High Flux Isotope Reactor Supercritical Hydrogen Cold Source

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Abstract

A super critical hydrogen cold source system is being designed and fabricated for installation into the HB-4 beam tube of the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). The cold source will provide gain factors comparable to existing operating hydrogen cold sources and will be designed and operated in a manner that does not significantly impact the safe operation of the reactor.

1. INTRODUCTION

In February of 1995, Oak Ridge National Laboratory's Deputy Director formed a group to examine the need for upgrades to the HFIR system in light of the cancellation of the Advanced Neutron Source Project. One of the major findings of this study was that there was a need for the installation of a cold neutron source facility in the HFIR reactor. During the summer of 1995 a team was formed to examine the feasibility of retrofitting a liquid hydrogen cold source facility into the HB-4 beam tube. These preconceptual studies were completed and documented in December of 1995 in Ref. [1].

Funding was received in 1996 to initiate the development of a reference design concept. This led to the documentation of a reference concept in 1998 (Ref. [2]). Between 1996 and 1998 the design approach was twice impacted by major changes in the design ground rules that led to significant modifications in the concept:

(1) It was determined that it would be possible to replace the existing HB-4 beam tube with one that was significantly larger. This allowed for a larger moderator vessel and also created more space in the beam tube for hydrogen transfer lines.

(2) Later it was determined that a supercritical hydrogen system was more stable under transient conditions and that it could be implemented with little impact on the design concept. Thus, the reference concept was changed from a liquid hydrogen system to a supercritical hydrogen system operating at a pressure between 1.4 and 1.5 MPa.

Since 1998 the project has proceeded with detailed design and procurement of key components. Over the next 18 months the system will be assembled and tested on the HFIR site. Following the successful completion of the out-of-pile testing, the system will be installed in the reactor as part of the HB-4 beam tube.

2. FUNCTIONAL REQUIREMENTS

There are a number of key requirements and goals for the design of the HFIR cold source that are documented in Ref. [2]. However, there are two major requirements that drive most of the design considerations:

(1) The purpose of the HFIR cold source is to increase the available neutron flux delivered to instruments at wavelengths from 4 to 12 Å. Optimization is to be based on the neutron brightness (/s/cm^2/steradian/Å). The gain factor on brightness, as measured on HB-4, for these wavelengths should be comparable to existing hydrogen cold sources.

(2) The HFIR cold neutron source facility will be designed such that there is a low probability (less than 1 x 10-6 per year best estimate frequency) that neither the reactor nor the public will be endangered by accidents that occur within the cold source or as a result of the cold source facility interacting with the reactor or its safety systems. In addition, the design and operation of the HFIR cold source will follow National Aeronautics and Space Administration (NASA) guidelines and the U.S. Department of Labor Occupational Safety & Health Administration (OSHA) standard 29 CFR 1910.103 for the use of hydrogen in either a gas or liquid state.

3. REFERENCE CONCEPT DESCRIPTION

In simple terms the HFIR cold source system consists of a variable speed magnetic bearing hydrogen circulator that forces hydrogen at 15 bar pressure to a moderator vessel in the nose of the HB-4 beam tube returning flow to a helium heat exchanger and back to the circulator. A total of approximately 3 kw of heat is deposited into the hydrogen and removed by the helium heat exchanger. The helium is in turn cooled by a refrigeration system that can provide up to 3.8 kw of cooling at 20 K. Additional information on the main components is provided in the following sections.

3.1. Pump Module

The pump module is the heart of the system and consists of three variable speed magnetic bearing circulators (only one of which is in operation at any given time), temperature and pressure monitors, and piping and isolation valves that allow the isolation of any given circulator. The pump module is vacuum insulated and also includes a helium cover gas barrier around all hydrogen systems. At this time the variable speed circulators have been fabricated and tested and the fully functioning pump module is expected to be delivered to ORNL by the end of the calendar year.

3.2. Hydrogen Transfer Lines

Transfer lines are required to transport cryogenic hydrogen between discrete components of the system. All cryogenic transfer lines are vacuum insulated and include a helium cover gas region. A semi-flexible steel tubing system designed for hydrogen flow is used where ever possible. The first of three main transfer lines is expected to be delivered in October of this year. The remaining two sections of transfer line will be ordered as soon as the first section passes acceptance testing.

3.3. Moderator Vessel

The moderator vessel will be located in the nose of the new HB-4 beam tube. The material used in the fabrication of the vessel is aluminum 6061-T6. The moderator vessel (shown in Fig. 1) is made by machining two pieces out of a solid block of aluminum and joining them with a single electron beam weld. The electron beam weld has been tested to failure which occurred at about 10 times the normal operating pressure. Extensive flow modeling within the moderator vessel has been performed to assure that adequate cooling is provided for all surfaces of the moderator vessel.

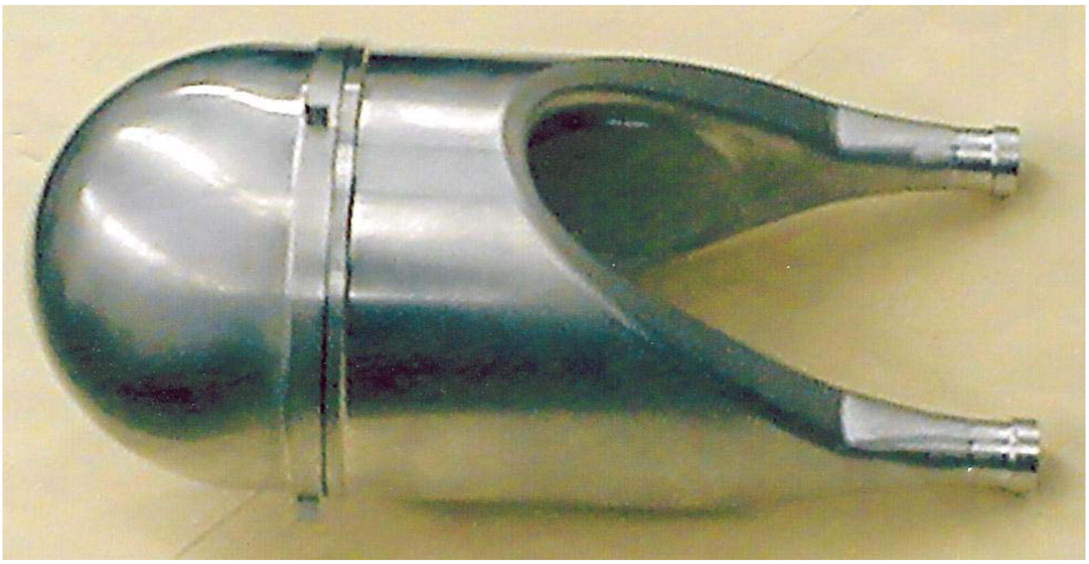


Figure 1 - HFIR Cold Source Moderator Vessel

3.4. Heat Exchanger

The heat exchanger provides a vacuum insulated interface between the hydrogen loop and the helium refrigerator system. Temperature sensors within the module provide temperature control during cool-down to prevent possible freezing of the hydrogen. The heat exchanger is of the aluminum core type used in the construction of cryogenic refrigerators. The heat exchanger is surrounded by a double-walled containment vessel. The inner wall provides vacuum insulation and the outer wall provides space for an inert blanket. The heat exchanger has been fabricated and has been delivered to ORNL.

3.5. Refrigerator System

The refrigerator provides the cooling power needed to maintain the hydrogen in the moderator vessel at approximately 20 K. The refrigerator system is composed of five major equipment items: a bank of five helium screw compressors, a vacuum-insulated cold box that contains all interstage heat exchangers, a second cold box containing four two-cylinder piston expanders, a motor control center, and an inventory control system. Refrigeration power depends on the number of compressors and expanders used, but fine operational control is provided by in-line heaters in the helium refrigerant circuit. The complete refrigerator system is located in a dedicated separate structure outside of the reactor building. The refrigerator system has been installed and has been satisfactorily tested beyond the design requirements.

3.6. Support Systems

Although the cold source system has been described in simple terms, there are a number of complex systems that are required to make the cold source functional. These systems include the vacuum systems, gas-handling systems, inert blanket systems, instrumentation and control systems, and vent systems. These systems are in various stages of fabrication or design, but are expected to be completed during the first half of 2004.

4. COLD SOURCE PERFORMANCE AND OPTIMIZATION STUDIES

A number of analyses and optimization studies have been performed to address the physics performance of the HFIR cold source.

4.1. Predicted Cold Source Performance

As stated in Section 2 of this paper, the purpose of the cold source is to provide gains in the number of 4 to 12 Å neutrons comparable to that provided by other hydrogen cold sources. Figure 2 provides a plot of the calculated gain factors for the HFIR cold source and compares them with gain factors determined for other existing hydrogen cold sources. As seen from this figure, the estimated gain factors are comparable with those obtained by several existing hydrogen cold sources at other reactor facilities around the world. The estimated brightness of the cold neutron beam is provided in Fig. 3.

Figure 2 - Comparison of Estimated HFIR Cold Source Gain Factors With Existing Hydrogen Cold Sources

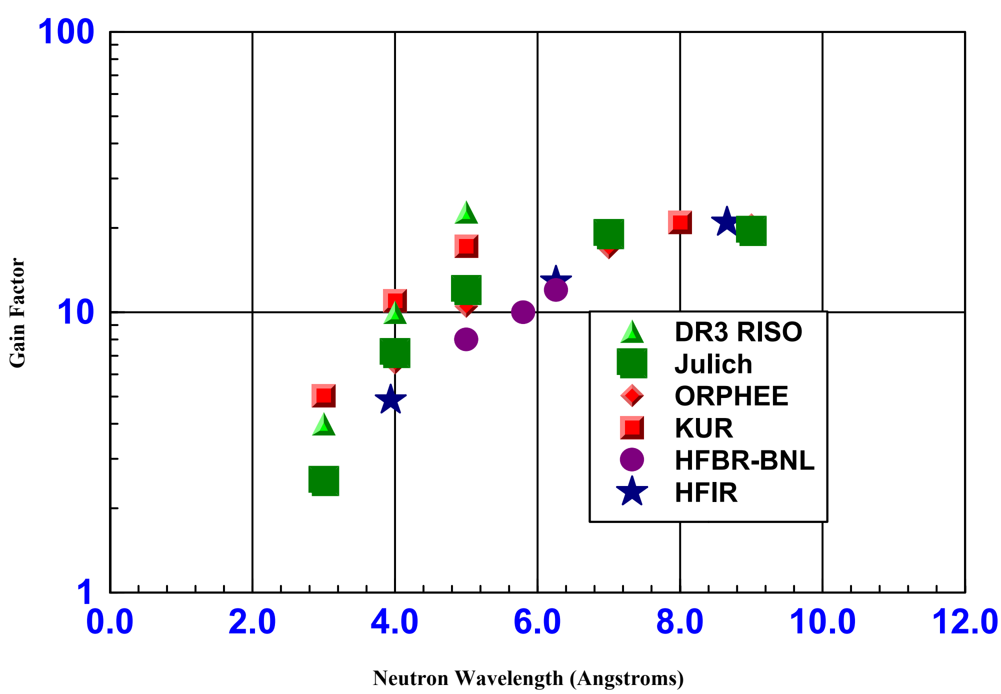
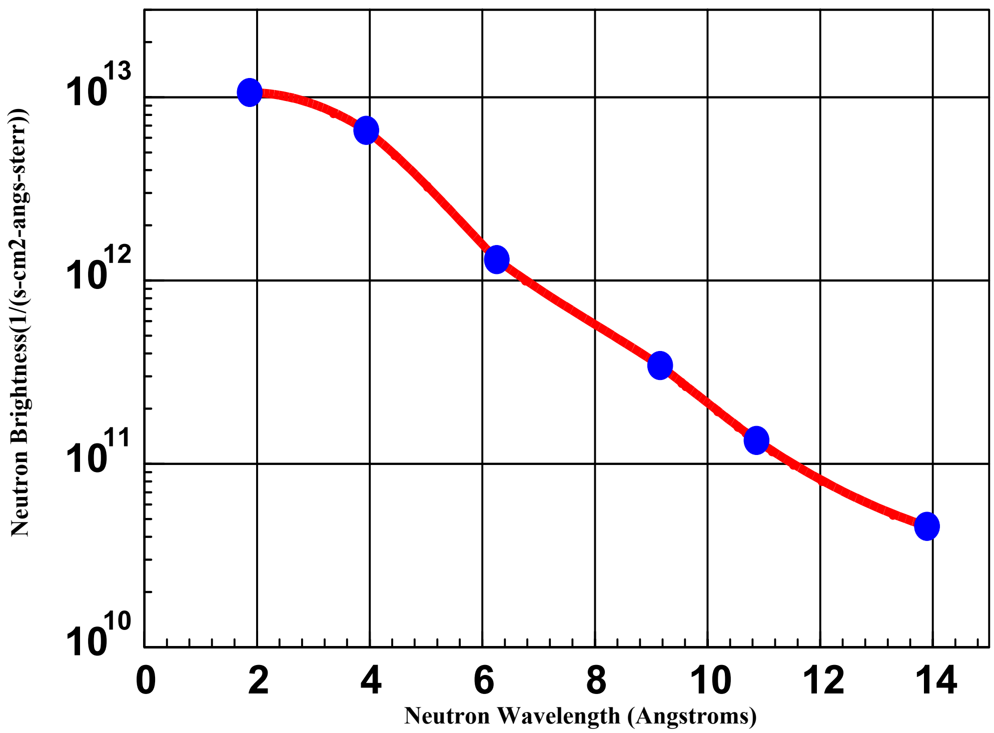


Figure 3 - Predicted Neutron Brightness for the HFIR Cold Source



4.2. Reentry Cavity in Cold Source Geometry

It has been know for some time based on measurements at the Institut Laue-Langevin (ILL) that reentry cavities in a deuterium cold source could lead to significant gains in the cold neutron current down the beam tube. In addition, the experience at the National Institute of Standards and Technology (NIST) reactor implies that such gains can also be achieved with reentry cavities in hydrogen cold sources. Therefore early in the development of the HFIR moderator vessel geometry considerations were made to design the transition from hydrogen flow lines to moderator vessel in a manner that would create a geometry resembling a reentry cavity. The analysis performed for this arrangement showed an approximate 30% increase in the cold neutron current down the beam tube when compared with other geometries.

4.3. Impact of Ortho/Parah hydrogen ratio

Early infinite slab parametric studies (see Ref. 1) implied that the ortho-hydrogen to parah-hydrogen ratio would have a significant impact on the performance of the HFIR cold source for the moderator thickness being considered. This was supported by evaluations performed at NIST. However, when various ratios were used in the model of the HFIR cold source the results documented in Ref [2] indicated that the ortho/parah hydrogen ratio had very little impact on the performance of the HFIR cold source for the neutron wavelengths of interest. This was a concern to us because the results were contradictory to the previous studies. As a result, a Monte Carlo study was performed where the HFIR cold source geometry was changed to the NIST cold source geometry in a series of steps. It was found and documented in Ref [2] that the effects of the ortho/parah hydrogen ratio were measurably impacted by the actual geometry of a cold source. It was determined that the impact was significantly different for the smaller HFIR cold source located in a beryllium reflector when compared with the larger NIST cold source. The ORNL model of the NIST cold source, in fact, exhibited ortho/parah ratio effects very similar to those reported by NIST. This provided confidence that the HFIR cold source was relatively unaffected by the ortho/parah hydrogen ratio and thus, the uncertainty in this ratio was no longer considered an issue.

5. HFIR COLD SOURCE OPERATING MODES

The HFIR cold source system will have two approved operating modes. The first mode of operation or primary operating state represents the normal operating mode with hydrogen temperature between 18 and 21 K. The second operating mode has been defined as a standby operating state and will be used when the normal refrigerating system is offline and cooling is provided by once through flow of liquid nitrogen from a 42 m^3 tank located on a hill above the cold source refrigerator equipment. This mode of operation provides hydrogen flow at reduced pressure with a temperature between 100 and 120 K which is sufficient to cool the moderator vessel with the reactor operating at normal power levels.

6. SAFETY PHILOSOPHY AND PRINCIPAL SAFETY FEATURES OF THE HFIR COLD SOURCE

The primary purpose of the cold source safety evaluations is to ensure that the reactor safety systems and the overall safety level of the reactor are not impacted by the cold source or any of its systems. A secondary purpose of the cold source safety evaluations is to ensure that on-site personnel and equipment also are not adversely impacted by the cold source or any of its systems. The safety goal for effects on the reactor is to have a low probability ($<1 \times 10^{-6}$ per year best estimate frequency) that fuel will be damaged or a nuclear safety function lost because of the cold source or any of its equipment. The safety goal for the cold source facility is that a major release of hydrogen into the reactor building should be a low probability limiting event, with no loss of the reactor confinement safety function.

The cold source safety work is proceeding in parallel with development of the cold source design. At each stage of the design and testing, the safety evaluations have provided input to the decision-making. The final safety evaluations of the cold source facility will be used as an authorization basis document to support the safety review by ORNL safety committees and by the United States Department of Energy (DOE). This analysis is expected to be an attachment to an Unreviewed Safety Question Determination (USQD) document that will be submitted to add the cold source facility to the HFIR authorization basis. The appropriate amount of summary descriptive and safety information is expected to be inserted into Chap. 10 of the HFIR SAR following initial operation of the cold source.

The safety of the cold source is being ensured by multiple approaches. Adequate conservatism is being given to the design of the liquid hydrogen boundaries to ensure a high integrity boundary. A quality assurance (QA) program is in place to control design, analysis, procurement, fabrication, installation, and operation of the facility. Development testing is being carried out as part of the design, and final testing will be performed as part of the start-up of the facility. An accident analysis is being performed to examine the bounding aspects of the design, as well as the probability and consequences of various event sequences.

The HFIR cold source safety design philosophy is a defense-in-depth approach that provides several means to avoid the accidental contact between hydrogen and air and also provides the means to mitigate a hydrogen release, given that a release is assumed to occur. The principles of conservatism, simplicity, redundancy, fail-safe design, and passive safety features are included in the design as much as possible.

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[2] SELBY, D.L., A.T. Lucas, et al, High Flux Isotope Reactor Cold Source Reference Design Concept, ORNL/TM-13498 (1998).