Spallation Neutron Source Upgrade Status and Operational Success of the Cryogenic Moderator System

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Abstract. The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) utilizes the Cryogenic Moderator System (CMS) to provide supercritical hydrogen cooling at 20 K to three neutron moderators. As part of the Proton Power Upgrade (PPU) project, two significant enhancements were made to the CMS: the integration of ortho-hydrogen into para-hydrogen catalyst beds and an expansion of hydrogen supply capacity through a new Hydrogen Refill System (HRS). This paper will detail the design, installation, and commissioning of these subsystems. PPU increased SNS beam power on the First Target Station (FTS) from 1.4 MW to 1.7 MW. Implementation of new controls for the CMS helium cryogenic cold box for this higher beam power will be discussed. Future work to ensure successful operation at a 2.0 MW beam power will also be outlined.

1. Introduction

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) is a major scientific facility dedicated to neutron scattering research [1]. It accomplishes this mission by generating a neutron beam via the spallation process, wherein high-energy protons are accelerated and directed onto a liquid mercury target. SNS commenced operations with proton beam collision in 2007; however, it did not achieve its design specifications of 1.4 MW beam power at an energy of 1.0 GeV until 2018. In 2024, the Proton Power Upgrade (PPU) project [2] was completed, enhancing the SNS accelerator to provide 2.8 MW of beam power at 1.3 GeV. This upgraded capability is currently being utilized by neutron science stations at the First Target Station (FTS), operating at a beam power of 1.8 MW. Furthermore, the PPU project ensures sufficient beam power to facilitate advanced neutron science investigations at the Second Target Station (STS) [3].

The Cryogenic Moderator System (CMS) is integral to the optimization of SNS, facilitating the generation of high-quality neutrons for various scientific applications [4]. The CMS consists of a helium refrigerator designed to deliver 250 g/s of 20-K helium to three parallel-flow helium/hydrogen heat exchangers. The helium refrigerator has a specified design capacity of approximately 8000 W, determined by measuring the power supplied to the helium return heater. Prior to the completion of PPU, maintaining stable and reliable operation of this helium refrigerator presented significant challenges [5].

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The Cryogenic Moderator System (CMS) delivers forced-flow supercritical hydrogen to three independent hydrogen loops, with each loop specifically designed to provide cooling to a dedicated neutron moderator. An invar cryogenic hydrogen transfer line serves as the connection between the equipment located in the Hydrogen Utility Room (HUR) and the moderators situated within the Inner Reflector Plug (IRP) near the FTS liquid mercury target. Each hydrogen loop consists of key components, including a helium/hydrogen heat exchanger, circulator pump, accumulator bellows, and neutron moderator. The PPU project introduced an ortho-hydrogen to para-hydrogen converter to each hydrogen loop. Figure 1 depicts the arrangement of the CMS equipment for both the helium and hydrogen systems.

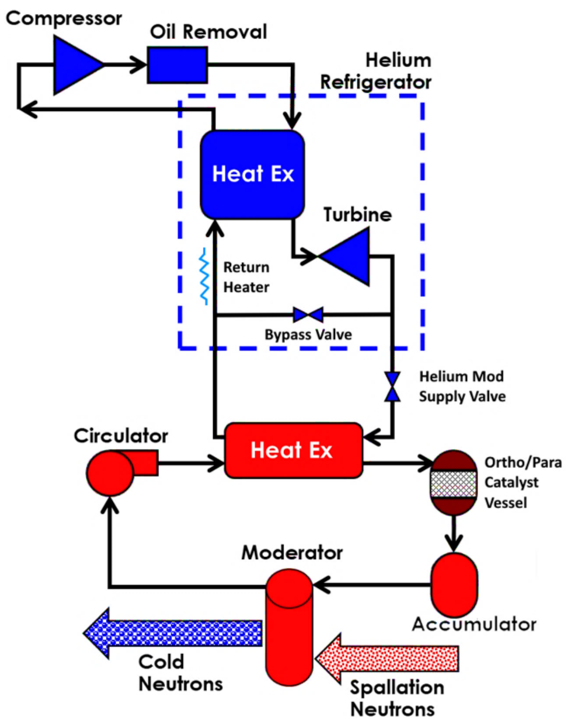

Figure 1. CMS Cryogenic Helium and Hydrogen Cycle and Major Equipment After PPU

2. PPU Ortho-hydrogen/Para-hydrogen Catalyst

The performance of SNS instruments relies on the low scattering angle of para-hydrogen [6]. Para-hydrogen is a molecular form of hydrogen, consisting of two hydrogen atoms (H_2) that have their nuclear spins aligned in a specific way. In para-hydrogen, both hydrogen nuclei (protons) have their spins anti-aligned (opposite directions), resulting in a total nuclear spin of zero. This configuration contrasts with ortho-hydrogen, where the spins are aligned (both protons have the same direction), giving a total nuclear spin of one.

Each of the three CMS moderator loops has been installed with an Ionex catalyst media [7] to assist in the natural process of converting ortho-hydrogen to para-hydrogen at cryogenic temperatures. This media is contained within layers of perforated metal sheets and dense fibrous filters. The conversion of ortho-hydrogen to para-hydrogen using ion exchange media involves a process known as "hydrogen desorption." When ortho-hydrogen is passed over or through the ion-exchange media, the ortho- and para-hydrogen molecules interact with the catalyst and each other, allowing for spin flipping and establishing a new equilibrium that favors para-hydrogen.

The design of PPU ortho-/para-hydrogen converter allows for Raman spectroscopy [8] to be performed directly on the cryogenic hydrogen fluid to precisely determine the para-hydrogen fraction of the fluid. Raman spectroscopy is a spectroscopic technique used to observe vibrational, rotational, and other low-frequency modes in a system. It is based on the inelastic scattering of monochromatic light, usually from a laser. When light interacts with molecular vibrations, most of it is elastically scattered (Rayleigh scattering), but a small portion of the scattered light is inelastically scattered, leading to a shift in energy corresponding to the vibrational energy levels of the molecules. This inelastic scattering is known as Raman scattering.

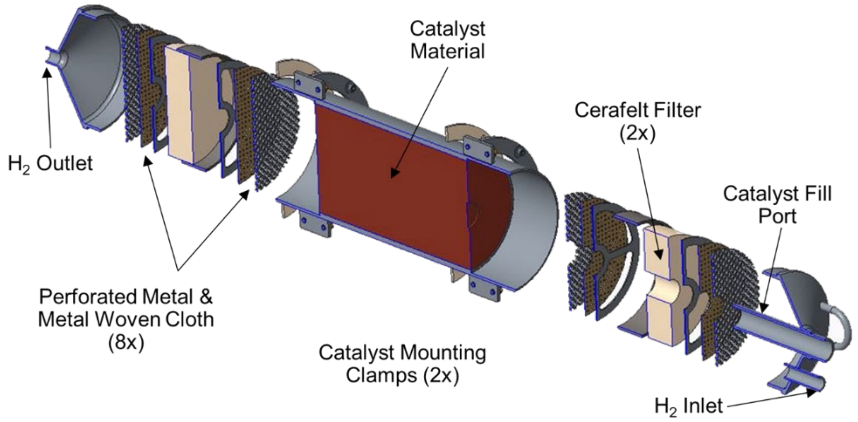

Figure 2. Exploded View of Ortho/Para Catalyst Vessel

Figure 2 demonstrates how the Ionex catalyst media is contained within the housing. Several layers of metal screens surround filter elements which hold the media fixed with respect to the hydrogen flow. Any migration of catalyst media into hydrogen fluid could potentially carry radiation from near the target into the utility room, where it is not desired. The screen/mess assembly has been classified as a Credited Engineering Control (CEC) element which is essential to the safe operation of the facility. The arrangement of the hardware within a dedicated vacuum vessel is shown in Figure 3.

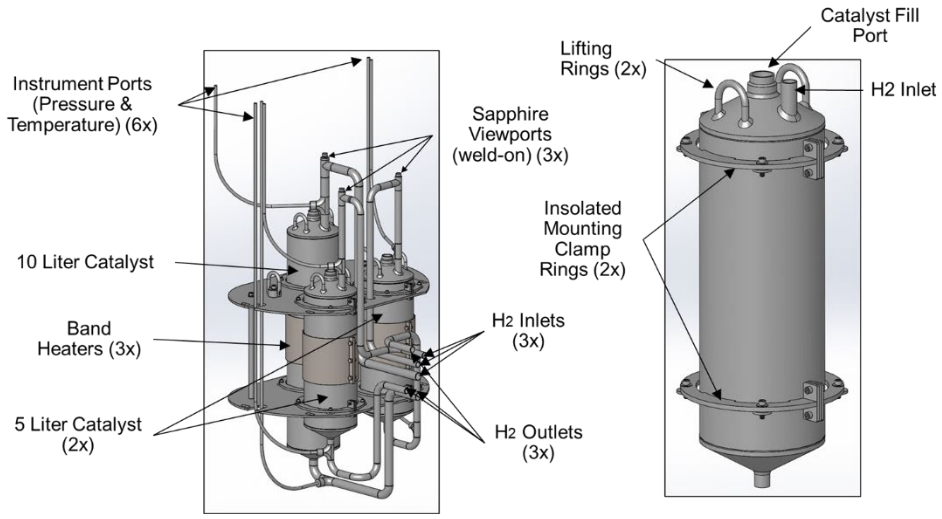

Figure 3. CMS Ortho/Para Catalyst Bed Assemblies with Piping

The alignment of the two optical windows is critical for obtaining accurate Raman readings of cold hydrogen. Sapphire windows were selected for both their optimal optical transmission of the laser and their mechanical integrity at cryogenic temperatures. The design process focused on minimizing the distance between the two sapphire windows, positioning the cryogenic window in close proximity to the vacuum vessel head. This arrangement resulted in damage to two of the windows during transportation

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and installation in the HUR room of the FTS building, located on the fourth floor. The damage was identified during the removal of shipping restraints inside the vacuum vessel, necessitating the replacement of both compromised windows. Figure 4 illustrates the configuration of both the warm and cold windows within the vacuum vessel.

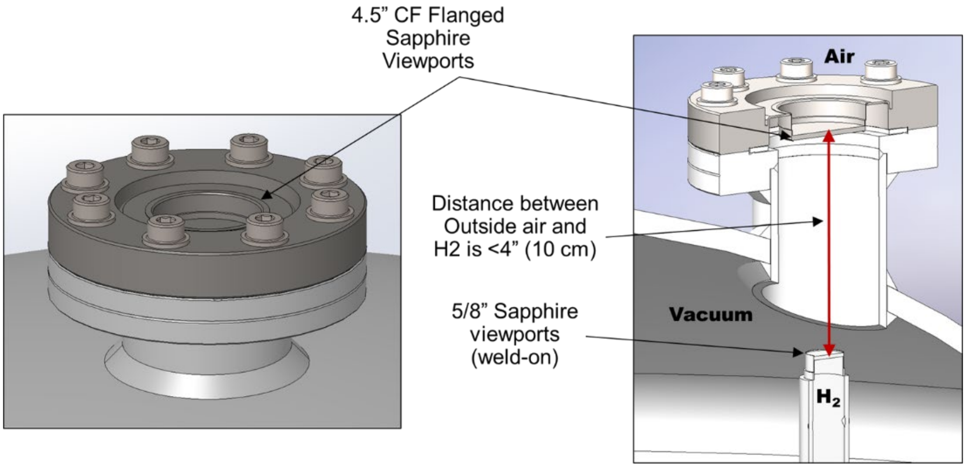

Figure 4. Alignment and Relative Distances of Sapphire Windows

Figure 5 shows the vertical arrangement of the cold, inner windows with the vacuum head of the vessel removed. Due to the heaters on the catalyst media vessels, no MLI was included in the cryogenic ortho/para cryogenic piping around the catalyst vessels. Instead, the inner surface of the vacuum vessel was electroplated to reduce surface emissivity.

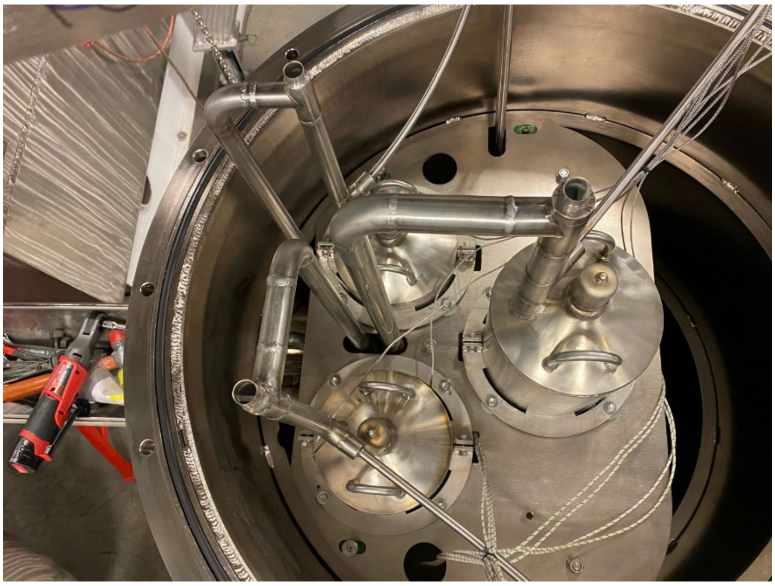

Figure 5. Installation Details During Removal of Shipping Restraints

Once the vacuum vessel and connection piping were integrated into the CMS hydrogen system, the final step prior to cooldown was removal of any residual moisture from the Ionex media. Aside from being a contaminant at cryogenic temperatures, the presence of moisture within the media would significantly degrade the performance of the media in producing the desired para-hydrogen conversion. The three catalysts vessels were dried in parallel using both the installed band-heaters on the outside of the media housing and heated nitrogen gas flow. The vessels were heated to around 250 F and the dew point on the exhaust nitrogen was monitored. Once no change was measured on the hygrometer for several days, the media was deemed clean and the system was made ready for cryogenic operations.

Figure 6. New CMS Oil Processor (a) and Existing CHL Oil Processor (b)

Data was taken during both the first cooldown of the CMS and the first beam on target operation after completion of the PPU project. The Raman-based ortho-hydrogen diagnostic performance exceeded expectations, demonstrating sensitivity to changes in ortho-hydrogen levels of less than 0.02%. This accuracy enabling real-time confirmation of the effectiveness of the ortho-hydrogen to para-hydrogen converter system and integration into neutron scattering measurement data acquisition systems as an optional veto parameter to ensure stable and reliable data collection. Figure 7 shows the results of the Raman data during the first month of SNS neutron production after completion of the PPU project.

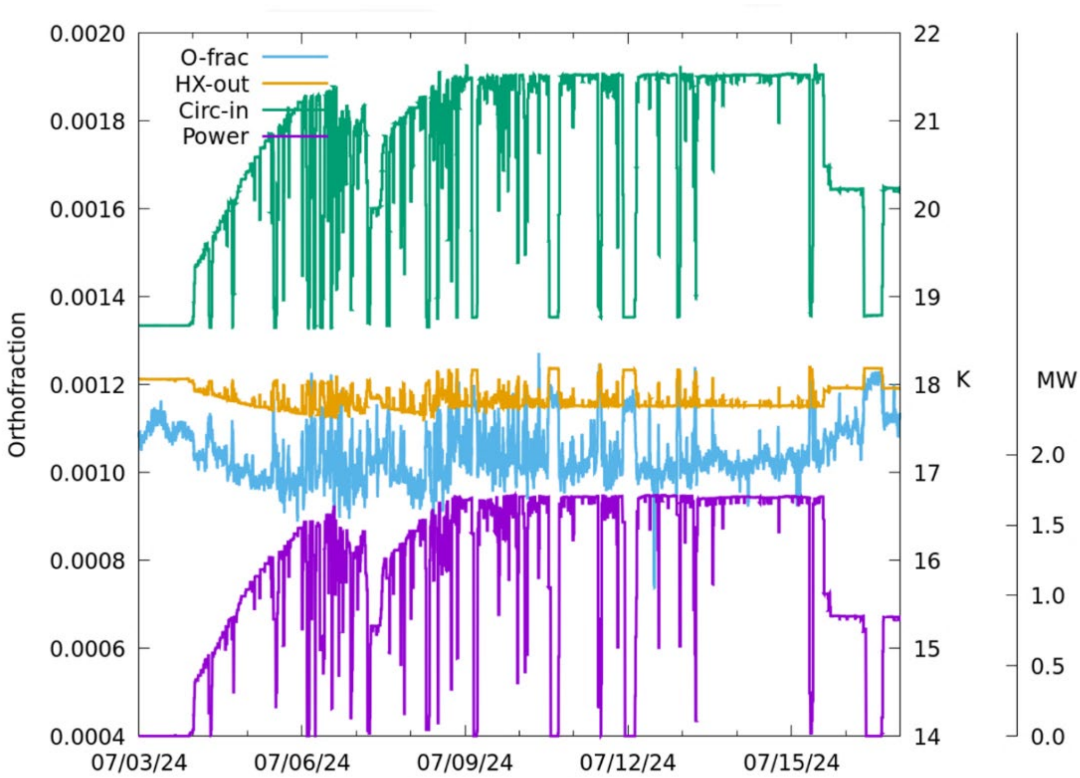

Figure 7. New CMS Oil Processor (a) and Existing CHL Oil Processor (b)

3. New Hydrogen Refill Gas Supply

Addition of ortho-hydrogen to para-hydrogen catalyst vessels into the CMS moderator hydrogen loops increased the internal volume in the hydrogen piping by 34.86 L. This increased volume exceeded the capacity of the original CMS Hydrogen Refill System (HRS) to supply enough hydrogen for operation at 185 psig. PPU project recognized this need and included scope for a new HRS for the CMS. New HRS is modelled after the CMS for ORNL High Flux Isotope Reactor (HFIR) and uses 12-packs of hydrogen cylinders instead of the original SNS CMS design which relied on single hydrogen cylinders located in a safety cabinet inside the CMS compressor building.

The new HRS has receiving bays for four 12-packs of hydrogen cylinders, two of which are necessary each time the CMS is charged and cooled to 20-K. Each 12-pack assembly contains a common header that has tubing connected to individual cylinders. This common header runs down the long axis of the assembly and terminates into both a quick disconnect fitting and a valve for vendor filling on each end. Each assembly also has a local pressure gauge on the common header.

Both the hydrogen storage and valve panel are located outside to minimize the flammability hazard that hydrogen poses. Whenever possible, welded connections are preferred to any pipe fittings. However, some elements of the design (e.g. relief valves), necessitate connection. A helium leak check was performed on all the hydrogen piping prior to commissioning the system with hydrogen. Figure 8 shows both the new dual 12-pack receiving station and the new gas panel for valving and instrumentation.

Figure 8. Hydrogen Refill System (a) Gas Supply Stations (b) Instrumentation & Control Panel

The new HRS flow panel provides several features: pressure monitoring of all hydrogen 12-packs, pressure monitoring of supply piping into CMS, control valve to modulate hydrogen supply pressure before reaching the moderator circuits, particulate filtering of hydrogen prior to injection, and hydrogen flow measurements for "not-to-exceed" safety monitoring. As additional safety against hydrogen ignition, all electronics for pressure, flow and valve actuation are NEC Class 1 Div II Group B compliant (hydrogen safe) and located at the bottom of the panel with a partial flow obstruction screen so that if any hydrogen does leak during operation, the electrical elements are the farthest distance away form any such leak.

4. CMS Performance During SNS FTS Beam Operation

PPU power ramp past the previous operating limit of 1.40 MW posed interesting challenges for the CMS. CMS capacity is measured in helium return heater power. A combination of loop tuning and feed forward control was necessary to stabilize the helium refrigerator during rapid beam trips and ramps. In the year since PPU completion, the CMS has successfully supported beam ramp on schedule and is currently handling 1.80 MW. Increasing CMS compressor suction pressure provided a comfortable margin at the current beam power. It is projected that without any further improvements in CMS refrigerator capacity, operation at 2.0 MW is possible with ~300 W reserve capacity.

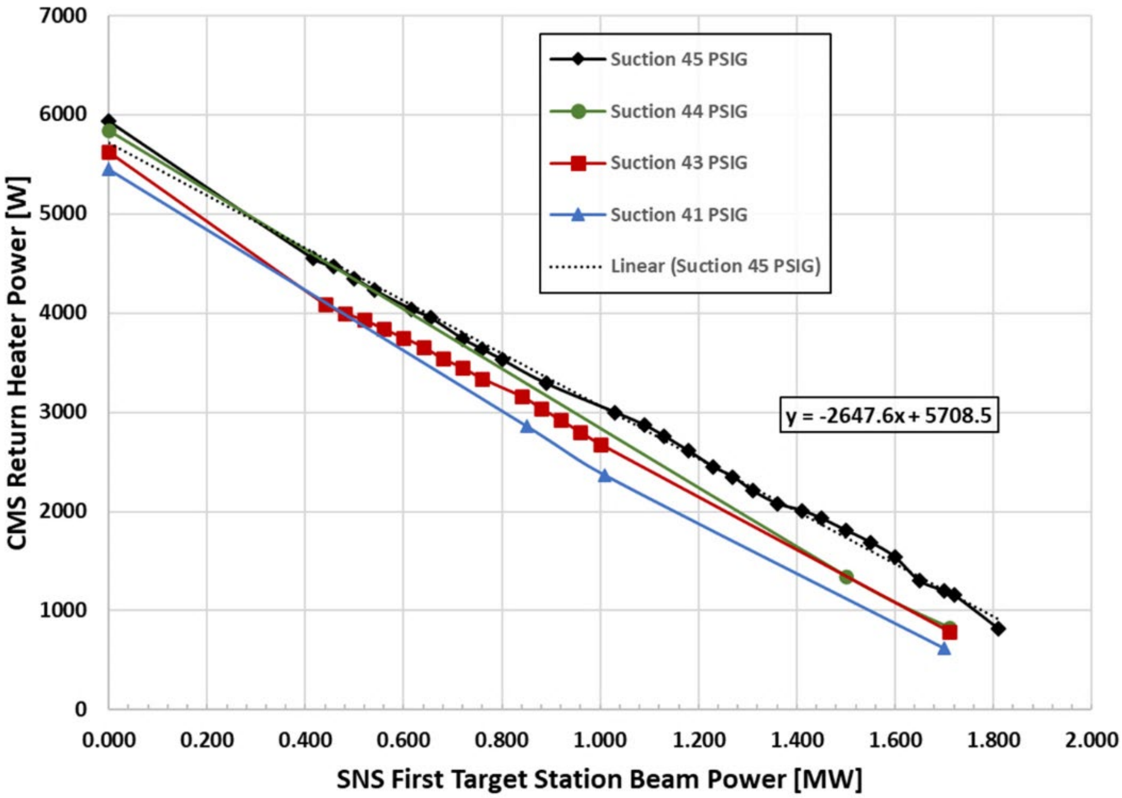

Figure 9. SNS Beam Power on Target from 0 MW in 2006 to 1.55 MW in 2023

CMS will continue to strive for increased performance from the helium refrigerator. Any increase in refrigeration capacity will allow for greater operating margin with beam power at 2.0 MW. Three areas have been identified and will be explored in the near term: decreasing the pressure drop from the helium compressor to inlet of cold box, implement further increases to helium compressor suction pressure, and replace helium turbine inlet vanes.

5. Conclusion

Monitoring of the hydrogen ortho-para fraction during SNS beam operation represents a world class achievement. Not only does this catalyst allow for SNS to achieve greater than 70% para fraction, but beam effects of ortho-fraction generation can now be studied. The CMS is reliably supporting SNS beam operation at 1.80 MW. HRS functions to supply sufficient hydrogen to fill the increased moderator volume during CMS cooldowns. CMS is well situated for final PPU beam power at 2.0 MW.

6. References

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