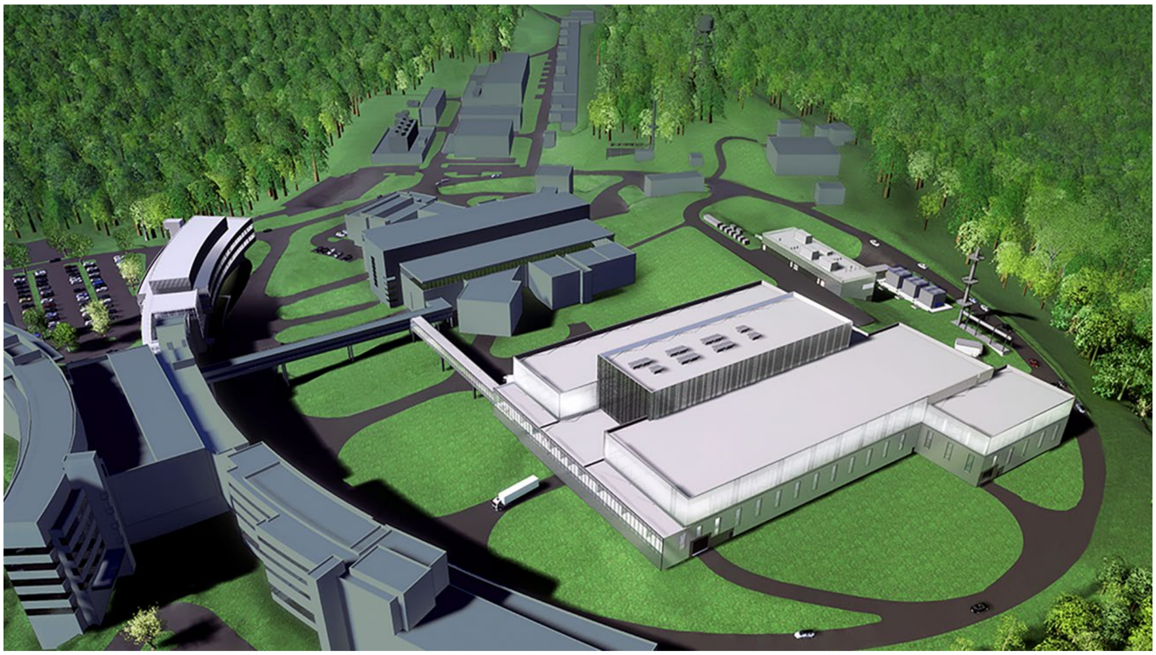
S03040000-TRT10000-R0A

# Second Target Station Project: Assessment of the Need for a Tertiary Inert Layer around the MRA/CMS Hydrogen Boundary



Jim Janney

**March 2024**

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

**S03040000-TRT10000-R0A**

Second Target Station Project

# Assessment of the Need for a Tertiary Inert Layer around the MRA/CMS Hydrogen Boundary

Jim Janney

March 2024

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

## CONTENTS

# 1. PURPOSE

The purpose of this document is to assess the safety implications of not including a tertiary inert blanket layer around the hydrogen boundary of the Second Target Station (STS) Moderator Reflector Assembly (MRA) and Cryogenic Moderator System (CMS).

# 2. BACKGROUND

## 2.1 TERTIARY HELIUM LAYERS AT EXISTING NEUTRON SOURCES

Liquid hydrogen moderators have been implemented at many reactor and accelerator based neutron sources. In order to condense and maintain liquid hydrogen, the moderator hydrogen systems must be enclosed within a vacuum layer to minimize heat transfer to the hydrogen. While the vacuum layer is itself an inert boundary, many neutron source cryogenic hydrogen systems, including at NIST, HFIR, ISIS, and JParc, have included a tertiary helium layer to further maintain separation between the liquid hydrogen and the surroundings.

The early SNS Cryogenic Moderator System design included a tertiary inert helium layer; however, this layer was removed outside the SNS core vessel (which is filled with helium during operation) during project construction as documented in [1]. Recently, due to a water leak, SNS operated with water filling the annular helium region surrounding one the moderators and transfer lines, surrounding the vacuum layer in water, as documented in [2].

The European Spallation Source (ESS) has opted not to include a tertiary helium layer during their design, although they have yet to begin operations.

## 2.2 TERTIARY HELIUM LAYER PURPOSE

The tertiary helium layers offer additional defense in depth to the facilities that include them in their design. If a vacuum leak develops into a vacuum layer surrounded by a tertiary helium blanket, the vacuum quality will be spoiled by small quantities of helium, which will add additional heat load to the cryogenic system and be detectable by vacuum gauges.

Without the helium layer, the general surroundings of the vacuum layer would enter the vacuum (air, water, etc.); however, because of the relatively large surface area available at liquid hydrogen temperatures (14-33 K), all species other than helium and hydrogen will freeze on the cold surfaces. While a large leak would rapidly overwhelm the cryogenic system, a small leak could potentially go undetected for long periods of time or until the system was warmed up, as only the hydrogen and helium will degrade the vacuum quality.

# 3. STS CMS/MRA HYDROGEN CONFIGURATION

The STS CMS process equipment is located within the hydrogen cold box in the hydrogen utility room. A single hydrogen transfer line routes hydrogen from the hydrogen cold box to the hydrogen moderators within the MRA, without a tertiary inert layer. There is a vacuum break between the cold box and hydrogen transfer line, but the vacuum is common for the transfer line from the hydrogen utility room to the moderators. The transfer line vacuum boundary is all welded and is planned to be operated statically while hydrogen is in the system with anticipated vacuum levels of $10^{-8}$ to $10^{-6}$ mbar. The operating temperature of the hydrogen lines are anticipated to be between 18 and 24 K. The transfer line is routed through air from the hydrogen utility room to the core vessel. Inside the core vessel, the transfer line is routed through helium until it reaches the MRA reflector vessels, where the vacuum is surrounded by water. These different surroundings present different scenarios if leaks in the vacuum layer were to occur, as discussed in the following sections

## 4. STS TRANSFER LINE SURROUNDED BY AIR

Where the STS transfer line is surrounded by air, any small leaks would lead to all air constituents other than helium and hydrogen freezing on the cryogenic surfaces. Note, while the freezing point of neon is 25K, it has a vapor pressure of about 1 mbar at 18K, so it will not stay in place on the transfer lines at the operating vacuum pressures of $10^{-8}$ to $10^{-6}$ mbar. While air primarily consists of nitrogen and oxygen, helium and neon make up 5 ppm and 18 ppm of air, respectively. Given the current estimated transfer line vacuum volume of 170 L, 0.009 kg of air would need to enter to bring the vacuum level to $10^{-6}$ mbar, where it would be noticeable by vacuum diagnostic equipment, and 0.9 kg of air would need to enter to bring the vacuum level to $10^{-4}$ mbar, where it would start to increase heat transfer to the hydrogen system. Note that 0.9 kg of frozen air would almost certainly form an ice bridge between the cold surface and exterior of the vacuum boundary, also increasing heat load on the hydrogen system. In these scenarios, the loss of vacuum and ice bridge would eventually cause the hydrogen system to vent as the heat load to the hydrogen system became caused over pressurization of the hydrogen, but without any safety concerns.

An additional possible occurrence with the solidification of air, including oxygen, in a radiation environment is the possible formation of ozone and subsequent potential for explosion. Ozone explosions have occurred many times in radiation environments, but almost always associated with large liquid nitrogen dewars which where either initially contaminated with oxygen or subsequently exposed to air allowing oxygen infiltration. These large dewars with oxygen contamination, when exposed to radiation, allowed for the concentration and solidification of ozone, and subsequent explosion. On the other hand, freezing of air on cryogenic surfaces has only led to 2 known accidents [3]. The first incident occurred during a test of the Rover nuclear rocket engine, when a liquid hydrogen line without vacuum insulation accumulated frozen air adjacent to the nuclear engine, causing ozone formation and subsequent explosion [4]. The second incident occurred at the ORNL graphite reactor, when a vacuum line ruptured causing gross air infiltration to a helium cryostat, and the cryostat exploded upon warm up [5]. Note that in both cases, large quantities of air were frozen in intense radiation fields. In the case of the STS hydrogen transfer lines, the opportunities for air to freeze on the transfer line are outside of the core vessel, 5 m or more from the neutron source and intense radiation fields. Therefore, it is assessed that ozone explosions from solidification of air adjacent to the source are not a significant safety hazard for the STS hydrogen transfer lines.

Note, an equivalent situation underwent an Unreviewed Safety Issue Determination resulting in a negative determination for the SNS hydrogen transfer lines [1].

## 5. STS TRANSFER LINE SURROUNDED BY HELIUM

Within the core vessel environment, the STS hydrogen transfer line will be surrounded by helium. In this situation, any minor leak in the vacuum boundary would immediately lead to a degradation of vacuum and straightforward detection.

## 6. STS TRANSFER LINE SURROUNDED BY WATER

Within the MRA reflector vessels, the vacuum boundary is surrounded by a light water cooling of the premoderator zone. In this zone, vacuum gap sizes are kept to a minimum, only 3 mm around the hydrogen vessel and 1 mm around the hydrogen feed lines, because they negatively affect neutronic performance. As a result, minimal ice accumulation would be required to cause a significant heat load on the hydrogen system.

The primary concern with freezing water in the vacuum gap is closing of the vacuum vent path and potential for obstructing proper venting of hydrogen upon a subsequent hydrogen vessel leak. Leaks which are directly adjacent to the hydrogen vessel are unlikely to obstruct the vent path, but freezing onto the hydrogen feed lines does have the potential to impede venting. Scaling linearly from the heat transfer calculation in [6], with the conduction length reduced from 4.5 mm to 1 mm, results in a 40 W heat leak for a 4.5 mm diameter cylindrical ice bridge. If the diameter of the bridge were increased to 14 mm, the resulting heat leak would increase to 400 W, which would certainly be noticed by the CMS operations team and likely cause the hydrogen system to lose control of pressure and vent the hydrogen through the hydrogen safe vent. Additionally, for the lower tube moderator, each hydrogen line to the hydrogen vessel has an independent vacuum line, which would be exceedingly improbable to impede simultaneously from ice blockages.

The final potential concern for ice accumulation in the vacuum layer adjacent within the reflector vessel is energetic releases from recombination of radiolysis products within the ice. Tests conducted at IBR-2 showed a maximum energy release of 240 J/g, and theoretical work indicates potential for up to 330 J/g of stored energy prior to recombination [7]. This amount of energy storage is enough to bring the ice to the melting point and melt 10% of the ice, which when enclosed produces pressure spikes, but in a vacuum system with free surfaces, will not cause any damage to the MRA structures.

Note, a similar situation, except for with stagnant water instead of flowing adjacent to the vacuum, underwent an Unreviewed Safety Issue Determination resulting in a negative determination for the SNS hydrogen transfer lines [2].

## 7. CONCLUSIONS

Scenarios for potential leaks into the vacuum space were considered for all regions of the STS hydrogen transfer line without a tertiary inert layer. While omission of the tertiary inert layer does allow for the possibility of freezing in leaking species on the cold surfaces of the hydrogen boundary, no resulting safety issues have been identified. This conclusion is supported by Unreviewed Safety Issue Determinations resulting in negative determinations for similar configurations for the operating SNS CMS hydrogen system [1,2]

# 8. REFERENCES


| Ref | Document Titles | Reference |
|---|---|---|
| [1] | USID for Elimination of Cryogenic Moderator System Helium Layer | 102030102-ES0020 |
| [2] | USI Evaluation of continued Inner Reflector Plug (IRP) operation with a Light Water System 3 (LWS3) water leak into the Top Downstream Moderator (TDM) helium annulus and the new Leak Monitoring and Collection System (LMCS) equipment. | 102030102-ES0091 |
| [3] | Cryogenic System Operating Experience Review for Fusion Applications | Cadwallader, EGG-FSP10048, Idaho National Engineering Laboratory, 1992 |
| [4] | Overview of Rover Engine Tests, Final Report | Finseth, NASA-CR-184270, National Aeronautics and Space Administration, 1991 |
| [5] | Techniques and Equipment Utilized in Low Temperature Reactor Irradiations | Coltman et al., Review of Scientific Instruments 28, 375, 1957 |
| [6] | Water Leak Report 2-13-2017 | Laughon, Attached Report |
| [7] | Radiation Effects in Cold Moderator Materials: Experimental Study of Accumulation and Release of Chemical Energy | Keligan et al., Nuclear Instruments and Methods in Physics Research B, 215, 2004 |


[6] is the report referenced in [2] as reference [17].