Liquid deuterium cold source concept for the NIST neutron source

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Abstract. The National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) houses an aging reactor that serves more than 40 % of all cold neutron research needs in the U.S. First critical in 1967, the National Bureau of Standards Reactor (NBSR) is now more than 50 years old. NCNR engineers have initiated a design effort for a replacement reactor, namely the NIST Neutron Source or NNS. The NNS is conceived as a 20-MWth light-water cooled and moderated, and heavy-water reflected compact core design. The NNS will include two liquid deuterium cold sources to moderate neutrons to effective temperatures well below that of thermal neutrons. These cold neutron sources will require new cryogenic infrastructure to operate. This report describes a preliminary proposed design concept for the NNS cold sources and associated ancillary infrastructure.

1. Introduction

The National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) houses the National Bureau of Standards Reactor (NBSR), which serves more than 40 % of all cold neutron research needs in the U.S. [1]. First critical in 1967, the NBSR is now more than 50 years old and is licensed to operate until 2029 at which point it will need to be relicensed. It is currently one of only two major steady-state neutron scattering facilities in the U.S. NCNR engineers have initiated a design effort for a replacement reactor, namely the NIST Neutron Source or NNS. This report describes a preliminary proposed design concept for the NNS cold sources and associated ancillary infrastructure.

1.1. NNS overall architecture

The proposed siting of the NNS is adjacent to the existing NBSR facility, allowing the latter to continue operation during the NNS construction and sharing existing NCNR infrastructure and personnel resources. At initial start-up (commissioning), the NNS would deliver equivalent measurement capabilities to the existing NBSR neutron source. Once at full capacity, the facility should significantly alleviate the current over-subscription of scientific instruments [2] as well as provide new measurement opportunities.

The proposed NNS user facility is envisioned to provide cold and thermal neutron beams as well as several in-core irradiation positions to meet the needs of the neutron research community [3]. The NNS pre-conceptual design proposes two (2) cold neutron sources.

The NNS reactor concept was influenced by several neutron science reactor facilities [4]–[6]. The NNS is proposed to be an open-pool research reactor with a nominal thermal power of 20 MW. It is composed of a light-water-cooled compact reactor core located inside a vertical channel (the "core chimney") that is surrounded by heavy water in a reflector tank. All reactor components are located at the bottom of a reactor pool filled with demineralized light water.

The reflector tank encompasses the cold neutron sources and associated beam guides as well as beam tubes for thermal neutrons. The core is cooled by an upward flow of demineralized light water, which also acts as a neutron moderator. The core chimney channels the coolant to where it is pumped away by the primary cooling system (PCS) for heat removal by the secondary cooling system.

The general layout of the reactor including the PCS is shown in Figure 1. At the center of the figure is the reflector tank. The internals of the reflector tank, including the reactor core at the center, two cold neutron sources, and beam tubes are shown in Figure 2.

1.2. Cold and thermal neutrons

Thermal neutrons are typically characterized by a room-temperature Maxwellian energy distribution, while cold neutrons may be characterized by Maxwellians with lower effective temperatures, sometimes in the tens of Kelvin range. The NCNR adopts the definition of cold neutrons as having energies less than 0.005 eV or neutron wavelengths, λ, greater than about 4 Å.

1.3. CNS Design and performance

Production of cold neutrons requires a dedicated Cold Neutron Source (CNS) and the resulting cold neutron beam must have minimal epithermal and fast neutron contamination. The CNS comprises a localized region of cryogenically cooled moderator placed in or near the peak of the unperturbed thermal neutron flux in the moderator/reflector of a research reactor [7]–[9]. Its objective is to shift the thermal Maxwellian neutron flux distribution towards lower energies (lower temperatures).

The proposed NNS CNS model is similar to the OPAL CNS design [5], [10], [11], in which liquid deuterium (LD_2) is maintained as a single liquid phase in the moderator, operating under a thermosiphon rather than relying on a deuterium pump or circulator. The single-phase LD_2 is maintained in the moderator via a helium/deuterium heat exchanger, wherein the helium with an inlet temperature of about 19 K maintains the LD_2 in the moderator by recondensing boiling LD_2.

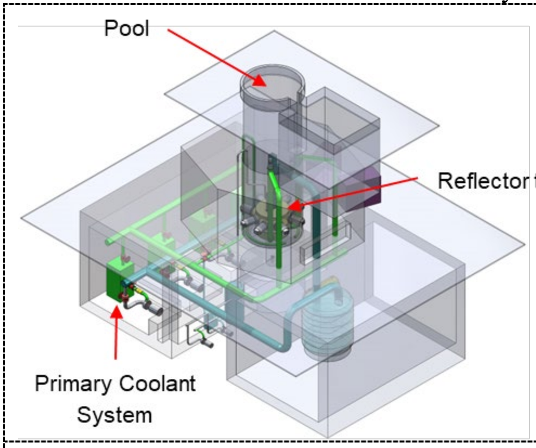

Figure 1. Reactor pool and primary coolant system

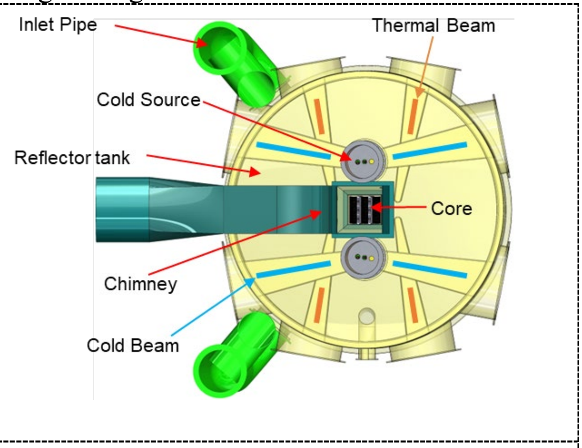

Figure 1. Reflector tank with core, cold sources, and beam tubes

Currently, the NNS design has two identical LD_2 sources, although the possibility of having dissimilar CNSs, optimized differently for different instrument requirements is not excluded. A fixed-diameter CNS thimble may be employed with residual space surrounding a smaller diameter CNS filled with D_2O.

2. Cold neutron source

In a recent study, radiation heat load estimates were obtained for the cryogenically cooled circuit of the NNS CNS based on a "default" 30 cm diameter LD_2 CNS model [12]. The nuclear heating components included prompt gamma heating, saturation level ^{28}Al decay β heating, and neutron heating.

In a separate study , the dependence of the cold source brightness spectrum on the CNS diameter was simulated. The results in Figure 3 showed the potential for an increase in the cold neutron (> 4Å) brightness with a moderate increase in vessel diameter above 30 cm which appears to have diminishing returns as the diameter approaches 40 cm [12]. Results from an analysis of vessel diameter-dependence of the nuclear heat load and how it scales with vessel diameter [12] are shown in Table 1 and Figure 4. Based on this analysis, this report will consider evaluating the 30-cm and 36-cm moderator cases.

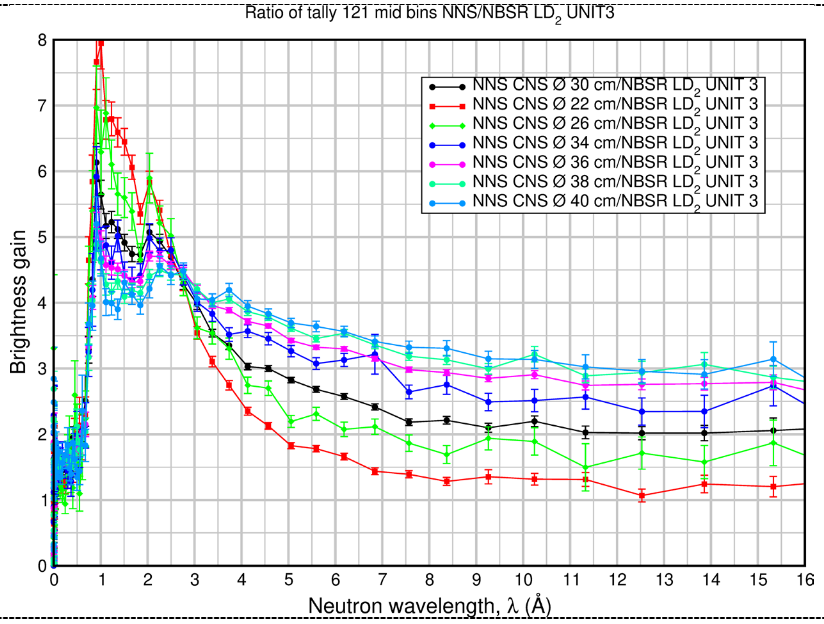

Figure 2. Simulated cold neutron brightness gains versus CNS vessel diameter (constant height).

Table 1 Summary of total heating contributions due to various radiation components and grand total minimum cryogenic heat loads for NNS CNS as a function of CNS diameter.

Component	Total Nuclear Heating (W)						
	Φ 22 cm	*Φ* 26 cm	*Φ* 30 cm	*Φ* 34 cm	*Φ* 36 cm	*Φ* 38cm	*Φ* 40 cm
Υ	1347	1782	2220	2857	3175	3512	3873
Saturation ^{28}Al, β	1142	1439	1710	2084	2252	2423	2591
Neutron	219	358	583	885	1091	1340	1630
Total	**2708**	**3579**	**4513**	**5826**	**6518**	**7275**	**8094**

3. CNS System design

The baseline NNS design has two identical LD_2 sources. Additionally, the NNS will be configured initially with only one cold source operating and a second cold source started thereafter. Therefore, the helium refrigeration system must be likewise configured to support a wide range of CNS heat loads. This report evaluates trade-offs on cryoplant required capacity based on Table 2:

Table 2 CNS total heat load vs. cold source diameter

Cold source diameter (cm)	30		36	
Number of cold sources	1	2	1	2
Neutronic heat load (W)	4,500	9,000	6,500	13,000
Static heat load $^{(10\%)}$ (W)	450	900	650	1,300
Contingency $^{(15\%)}$ (W)	743	1,485	1,073	2,145
Total heat load (W)	5,693	11,385	8,223	16,445

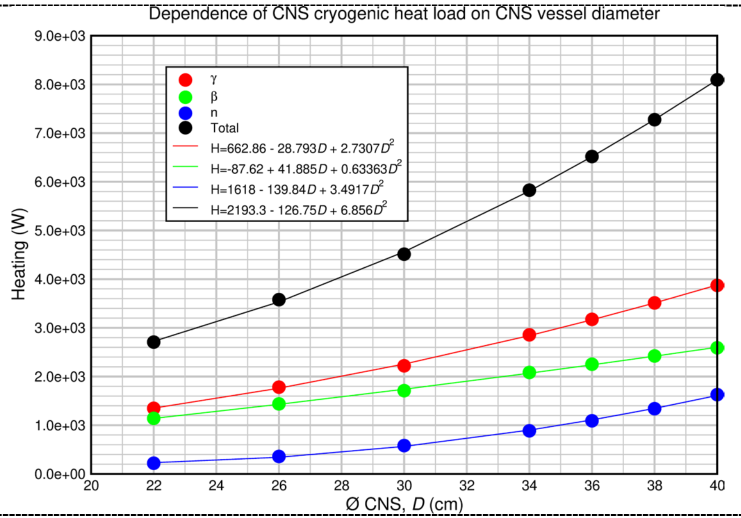

Figure 4. Dependence of CNS cryogenic system radiation heat load vs. CNS vessel diameter

The resulting maximum expected required cooling capacity of the helium cryoplant is either ~ 11,400 W at 19K for the 30-cm moderator or ~16,500 W at 19K for the 36-cm moderator.

The overall CNS configuration follows a well-established pattern that has worked successfully in several other cold neutron source facilities [13], [14], [15]. The concept includes a moderator cryostat containing LD_2 for moderating the neutron flux from the reactor, a deuterium/helium heat exchanger that reliquefies deuterium vapor returning from the cryostat, a helium cryoplant to provide cold helium to the deuterium/helium heat condenser heat exchanger, a ballast vessel to hold the deuterium vapor when the system is warm, a helium containment surrounding the entire deuterium system to provide a safety barrier between the deuterium and surroundings, and interconnecting piping and controls. This design emphasizes simplicity, passive safety features, and a robust cryostat designed to withstand the ignition and deflagration of a hypothetical air/deuterium mixture.

The CNS circuit utilizes a thermosiphon design. A condenser, cooled by helium gas at about 19 K, provides a driven flow of LD_2 into the moderator chamber. The largely radiation-induced heat load to the moderator is removed via boiling of the liquid and return of the vapor to the condenser to complete the cycle. The deuterium-containing system components have no moving parts, and the entire deuterium inventory is contained in a large-volume closed system with no automatic or remotely operated valves or rupture discs. A simplified schematic of this configuration is shown in Figure 5.

The deuterium system is inherently safe, with no pressure relief devices. The deuterium-containing components are sealed in a triple-skinned containment to assure the integrity of the system. With the passive thermosiphon design, operator intervention is not required to maintain the safety of the system. Should cooling fail (refrigerator failure) the deuterium simply boils off and safely returns to the buffer tank. The deuterium inventory and ballast tank volume are designed such that during normal operation (LD_2 in the moderator), system pressure is approximately 1 bar(abs). When LD_2 boils off and the system warms up, the system pressure rises to approximately 5 bar(abs).

The deuterium moderator cryostat is composed of three layers – the inner vessel containing the liquid deuterium, surrounded by an insulating vacuum layer, and a third helium barrier layer. The helium layer is designed to contain any pressure spike from a deflagration or detonation event due to the mixing of deuterium and air. The entire moderator assembly is submerged in a D_2O vessel. All layers are manufactured from 6061-grade aluminium.

The deuterium condenser assembly utilizes a cold gas stream supplied from the helium refrigerator via vacuum-insulated piping to liquefy the deuterium in the cold source moderator chamber. Under normal operating conditions, cold helium gas enters the heat exchanger at approximately 19 K. There it is warmed as it condenses the deuterium vapor returning from the moderator cryostat and returns to the refrigerator coldbox at approximately 22 K. Liquid deuterium drains to the bottom of the heat exchanger into a phase separator region, allowing the incoming vapor stream to expand and any liquid carried over to be separated and returned to the cryostat through the liquid supply line. The operating point for the condenser is controlled by the incoming helium temperature and mass flow, which in turn are regulated by the system deuterium pressure.

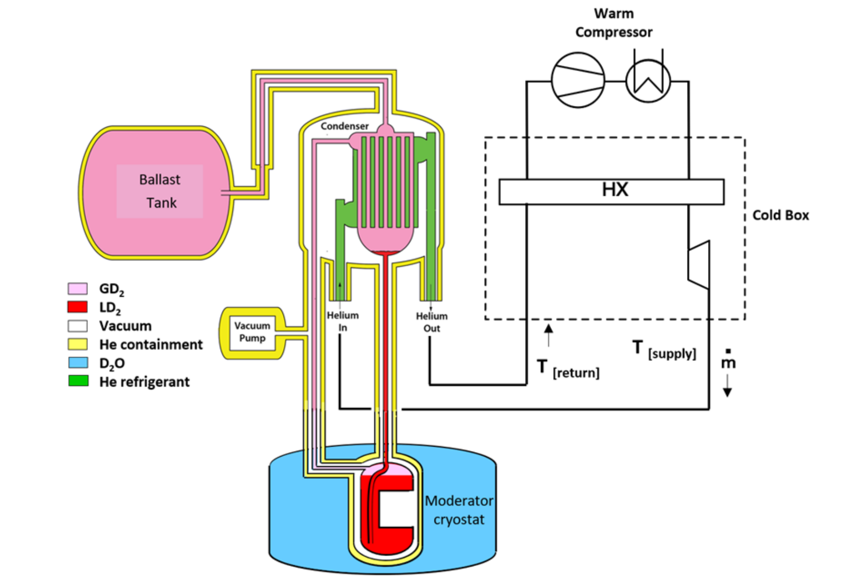

Figure 5. Simplified CNS Thermodynamic Loop Schematic

The deuterium condenser will be a brazed aluminium plate-fin heat exchanger similar in design to the current NBSR deuterium condenser. The working pressures and heat transfer capability will be determined through future trade studies but could nominally be approximately 2100 kPa and 700 kPa respectively for the helium and hydrogen sides, and a 9 kW to 13 kW heat transfer capability.

The condenser is surrounded by an insulating vacuum jacket and a helium containment jacket in the same manner as the moderator cryostat. The entire assembly is located above the moderator cryostat at a height to provide sufficient liquid head to drive the thermosiphon. The moderator cryostat and condenser will be integrated into a single assembly that can be inserted and removed from the reactor.

Deuterium is initially charged into the system through fill valves at the ballast tank, which are then closed and locked. The ballast tank is sized to safely hold the entire deuterium inventory. The tank is also surrounded by a helium containment jacket designed to prevent undetected air from entering the deuterium system. As the inventory of deuterium is fixed, the system pressure is never expected to rise above 5 bar(abs) which precludes the requirement for any pressure relief devices.

4. Helium refrigeration system

A planned helium refrigeration plant will provide the required refrigeration capacity with good efficiency over a wide heat load range. Table 2 shows the expected heat load for the two moderator configurations mentioned previously. Based on these parameters, the features of the helium refrigerator are as follows:

- Two warm helium compressor modules (one online, one spare)
- An oil removal skid consisting of coalescing filters and a final charcoal oil removal vessel
- Helium gas management controls
- Cold box containing expansion turbines, heat exchangers, and helium purification vessel
- Low-pressure helium storage vessel

A simplified process flow diagram is shown in Figure 6. Warm high-pressure helium enters the coldbox at approximately 300 K and is initially cooled by passing through a counterflow heat exchanger. A portion of the flow is diverted to a first stage 80 K turboexpander to the return side, the remaining flow passing to a second counterflow heat exchanger. A molecular sieve purifier captures any impurities before entering the third heat exchanger. The final stage of cooling to ~ 19 K occurs at the second stage turboexpander. Cold helium then flows in parallel to the CNS helium/deuterium condenser heat exchanger (Figure 7). Low-pressure helium at ~ 22 K from the CNS returns to the cold box, provides counterflow to the heat exchangers, then returns to the compressors low-pressure side to repeat the cycle.

As the refrigeration system requires sufficient flexibility to efficiently accommodate the expected load range, it is anticipated to operate using the Ganni cycle / floating pressure process [16].

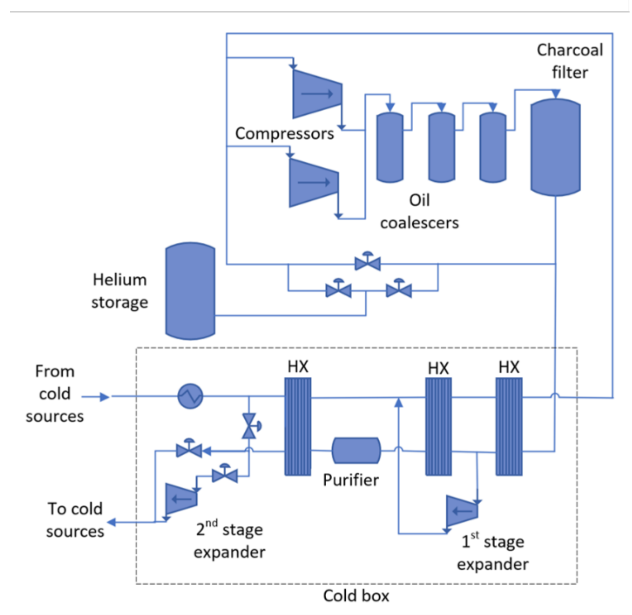

Figure 6. Simplified Helium Cryoplant Process Flow Diagram

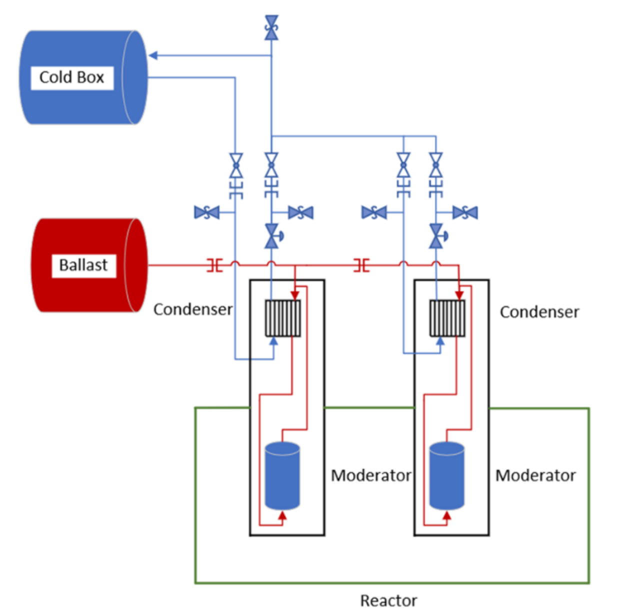

Figure 7. Simplified Moderator cooling circuit

With floating pressure process control, the compressor discharge pressure is adjusted to match the required CNS load while approximately maintaining the compressor pressure ratio. At full load, the compressor bypass is normally closed or mostly closed, and partially open under reduced loads (approximately 50 % of the maximum load).

The helium refrigerator cold box was modelled referencing REFPROP [17] fluid properties. Heat exchangers were modelled as simple heat exchange between the warm and cold streams, using known temperatures, flow rates, and fluid enthalpies to determine unknown values and heat exchanger balance. Expansion turbine outlet temperatures were calculated assuming isentropic expansion corrected with an assumed isentropic effectiveness of 0.75.

Analysis results are shown in Table 3, which also lists the cryoplant heat load for each configuration evaluated (cold source quantity and moderator diameter), compressor high pressure (HP) and low pressure (LP), and helium mass flow rate. Figure 8 shows the temperature-entropy (T-S) diagram for the 9 kW neutronic heat load case.

Table 3 – Cryogenic heat load, pressures, and flow rate for 30, 36 cm diameter cold sources

CNS dia. [cm]	Number of CNS	Heat load [W]	HP [bar(abs)]	LP [bar(abs)]	PR	Flow rate [g/s]
30	2	11,385	15	3	5	790
	1	5,693	7.5	1.5	5	395
36	2	16,445	15	3	5	1,141
	1	8,223	7.5	1.5	5	570

These calculations were performed using purely thermodynamic balances to arrive at a reasonable functional specification for heat exchangers and turbines. At this stage of the project, specific equipment has not been sized. At a future time when the cold source heat loads are finalized, additional effort will be required to specify equipment, evaluate off-design cases, etc.

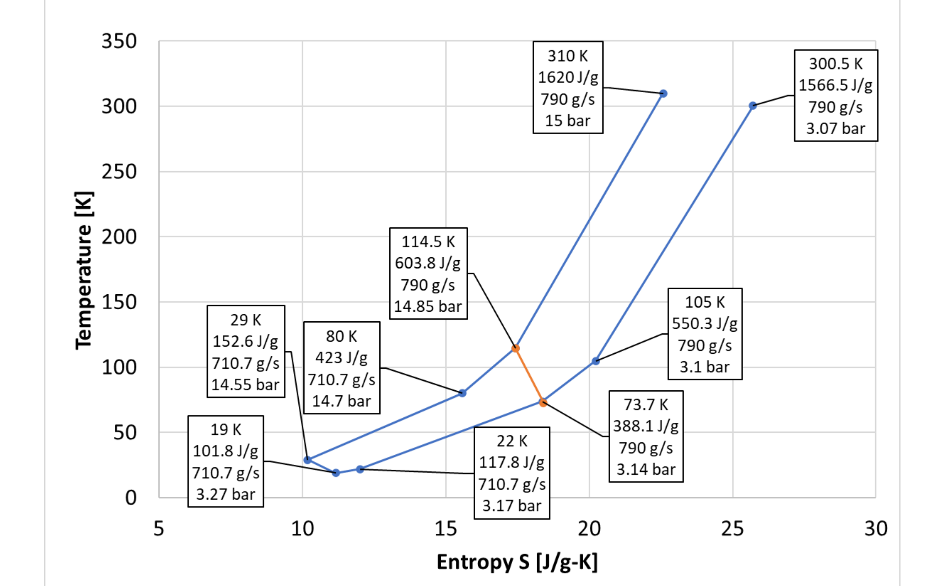

Figure 8. T-S diagram for 9 kW (2 cold sources) heat load

5. Summary

The NCNR has operated since 1967, providing a neutron source for thousands of visiting researchers annually. It is currently one of only two major steady-state neutron scattering facilities in the U.S. The NBSR reactor's age demands attention to address future neutron science research in the US. A study on future options for the NCNR neutron source determined that a replacement reactor is the best option to ensure a reliable neutron source in the long term. To that end, work has started to develop a pre-conceptual design for a NIST Neutron Source to satisfy the neutron science community's needs for the remainder of this century. The pre-conceptual design attempts to define the functional design of the proposed NNS, including the neutronic and thermal-hydraulic design, associated components mechanical design, and required instrumentation and control. The report will also satisfy a portion of the NIST appropriations act [18] that addresses congressional legislation recommendations calling for a strategic plan for the NIST neutron reactor. The strategic plan must address succession planning for the NBSR reactor, a conceptual design of a new reactor and accompanying facilities, and a plan to minimize disruptions to the neutron science user community. This report summarizes a pre-conceptual cold source and cryogenic helium refrigerator design that will be an integral part of the new NIST Neutron Source.

6. Disclaimer

Certain commercial equipment, instruments, or materials may be identified in this study in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that materials or equipment identified are necessarily the best available for the purpose.

7. References

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