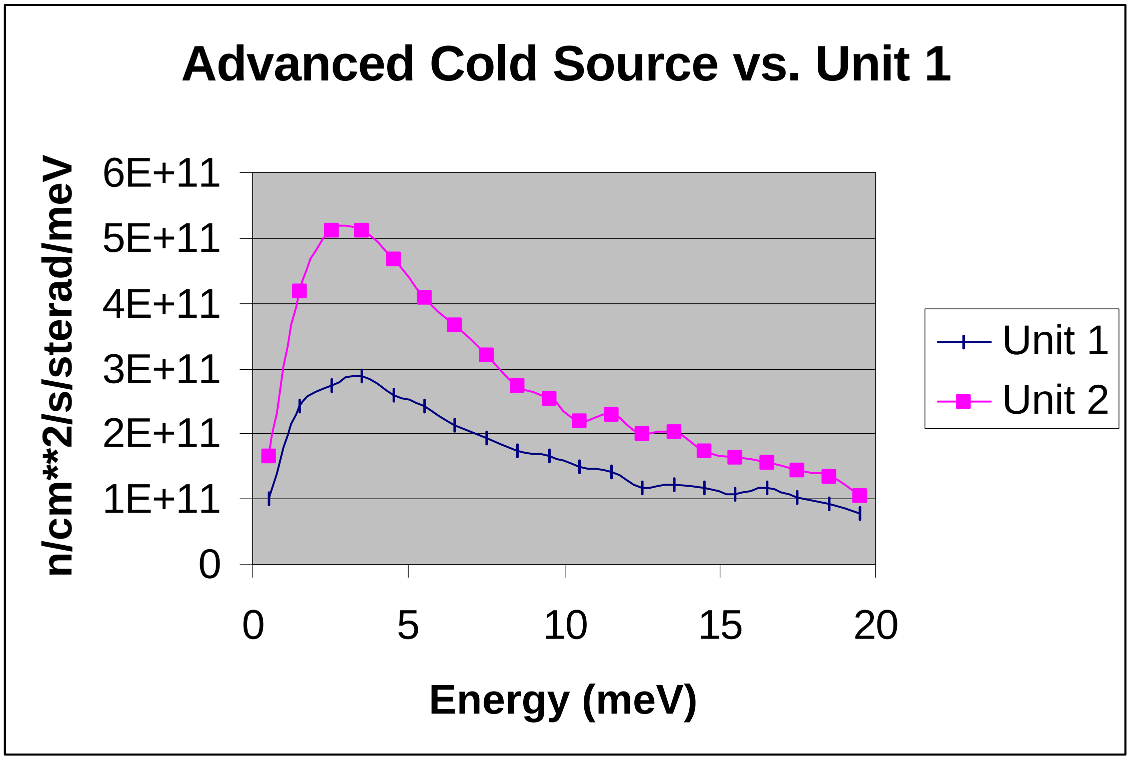

Figure 2. Brightness as a function of energy for Unit 2 compared to Unit 1. The integrated gain for cold neutrons (0 to 5 meV, or wavelengths greater than 0.4 nm) will be 1.8.

Description

Unit 2 will differ from Unit 1 in many key respects. The most import change is that the volume of the insulating vacuum will be reduced by half, adding about 60 liters of D_2O that will partially surround the moderator chamber (see Figure 3). The moderator chamber itself will no longer be spherical. Unit 2 is an ellipsoidal annulus with outside major axes of 320 mm along the beam axis and vertically, and a 240-mm minor axis in the horizontal direction. The center of the inner ellipsoid is moved 5 mm behind that of the outer ellipsoid, so that the annulus between them is 30 mm thick near the core, and 20 mm thick at the exit hole. The inner ellipsoid will be evacuated through a small vacuum port, 5-mm in diameter, through the exit hole into the insulating vacuum region. Unfortunately, hydrogen vapor will fill the exit hole, but in Unit 2, the cold neutron beam will pass through only 20 mm of vapor, rather than 300 mm. Our effort to design a completely evacuated exit hole had to be abandoned because the support ring sealing the annulus from the vacuum was too massive. Completing the ellipsoidal shells, except for the very small vacuum port, provides the necessary strength to the chamber. A thin ring between the shells defines the exit hole, which is 200 mm high and 150 mm wide. It will be vapor-filled because it is open to the LH_2 through only a small tube hole at the bottom. The mass of the Al moderator chamber will be about 2800 grams, and it should contain about 310 grams of LH_2 during operation.

An ellipsoidal annulus provides three advantages. Because it has a smaller volume, more D_2O can be introduced in the cryostat assembly. It is also possible to increase the LH_2 thickness but keep the same 5-liter volume as Unit 1. Its mass (and heat load) is also less than that of a comparable 320-mm spherical annulus. An elliptical shape is possible because the neutron guides at NIST are all rectangular, most 60-mm wide and 150-mm tall. A disadvantage is that the ellipsoidal annulus and the surrounding vacuum and helium vessels are more difficult to fabricate. Finite element analysis (FEA) was used in the design of all the vessels to ensure their mechanical strength at the desired working pressures.

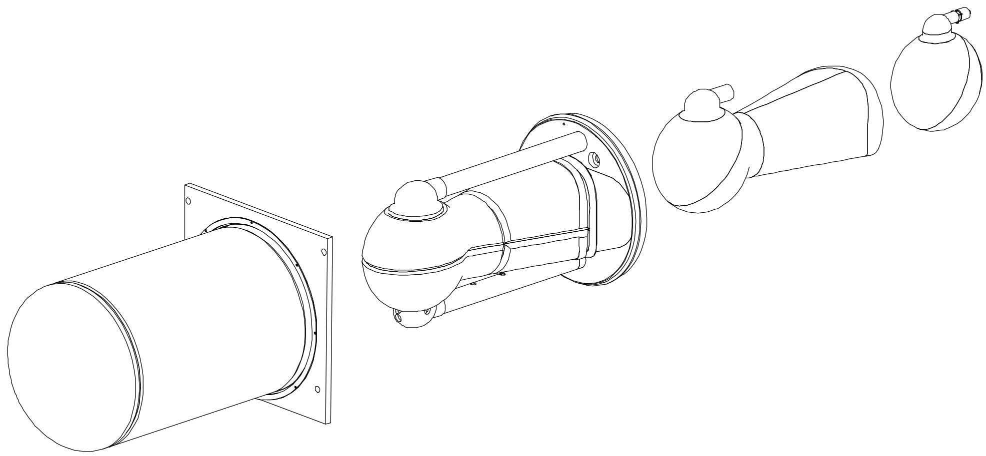

Figure 3. An expanded view of the advanced cold source, showing, from right to left, the moderator chamber, the vacuum jacket, the He containment vessel, and the D_2O jacket. The D_2O volume outside of the He vessel is much larger than that of Unit 1, providing better neutronic coupling to the reactor fuel.

Surrounding the moderator chamber are aluminum vessels for the insulating vacuum, helium containment, and the D_2O cooling water. The vacuum jacket is an “hour-glass” shaped vessel providing a layer of thermal insulation for the moderator chamber and the LH_2 supply line. It is approximately 2 mm thick, and designed to have an external working pressure of 300 MPa (45 psid). The helium containment layer is quite thin, just a few millimeters, and is filled with sheets of extruded aluminum to augment the heat transfer between the vacuum jacket and the helium jacket, which is directly cooled by the D_2O system. The helium jacket has the same shape as the vacuum jacket, but it is much thicker, nearly 20 mm in places. This He jacket must withstand the highest possible internal pressure arising from the design basis detonation of solid oxygen and liquid hydrogen, 7.6 MPa (1100 psia), based on the measurements of Ward et al[6]. It also features two horizontal support cylinders; one tube is needed for the LH_2, vacuum, and helium lines, while the bottom tube is for symmetrical structural support. The D_2O jacket is the outermost shell of the cryostat assembly. It is cylindrical, with an ellipsoidal cap, closely following the contours of the cryogenic beam port thimble.

<u>Status</u>

Due to its complex geometry, components of the new cryostat assembly are being fabricated from blocks of solid aluminum, using a precision, high-speed mill in the NIST Instrument Shop. These components are being welded (TIG) together to form the moderator chamber, vacuum and helium jackets, etc. by NCNR personnel. As was the case with Unit 1, the cryostat assembly will feature all-welded construction. All welds will be certified by radiography. The hydrogen, vacuum, and helium vessels will be checked for leaks using a helium mass spectroscopy leak detector; all components must have leak rates below 10^{-8} STD cc/sec. Hydrostatic pressure tests to failure will be performed on a moderator chamber and He containment vessel to verify the rupture strengths predicted by the FEA. The replacement cryostat assembly must pass all these tests before the existing cold source will be removed.

Early in 2000, the reactor will have to be shutdown for shim arm replacement. Our goal is to replace the cold source at the same time. This shutdown should require 3 months.

CONCLUSION

The advanced liquid hydrogen cold neutron source will incorporate several design changes in the existing source to nearly double the cold neutron flux. The gain is largely due to enhanced neutronic coupling between the source and the reactor fuel. It is expected to be operational by the middle of next year.

REFERENCES

1. Robert E. Williams, J. Michael Rowe, and Paul Kopetka, "The Liquid Hydrogen Moderator at the NIST Research Reactor," Proceedings of the International Workshop on Cold Moderators for Pulsed Neutron Sources, Argonne National Laboratory, Sept. 29 – Oct. 2, 1997, J. M. Carpenter and E. B. Iverson, editors, pp. 79-86.

2. Briesmeister, Judith F., editor, "MCNP – A General Monte Carlo N-Particle Transport Code," Version 4B, Los Alamos National Laboratory, LA-12625-M, Los Alamos, New Mexico (March 1997).

3. J. Michael Rowe, Paul Kopetka, and Robert E. Williams, "Performance of the Liquid Hydrogen Cold Source," Proceedings of the Fifth Meeting of the International Group on Research Reactors, IGORR-5, November 4-6, 1996, Aix-en Provence, France.

4. Siegwarth, J. D., et al, "Thermal Hydraulic Tests of a Liquid Hydrogen Cold Source," NIST Internal Report, NIST-IR 5026, (July 1994).

5. Williams, Robert E., Rowe, J. Michael, and Blau, Mordechai, "Benchmark of the Nuclear Heat Deposition in the NIST Liquid Hydrogen Cold Neutron Source," Proceedings of the 9th International Symposium on Reactor Dosimetry, Hamid Ait Abderrahim, Pierre D'hondt, and Bohumel Osmera, editors, Sept. 2-6, 1996, Prague.

6. Ward, D. L., Pearce, D. G., and Merrett, D. J., "Liquid-Hydrogen Explosions in Closed Vessels," Adv. Cry. Eng. 9, 390 (1964).