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PROTON POWER UPGRADE PROJECT HAZARD ANALYSIS REPORT

June 2020

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1. Introduction

The initial issue of this hazard analysis report was prepared during the preliminary design (CD-2) stage of the Proton Power Upgrade (PPU) project, and this revision provides updated analysis to support CD-2/3 and reflect updates from the PPU Final Design Report (FDR) [1-1]. The report is a logical continuation of the preliminary hazard analysis report (PHAR) issued during the conceptual design (CD-1) stage [1-2] and it provides more detailed information that has resulted from design work done since the project gained CD-1 status. As is the case for the PHAR, this update report addresses the post-PPU operational period prior to the installation of the planned Second Target Station (STS) on the Spallation Neutron Source (SNS) site. The operational goal for this period is to achieve steady operation with a 2 MW beam directed onto the first target. Additional safety documentation will be issued to cover operation of the STS in which the accelerator will operate with a beam power up to 2.8 MW, supplying beams to both the First Target Station (FTS) and the STS. All the hazard and accident analyses in this report refer to the FTS. Section 7 refers to the proposed STS but is about the FTS.

The focus of this hazard analysis report is operational risk resulting from installation of the proposed upgrades, but there is also a need to manage hazards associated with construction and installation activities. SNS is a mature operating facility supported by the robust institutional framework of the Oak Ridge National Laboratory (ORNL), providing a rigorous system of programmatic requirements and procedures that together provide a cohesive and complete system for managing construction and installation risks. This institutional framework is described in the Standards Based Management System (SBMS). The highest level of the SBMS framework includes the Worker Safety and Health Management System, Work/Project Planning and Control Management System and the Integrated Safety Management System. These systems provide structure, requirements and key program elements that flow down into programs and subject areas that provide more detailed processes and procedures for the planning and execution of work. This systematic approach has proven to be both robust and flexible, ensuring work is performed safely in the dynamic research environment at ORNL.

Integration and implementation of these programs into the PPU project has already proven to be an effective strategy for managing construction and installation hazards during work authorized through CD-3a and CD-3b reviews. They have even proven capable of quickly and successfully managing the unexpected and unprecedented hazards resulting from the COVID-19 pandemic, allowing PPU construction projects to continue with appropriate controls to protect workers and limit the potential for spread of this novel virus.

The PPU project provides upgrades to the existing SNS accelerator facility. Therefore, the PHAR evaluated the safety of the upgrades within the unreviewed safety issues (USI) process as defined in DOE O 420.2C, *Safety of Accelerator Facilities*. The following five USIs were declared in the PHAR. The five USIs are listed below, along with the section in this report that provides a more detailed hazard evaluation consistent with the preliminary design information that is now available.

- USI: increased beam particle energy from 1.0 GeV to 1.3 GeV—effect on target spallation product inventory, Section 2

- USI: increased beam particle energy from 1.0 GeV to 1.3 GeV—effect on target core vessel component heat distribution, Section 3

- USI: increased maximum sustained beam to the ring injection dump from 150 to 200 kW, Section 4

- USI: injection of helium into the circulating target mercury in the target module to control the rate of cavitation erosion of the target module, Section 5

- USI: increased hydrogen inventory of the target cryogenic moderator system (CMS) due to the proposed installation of a catalytic conversion stage to convert ortho-hydrogen into para-hydrogen, Section 6

Section 7 of this report provides a USI determination and accompanying hazard evaluation of an issue not addressed in the PHAR: a hazard event defined as inadvertently generating a 2.8 MW beam and training it onto the first target for an indefinite period. The need to address this issue was identified in internal reviews conducted as a part of the PPU CD-2 design development activities. Section 8 is a brief summary of the overall results of this report.

1.1 References

1-1 *Final Design Report Proton Power Upgrade Project*, ORNL/TM-2020/1570-R0, PPUP-101-TD0001-R0, June 2020.

1-2 R. M. Harrington and S. M. Trotter, Preliminary Hazard Analysis in Support of the Proton Power Upgrade Project, PPU-P01-ES0001-R00, May 2017.

2. Safety Evaluation of Effects of Increased Beam Particle Energy from 1.0 GeV to 1.3 GeV—Effect on Target Spallation Product Inventory

2.1 Introduction

The PPU PHAR [2-1] identified the higher end-of-facility-life mercury spallation product inventory associated with post-PPU operations as a possible USI because of the potential for increased radiological consequences of previously analyzed hypothetical accidents. This section updates the post-PPU accident consequences and concludes that, although the unmitigated consequences do increase, all existing safety criteria are met and the mitigated consequences remain negligibly small or insignificant.

The safety analysis of the mercury target as documented in the *Spallation Neutron Source Final Safety Assessment Document For Neutron Facilities* (*FSAD-NF*) [2-2] presents source terms for hypothetical unmitigated airborne mercury release accidents in terms of fractional releases of groups of radionuclides in the spallation product inventory. Depending on the physical stresses and energy sources of each accident, the hypothetical fractional release of different groups of spallation products varies. Physical stresses and energy sources that have the potential to create airborne source terms for SNS accidents do not depend on the radionuclide inventory in the mercury, because they involve much higher amounts of energy than the heat released from radioactive decay. For example, at the full power of 2 MW, the proton beam deposits about 1.3 MW of thermal power directly into the target mercury (the rest is captured by surrounding structures in the core vessel and monolith), whereas total decay energy is a relatively negligible amount on the order of about 1 kW (i.e., <.1% of the proton beam energy). Given that the potential dispersive sources of energy that drive accidents are decoupled from the amount of radionuclides present, it is straightforward to compute revised accident doses from an updated listing of target radioactivity inventory.

The groups of spallation products range from gaseous nuclides to nonvolatile solids, to semi-volatile mercury. Although there are hundreds of spallation products, the accident consequences (radiation doses to persons) are dominated by a small handful of radionuclides. Gd-148 is foremost of these, with Hg-203, Hg-197, and Hg-194 following closely. Although the element gadolinium is a nonvolatile solid, its radionuclide Gd-148 dominates accident consequences because it is a long-lived alpha emitter (half-life ~74 years) with a large dose conversion coefficient for dose commitment by inhalation of postulated accident releases.

Recent calculations of long-term target operation after 60 years show that the Gd-148 activity reaches a level more than twice that of earlier predictions for 40 years of operation [2-3]. The 60-year life for PPU was derived as follows: operations under current limitations at 1.0 GeV energy beginning in 2005 and extending to 2025, followed by 40 years at 2 MW/1.3 GeV after completion of PPU modifications beginning in 2025. Much of the increase is due to the longer 60-year timeframe now involved, versus the previous 40-year period in relation to the 74-year half-life of Gd-148. The higher-energy protons associated with PPU and other factors affect the spallation product yields, as well. Based on the current calculation [2-3], the increase in the other risks dominating radionuclides is not as great. For example, Hg-197 (2.67-day half-life) is higher by 9% but Hg-203 (46.6-day half-life) decreases by 10%. Hg-194 is predicted to increase by 56% at the end of 60 years because of its relatively long 520-year half-life.

The higher PPU end-of-facility-life radionuclide inventory will result in increases to the bounding unmitigated doses for hypothetical unmitigated accidents, with increases depending on the type of accident involved. The PHAR [2-1] screened this change as a USI because the top end of the range is numerically significant.

2.2 Evaluation

This section provides updated post-PPU, end-of-facility-life bounding accident doses and evaluates their impact on the SNS first target safety basis by considering whether the increased consequences would require one or more additional levels of safety-credited mitigation and whether the mitigated risk remains insignificant. The SNS criteria for selection of credited levels of control (LOCs) are discussed in Section 4.2.2.4 of the *FSAD-NF* [2-2]. The criteria require either one or two LOCs to protect on-site workers and off-site members of the public. An LOC is a credited safety feature (or set of features that work together) that would prevent/arrest the accident or sufficiently mitigate its consequences to prevent excessive radiological exposure.

In the following discussions, it is assumed that accident consequences are not prevented or mitigated by credited LOCs or by noncredited features (e.g., ventilation exhaust filtration). Table 2.1 summarizes calculations [2-4] that show how the increase in spallation product inventory is reflected in increased bounding off-site radiological consequences for various accidents, with increases between about 6% and 60% to radiological consequences, depending on the accident involved. Toxicological consequences are not discussed because they do not change (i.e., the mass of mercury released does not increase). Furthermore, the radiological exposures shown in Table 2.1 apply to the most affected off-site individuals close to the reservation boundary (see Section 4.4 of the *FSAD-NF* [2-2] for more information and discussion of accident analysis calculations). The right two columns of Table 2.1 show the post-PPU impact on the unmitigated, as-constructed off-site radiological consequences. As discussed in Section 4.4.2.10 of the *FSAD-NF*, these calculations assume that all active and administrative controls fail and thus bound the credible postulated off-site consequences. As shown in Table 2.1, the post-PPU unmitigated, as-constructed off-site consequences are still well below 1 rem.

Table 2.2 shows the number of LOCs currently required for each defined accident, and how this number would be expected to change after PPU. As indicated in the table, the higher post-PPU end-of-facility-life accident consequences do not require additional levels of credited control for any accident. All the accidents currently require at least one credited level of control because of the conservative assumption that workers inside the target building might receive significant exposure to mercury made airborne by the accidents, combined with assumed failure of normal confinement and ventilation features. Accidents having excessive radiological consequence to workers outside the target building require either one or two LOCs depending on the frequency category of the accident. As seen in the table, the accidents in the unlikely and extremely unlikely frequency categories, involving significant sources of energy such as earthquake or fire, are already required to have two independent LOCs, either of which could successfully prevent or mitigate excessive consequences to workers outside the building, or members of the public outside the reservation. Since more than two LOCs are not required for any accident by the US Department of Energy (DOE)-approved SNS policy, the increases seen in the bounding consequences of these accidents do not require additional LOCs. Accidents in the anticipated category, which currently require only one LOC, are shown in Table 2.2 and do not require additional credited control. The anticipated event that comes closest to the threshold of needing another LOC is loss of heat sink (e.g., an extended loss of water-cooling of the mercury loop). The PPU end-of-life spallation product inventory increases the consequence for the loss heat sink accident by a factor of 1.56, whereas an increase factor of 2.3 would have been required to necessitate an additional independent, credited LOC.

Regarding the increases attributed to PPU for the unmitigated end-of-facility-life accident radiological consequences, the following question could be raised: is any increase in radiological consequences acceptable? The answer is that the credited LOCs ensure that there would be no significant radiological consequences of any SNS accident. Since the spallation product inventory increases associated with PPU do not require additional credited LOCs, and since no actual increases in radiological consequences of accidents are proposed or foreseen, the greater unmitigated consequences associated with the PPU project are acceptable.

The remaining potential impact of increased spallation product inventory needing consideration here is whether the associated increased decay heat of the post-PPU target would require credited control to ensure adequate cooling of the target mercury after the proton beam has been cut off. Recent calculations [2-6] show that the end-of-life decay heat will be about 40% higher after PPU operations. The previous (pre-PPU) design calculations [2-5] demonstrate the inherently passive decay heat dissipation characteristic of the SNS mercury target system, which combines a massive amount of mercury with decay heat levels on the order of 1 kW. The routinely preferred method of post-beam cooling is to use forced-water cooling to prevent or minimize a temperature increase of the target mercury. Passive heat removal is of interest, for example, in prolonged loss of off-site power scenarios that could occur after a severe seismic event. The previous calculations [2-5] were modified to address whether passive decay heat dissipation is still effective. It was found [2-4] that, even in the event of the loss of all water cooling of mercury and the target shroud, and the loss of the core vessel helium atmosphere and its replacement with air, the mercury would remain well below its boiling point and thus would not be able to generate a significant airborne source term. It was concluded that post-PPU operations will have passive heat dissipation capabilities and therefore not need a credited control to ensure adequate decay heat removal from the target after cutoff of the proton beam.

2.3 Conclusions

The PPU-proposed 1.3 GeV particle energy causes increased unmitigated accident consequences due to increased spallation product inventory at end-of-facility life, but assurance of safety is not compromised because

- elements of the DOE-approved SNS policy for selection of credited controls that could require additional credited LOCs (prevention and/or mitigation) are not exceeded, and
- the existing credited controls prevent or mitigate accidents so that they have no significant radiological consequences.

Table 2.1. Bounding offsite radiological consequences for postulated accidents (pre-PPU values from the *FSAD-NF*, Table 4.4.2.10-1 [2-2].

	Totally unmitigated accident (input for design) rad dose, end-of-facility life		**As-constructed facility[a] rad dose, end-of-facility life**	
Hazard Event (HE designation)	**Pre-→post-PPU (rem)**	**% increase**	**Pre-→post-PPU (rem)**	**% increase**
Target service bay fire (TS1-3, TS1-6)	1.4→1.75	25	0.066→0.080	21
Medium fire, spreads into the target service bay from anywhere in target building (TS1-2)	1.4→1.75	25	0/0	
Medium fire charcoal filter room (TS1-2)	0.035→0.037	6	0.0017→0.0018	6
Full facility fire (BG1-1)	2.1→2.5	19	0.081→0.1	23
Hydrogen explosion without follow-on fire (CM2-1b)	1.4→1.7	21	0/0	
Hydrogen explosion with follow-on fire (CM2-1a)[b]	≤3.9→≤5.6	44	0/0	
Loss of confinement (service bay) (TS3-7, TS3-10)	0.026→0.032	23	0.026→0.032	23
Loss of confinement (core vessel – helium inerted) (TS3-4, TS3-6, TS3-8, TS3-11)	0.034→0.04	18	0.034→0.04	18
Loss of confinement (core vessel – vacuum operation)	0.12→0.135	13	0.12→0.135	13
Partial loss of mercury flow (TS3-22, TS3-23, TS3-24, TS3-25)	0.3→0.45	50	0.3→0.45	50
Loss of mercury flow (TS3-22)	0.07→0.1	43	0.07→0.1	43
Loss of heat sink (TS3-13, TS3-14, TS3-15, TS3-16)	0.52→0.81	56	0.52→0.81	56
Load drop, service bay (TS3-18)	0.033→0.042	27	0.033→0.042	27
Load drop, high bay onto service bay (HB3-3)	0.093→0.14	51	0.093→0.14	51
Crane load drop (high bay crane) onto core vessel (no explosion) (HB3-7)	0.1→0.16	60	0.034→0.04	18
Crane load drop (high bay crane) with hydrogen explosion (HB2-2)[b]	Bounded by BG7-1			
External load crane drop (BG6-11)	1.3→2.1	62	0.43→0.7	63
Natural phenomena (seismic) including H_2 explosion and follow-on fire (BG7-1)	3.9→5.6	44	0.11→0.14	27
Natural phenomena (seismic) event including follow-on fire (no H_2 explosion) (BG7-2)[b]	Bounded by BG7-1			
Natural phenomena (seismic) including follow-on H_2 explosion (no fire) (BG7-3)[b]	Bounded by BG7-1			

[a] The as-constructed analyses consider passive robust structures and design features but take no credit for active controls or administrative controls.
[b] Consequences conservatively assumed to be bounded by Accident 17, Natural Phenomena (Seismic) Including H_2 Explosion and Follow-On Fire (BG7-1).

Table 2.2. Effect of post-PPU increased end-of-facility-life spallation product inventory on the required levels of credited control for SNS accidents.

Accident event (HE designation)	Frequency category[a]	Current number of credited LOCs	Increase due to PPU (factor)[b]	Increase to require added LOC (factor)
Target service bay fire (TS1-3, TS1-6)	Unlikely	2	1.25	N/A—2 LOCs already required
Medium fire, spreads into the target service bay from anywhere in target building (TS1-2)	Unlikely	2	1.25	N/A—2 LOCs already required
Medium fire charcoal filter room (TS1-2)	Unlikely	1	1.06	29
Full facility fire (BG1-1)	Extremely Unlikely	2	1.19	N/A—2 LOCs already required
Hydrogen explosion without follow-on fire (CM2-1b)	Unlikely	2	1.21	N/A—2 LOCs already required
Hydrogen explosion with follow-on fire (CM2-1a)[a]	Unlikely	2	1.44	N/A—2 already required
Loss of confinement (service bay) (TS3-7, TS3-10)	Anticipated	1	1.23	47
Loss of confinement (core vessel – helium inerted) (TS3-4, TS3-6, TS3-8, TS3-11)	Anticipated	1	1.18	37
Loss of confinement (core vessel – vacuum operation)	Anticipated	1	1.13	10
Partial loss of mercury flow (TS3-22, TS3-23, TS3-24, TS3-25)	Anticipated	1	1.5	4
Complete loss of mercury flow (TS3-22)	Anticipated	1	1.43	17
Loss of heat sink (TS3-13, TS3-14, TS3-15, TS3-16)	Anticipated	1	1.56	2.3
Crane load drop, service bay (TS3-18)	Anticipated	1	1.27	37
Crane load drop, high bay onto service bay (HB3-3)	Anticipated	1	1.51	13
Crane load drop (high bay crane) onto core vessel (no explosion) (HB3-7)	Unlikely	1	1.6	12
Crane load drop (high bay crane) with hydrogen explosion (HB2-2)[a]	Extremely Unlikely	2	1.44	N/A—2 already required
External load crane drop (BG6-11)	Unlikely	2	1.62	N/A—2 already required
Natural phenomena (seismic) including H_2 explosion and follow-on fire (BG7-1)	Unlikely	2	1.44	N/A—2 already required
Natural phenomena (seismic) event including follow-on fire (no H_2 explosion) (BG7-2)[a]	Unlikely	2	1.44	N/A—2 already required
Natural phenomena (seismic) including follow-on H_2 explosion (no fire) (BG7-3)[a]	Unlikely	2	1.44	N/A—2 already required

[a] Frequency categories: Anticipated frequency > 10^{-2}/y; Unlikely: 10^{-4}/y < frequency ≤ 10^{-2}/y; Extremely Unlikely: 10^{-6}/y< frequency ≤ 10^{-4}/y

[b] Increase due to PPU: Calculated as the ratio of end-of-facility-life consequence to current base case

2.4 References

2-1 R. M. Harrington and S. M. Trotter, *Preliminary Hazard Analysis in Support of the Proton Power Upgrade Project*, PPU-P01-ES0001-R00, May 2017.

2-2 *Spallation Neutron Source Final Safety Assessment Document For Neutron Facilities,* 102030102-ES0016-R03, September 2011.

2-3 I. I. Popova, *Radionuclide Inventory for Mercury in the SNS Target Loop for PPU Conditions at 2 MW*, 10610200-DA0077-R00, September 2016.

2-4 R. M. Harrington, *Effect of PPU Increased End-of-life Spallation Product Inventory on Radiological Consequences of Hypothetical SNS Accidents*, PPUP-103-ES0002-R00, September 2018.

2-5 M. W. Wendel, *Thermal-Hydraulic Analysis of the SNS Mercury Target*, 106010101-DA-0005-R01, January 2006.

2-6 I. I. Popova, *Decay Heat in Target Vessel Nose for PPU Conditions 1.3 GeV Proton Energy and 2.0 MW Power*, 106100200-CA0015-R00, July 2018.

3. Safety Evaluation of Effects of Increased Beam Particle Energy from 1.0 GeV to 1.3 GeV—Effect on Core Vessel Component Heat Distribution

The PHAR declares that the 1.3 GeV proton energy is a potential USI based on the following reasoning:

> The target module and surrounding components within the core vessel are designed to remove the heat deposited by the 2 MW/1.0 GeV proton beam. The PPU 2 MW/1.3 GeV sustained beam operating level does not increase the total heat load on cooling systems for components within the core vessel, but the higher energy 1.3 GeV protons will have a more forward peaked distribution of heat deposition. There is thought to be sufficient margin in cooling system capacities to keep the various components within desired temperature limitations but this will be examined in detail during the PPU project. One specific concern is the neutron beam windows that are part of the safety credited barrier confining mercury within the core vessel in the event of postulated mercury leakage inside the core vessel. The neutron beam windows in the forward (proton beam) direction would presumably be most affected. The neutron beam windows in the core vessel inserts are constructed of aluminum 6061-T6 which could lose its T6 temper (and thus strength) if operated for long periods of time above the 130°C design temperature (ASME Section VIII service temperature limit in this case). ***Since the change in heat deposition distribution has the potential to affect the performance of a safety credited feature, it is a USI.***

The core vessel inserts are rectangular cylinders that provide a pathway for neutrons to flow from the moderator area out to the neutron instruments. Each insert projects into the core vessel to within about 1 m of a moderator. The sides are stainless steel and the ends, the “beam windows,” are aluminum. The stainless steel sides are water-cooled (~1.5 gpm flow to each insert). The neutron beam windows are cooled by contact with the helium atmosphere (inside and outside), and by being attached at the periphery to the stainless steel. The inserts and neutron beam windows have the safety-credited mission of containing mercury vapor in the event of a mercury spill inside the core vessel. The aluminum 6061-T6 beam windows have a service temperature limit of 130°C in order to prevent loss of their T6 temper. The cooling water channels of the stainless steel inserts have a 100°C temperature limit to ensure that no boiling occurs.

Figure 3.1 shows a core vessel insert with beam window at the end. The inserts are arrayed radially around the target as shown on Figure 3.2. The inserts for beamlines 9, 10, and 11 are most affected by the more forward peaked nuclear heating with the 1.3 GeV proton beam (note: beamline 8 is not installed yet and thus has no insert). In order to verify that the inserts, including beam windows, remain adequately cooled with the higher proton energy, a detailed study was completed that investigated not only temperatures but also stress levels [3-1]. The study determined that the windows are well below the 130°C service temperature limit for 6061-T6 aluminum and that the insert stainless steel cooling channels are well below the 100°C no-boiling temperature limit. In conclusion, the safety-credited performance of the inserts including neutron beam windows is not adversely affected.

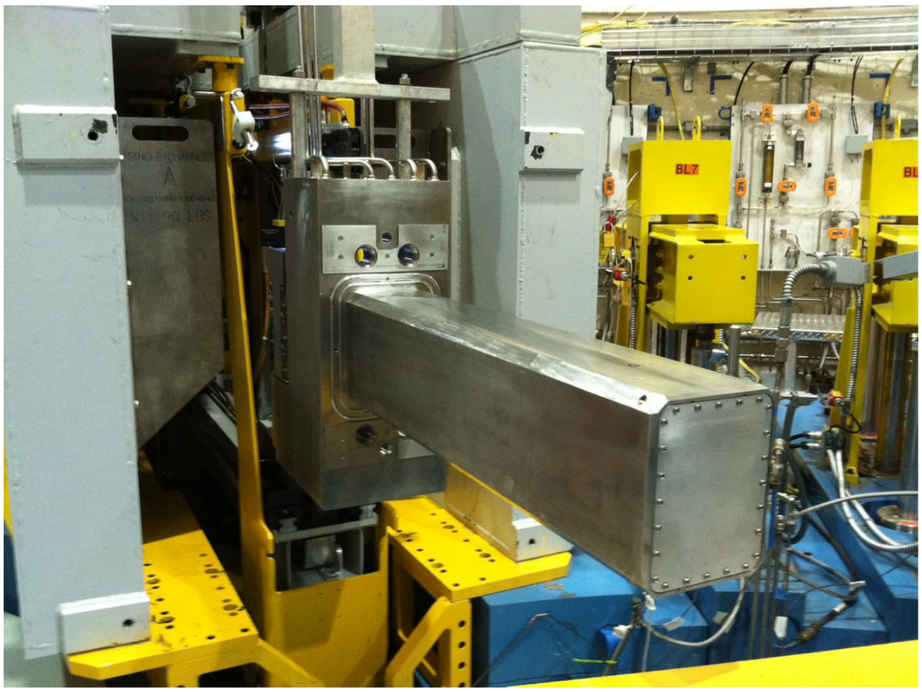

Figure 3.1. The core vessel insert for the Corelli beamline (BL-9) during installation (from [3-1]).

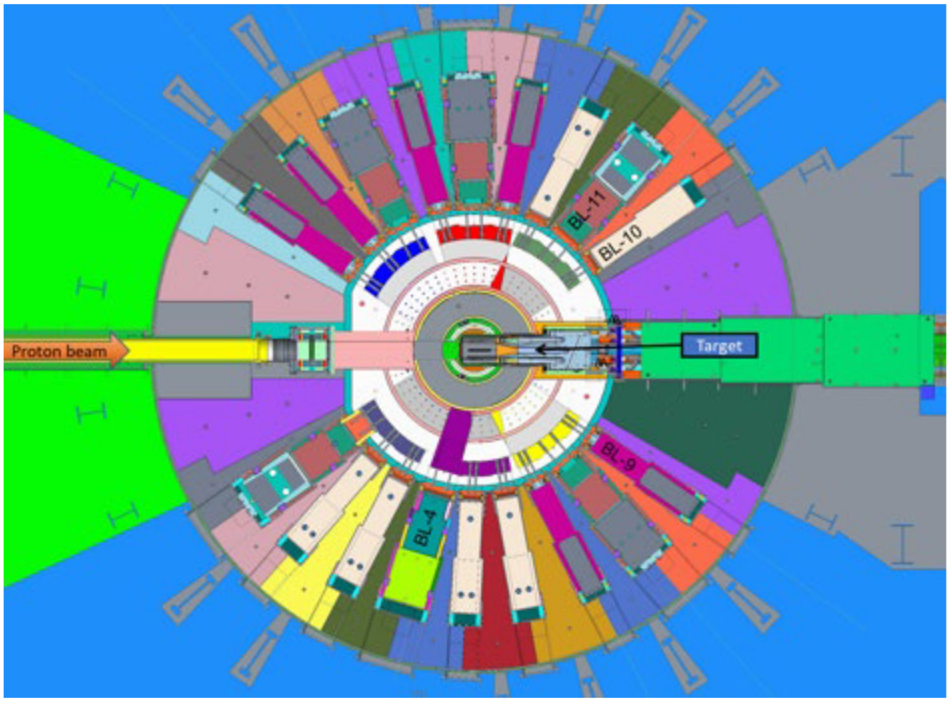

Figure 3.2. Section view inside target monolith illustrating locations of neutron beamlines 4, 9, 10, and 11. The core vessel inserts are located inboard of the beamline figure labels (from [3-1]).

3.1 References

3-1 Oscar Martinez, *Core Vessel Insert Thermal Structural Analysis with PPU Beam Operation*, PPUP-507-DA0001-R00, August 2019.

4. Safety Evaluation of Increasing the Maximum Sustained Beam to the Ring Injection Dump from 150 kW to 200 kW

During the CD-1 phase, post-PPU operations were thought to potentially necessitate discarding a greater proportion of the beam to the ring injection dump. As explained in the PHAR [4-1], this concern was labeled as a USI—although it does not invoke any of the USI determination criteria—because the existing 150 kW limit is incorporated into the SNS Accelerator Safety Envelope, so a higher limit would have to be approved by the DOE.

In preparation for CD-2/3, an investigation of the basis for the existing power limit of 150 kW for the Ring Injection Dump (RID) led to revisiting the thermal analysis of the RID and surrounding concrete with updated models. This ensures that the basis for the power limit is consistent across beam current and energy combinations and uses the as-built configuration with appropriate, conservative assumptions for operations scheduling. This updated analysis indicates that a 150 kW power limit will continue to be appropriate for operations at 1.3 GeV and 2 MW. Although this analysis has been completed, final documentation of the results is still pending completion under the document numbers listed as [4-2] and [4-3].

The analysis identified the potential for localized temperatures in the structural concrete surrounding the RID to exceed the American Concrete Institute (ACI) 349-13 [4-4] surface temperature limits for normal operations. However, provision in the code allows for increasing the allowable temperature based upon demonstration that the tested concrete strength is equal to or greater than 115 percent of the specified 28-day compressive design strength. Mix design and test data documentation from the construction of the RID facility meet this provision, allowing the temperature limitation to be increased. With the implementation of this provision, structural concrete temperatures all remain within the applicable limits during the conservatively estimated operations that were simulated in the analysis.

Concerns surrounding the power limit for the RID have been fully addressed. No further action is required.

4.1 References

4-1 R. M. Harrington and S. M. Trotter, *Preliminary Hazard Analysis in Support of the Proton Power Upgrade Project*, PPU-P01-ES0001-R00, May 2017.

4-2 106090200-TR0001-R00

4-3 106090200-TR0004-R00

4-4 American Concrete Institute 349-13, Code Requirements for Nuclear Safety-Related Concrete Structures.

5. Safety Evaluation for 20 L/min of Helium Injection inside Target Module

5.1 Introduction

This section provides an updated evaluation of the safety of the gas injection modifications proposed as part of the PPU project. Gas injection was identified in the PPU PHAR [5-1], submitted as part of the CD-1 review, as a potential USI:

> Operating the mercury loop with continuous helium injection ***does introduce the possibility of a new type of accident*** associated with postulated uncontrolled helium void accumulation at one or more points within the loop to the extent that the mercury in the pump tank could overflow into the mercury off-gas treatment system. Part of the MOTS is located in basement rooms that are not designed (e.g., with regard to shielding) to accommodate safely the presence of liquid mercury. ***Therefore, by this criterion, the proposed helium injection should be a USI.***

In combination with identifying gas injection as a potential USI, the PHAR made the following commitment:

> A safety evaluation of the PPU proposed modifications to accomplish long target life by helium injection will be written at an appropriate stage of the PPU project as needed to allow time for review and approval prior to operation. The safety evaluation for the PPU helium injection modifications will be informed by, and build on, not only the safety evaluation of the pilot program, but also by operational data and experience gained under the pilot program.

The focus of the current report is to summarize and evaluate accidents or hazard events that have the potential to cause excessive radiological exposure to workers and to determine whether new safety-credited administrative controls or engineered controls are required per the *Spallation Neutron Source Policy for Selection of Safety Related Credited Controls* [5-3]. Section 5.2 addresses the need for gas injection and experience to date with the Gas Injection Initial Implementation (GI3) program. Section 5.3 provides summary information of the modifications planned to achieve the PPU gas injection objectives, and Section

5.4 is the safety evaluation. Section 5.5 discusses functional testing under PPU gas injection conditions, both before and after the initial beam on target, and Section 5.6 summarizes major conclusions.

Radiation shielding and environmental protection are two essential aspects of protecting workers, the public, and the environment that have been incorporated into the PPU gas injection design and planning. They are summarized in the following paragraphs.

Any additional shielding needed for PPU modifications is included as part of the PPU scope, including associated analysis and design. Shielding requirements for existing components of the mercury loop and the mercury off-gas treatment system (MOTS) equipment will be met or exceeded for new components. Shielding for PPU components is designed to limit dose rates of less than 0.25 mrem/hr in areas under access control but with no occupancy restrictions for workers as defined in the *SNS Final Safety Assessment Document for Proton Facilities,* SNS-102030103-ES0018-R00 [5-4], which implements the *SNS Shielding Policy*, SNS-102030000-ES0008-R00, as needed to ensure compliance with 10-CFR-835. Most of the helium gas injection systems are in well-shielded areas, such as the target service bay, and basement utility areas. The mercury overflow tank and the mercury gas/liquid separator (GLS) are both located in the target service bay. Like all other mercury process systems (e.g., mercury piping and mercury pump tank), the new components to be added to the mercury loop are to be shielded by 4.5 in. of steel shielding or are housed under the existing mercury loop shielding. The shielding of the new components in the MOTS rooms in the basement systems was defined so as to not require that the MOTS rooms be brought under access control of the personnel protection system (PPS) because of the desirability of workers being able to periodically access one or more of the MOTS rooms during beam operation (note: the basement utility vault and shutter drive equipment room are under PPS control and cannot be entered during beam operation. This has proven workable since these rooms can be entered for necessary surveillance and maintenance during times when the proton beam is not running).

Environmental aspects of the proposed post-PPU operations have been analyzed and found to be acceptable [5-5]. Specifically, the PPU modifications will enable operation at 2 MW beam on target with 1.3 GeV proton energy, as compared with the current maximum achieved steady beam power of 1.4 MW with 1.0 GeV proton energy. The helium injection system will be designed to provide a higher flow, up to a total of 20 SLPM, as compared with the ~1.2 SLPM achieved through the GI3 gas injection. Consistent with this design objective, PPU scope includes upgrades to the MOTS treatment stages (see Section 5.3.4) to handle the additional flow in the off-gas stream and thus ensure best available treatment of effluent and negligible impact on the environment. The radiological emissions report [5-5] makes the following conclusion regarding post-PPU operation:

> …operation under the proposed PPU conditions has been evaluated with the conclusion that increased emissions will result in no significant increases of doses to members of the public or the environment. In addition, the modifications associated with the Proton Power Upgrade at the SNS will not require a permit to construct or pre-notification to the EPA or TDEC since the modification will result in an EDE (actual emissions) of 0.0845 mrem/yr. This is below the permit to construct threshold of 0.1 mrem/yr as established in the Title V Operating Permit 571359 Condition E3-5 and the approved ORR Compliance Plan. However, the U.S. EPA and TDEC will be notified of increased radiological emissions as the result of the PPU Project via the Rad NESHAPS Annual Report.

5.2 The Need for PPU Gas Injection and Experience with Gas Injection to Date

5.2.1 Need

The mercury target module is challenged by two mechanisms driven by the high pulsed beam power that limit its useful life: high-cycle fatigue and cavitation damage erosion. PPU will achieve reliable target operation requiring no more than four annual target exchanges through a combination of evolutionary target module design improvements and the proposed implementation of high-flow target helium gas injection. Fewer annual target exchanges are ultimately desired.

5.2.2 Experience

To operate reliably at high power, SNS started injecting gas into a target in October 2017. The initial goal of the GI3 program was to inject up to 1.2 standard liters per min (SLPM) using a ring of about 60 orifices (each ~10 microns diameter) in the target mercury bulk flow inlet region of the target module. Although lower flow rates were used during operation due to orifice clogging, a strong reduction in cavitation erosion was observed. Strain rate measurements suggest that higher gas injection rates would lead to better pressure wave mitigation. Since cavitation erosion is worse with increasing beam power, larger gas injection rate will be needed to operate at 2 MW. For PPU, a different bubbler design, a "swirl bubbler" (Figure 5.1) will be used that will deliver gas more reliably than the current inlet orifice bubbler (IOB) design. The swirl bubbler generates the desired admixture of small bubbles and mercury entering the target by shearing the gas into small bubbles as the mercury flows through. Compared with the IOB orifices, the gas injection nozzles can be fewer and larger (1.6 mm or more) and thus have less chance of clogging.

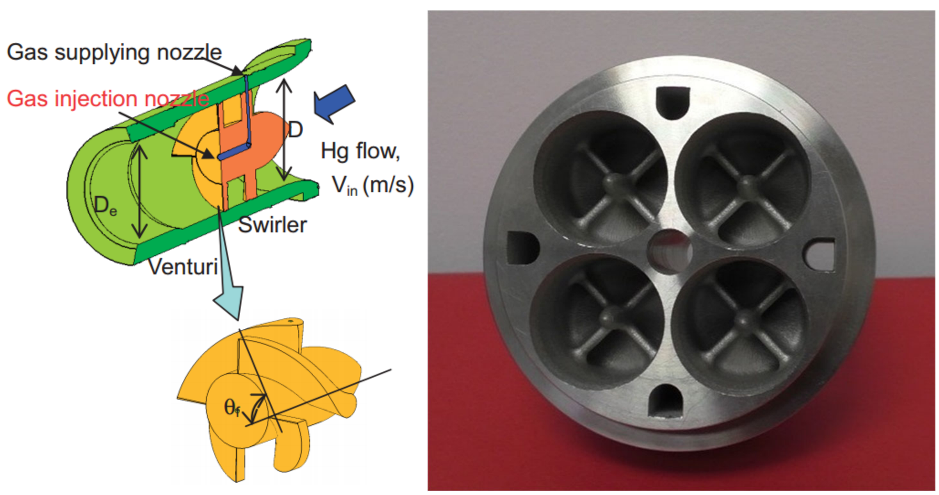

Figure 5.1. Schematic of the cross section of a swirl bubbler (left) and picture of a 4-unit swirl bubbler tested at the thermal hydraulic test facility.

One of the main safety concerns identified during hazard analysis before GI3 gas injection operations was the accumulation of helium voids in the mercury loop that could lead to the pump tank overflowing, especially during a pump trip where the gas will expand as it flows upwards. During operation with gas, it was found that void accumulation increases as gas injection flow rate increases (see steady state data on Table 5.1 and transient data on Figure 5.2). Considering only the data points at 350 rpm given in the table, gas accumulation is found to be almost linear with gas injection rate (see Figure 5.3). Extrapolating it to 20 SLPM, a gas accumulation volume of 56.2 L is found, which could be accommodated by the current (i.e., pre-PPU) mercury loop during steady operation; but a pump trip event would trigger the rise of gas toward the pump tank with accompanying expansion of the bubbles as they rise, creating a level swell that could overfill the pump tank and send liquid mercury toward the MOTS.

Table 5.1. Amount of volume of mercury displaced with gas injection. The mercury flow rate is estimated with the differential pressure (DP) measurements.

Date	Target	Gas injection rate (SLPM)	DP (psid)	Pump speed (rpm)	Q_{Hg} (gpm)	Volume displaced (L)
10/25/2017	T18	0.45	35.3	350	250	1.7
12/20/2017	T18	0.25	22.3	280	203	3.8
05/14/2018	T19	0.40–0.57	34.8	350	255	2.2
08/20/2018	T20	0.50	34.4	350	258	1.7
01/10/2019	T21	0.8	30.0	350	293	2.7
06/20/2019	T22	1.0	30.2	350	290	3.2

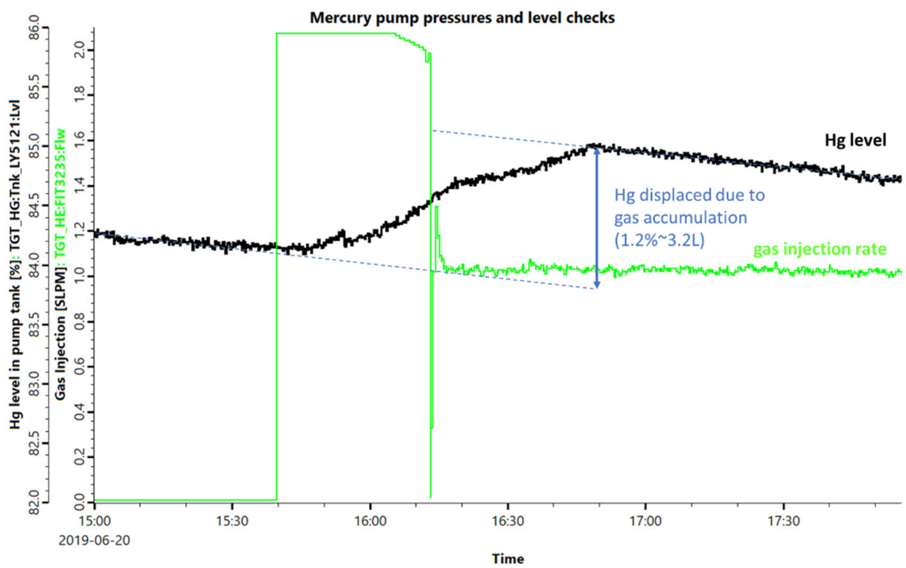

Figure 5.2. Mercury level response after adjustments of gas injection rate.

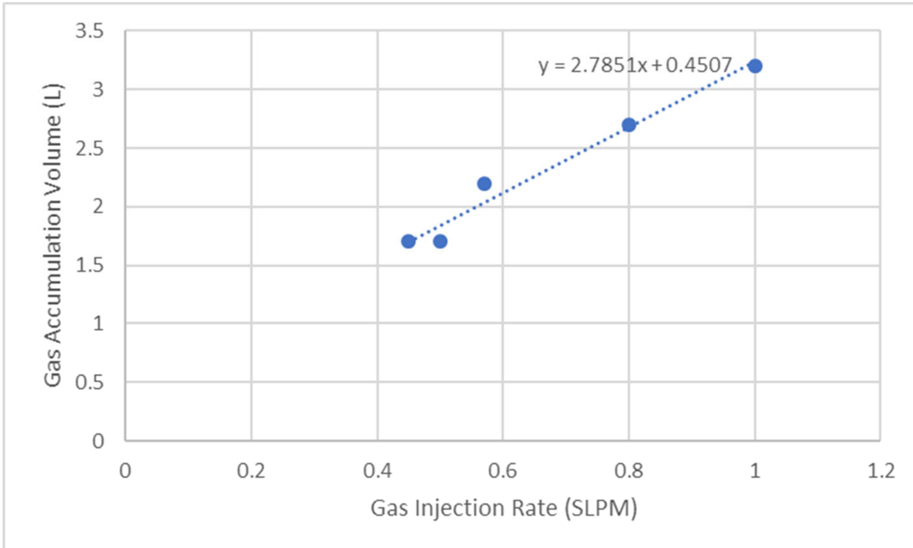

Figure 5.3. Gas accumulation versus gas injection at 350 rpm.

Another concern during GI3 safety reviews was that gas injection may affect the credited differential pressure (DP) reading at the pump. There are reasons that it should not, but the performance of the sensor needed to be verified during functional testing and operations. A procedure was written such that it can check that the DP sensors are not affected as the gas injection flow rate is increased. To date, gas injection has not impacted the DP reading at the pump.

The planning and design of PPU modifications for up to 20 SLPM of helium injection flow has benefited from the GI3 experience and will continue to benefit in the same way as the SNS plans over the next year to increase the gas injection capability to approximately 5 SLPM prior to shutdown of the target for installation and testing of the PPU gas injection equipment.

5.3 Identification and Description of PPU Changes to Implement Gas Injection

To address higher-pressure wave and cavitation activities at 2 MW, helium will be injected at two locations in the target module: (a) in the bulk mercury flow immediately upstream from the target nose with swirl bubblers (up to 10 SLPM); and (b) at the target's nose to generate a gas wall to protect the surface where the most cavitation damages has been observed (up to 10 SLPM). An upgraded target gas supply system will provide up to 10 SLPM of gas flow to each of the two locations (bubbler and gas wall) for a maximum flow of 20 SLPM. Two modes of gas injection will be provided. The primary mode will be to recirculate the gas through the MOTS back to the target; a secondary mode is once-through helium gas injection, which will vent through the MOTS to the hot off-gas (HOG) system (and then the SNS 80 ft ventilation discharge stack). More detailed descriptions are available in the preliminary design report (PDR) for PPU.

Following the successful conclusion of the CD-1 conceptual design stage, designers of the PPU helium injection modifications have followed closely, or been directly involved in, the modifications necessary to achieve target module gas injection for the GI3 project, applying lessons learned wherever possible. Design criteria based on the GI3 experience have informed the post-CD-1 preliminary design stage. A key objective has been to solve gas injection safety challenges in the most passive, inherently safe, and easily demonstrable way. For example,

- To prevent the helium injection gas supply system from providing a potential pathway for mercury to escape from the target service bay, the decision was made to route all the helium gas supply lines and the line that will be used for recycle mode from well above the target module, penetrating the wall of the target service bay at a point ~17 ft above the target. Thus, gravity drainage through a failed helium injection line is not a potential way for mercury to escape from the shielded confinement of the service bay. Furthermore, given the 13.6 kg/l density of liquid mercury, no source of gas pressure inside the service bay would be high enough to drive the escape of liquid mercury from the service bay by backflow into helium supply lines.

- To minimize the possibility of spillage of mercury even inside the service bay (not necessarily a safety problem), each of the two helium supply lines inside the target module carriage include a check valve and a filter, each of which would be capable of stopping excessive leakage through a broken helium supply line.

- The possibility of mercury surges is recognized by providing a surge volume in a new overflow tank that can hold the worst plausible mercury transient volume surge, with margin. The use of the overflow tank mitigates the helium voiding accident without the use of active controls. The GI3 project did not employ an overflow tank because it would have caused a much longer lead time item, which was not consistent with a pilot project to gain experience with gas injection and measure its value in preventing target module damage.

Injection of helium gas in either once-through or recycle mode will employ automatic controls to provide in-depth defense against accidental transients by monitoring variables such as mercury pump tank and surge tank levels and helium flows, and by automatically initiating interlocks designed to shut down the helium flow (or trip the recycle compressors as the case may be) in the event that the system gets outside of desired operational conditions.

5.3.1 Upgrades to the Gas Injection Helium Supply Systems

Figure 5.4 provides a basic gas injection flow diagram that represents the flow path and interconnections between the once-through and the recirculating gas injection supply systems, the target mercury process system, and the MOTS.

The locations in the target building that house the systems are designated on the diagram:

- The target service bay in the lower left of the diagram houses the mercury process system, which includes the mercury pump, the target and carriage, and the mercury storage tank.

- The basement gold amalgamation (GA) room and MOTS room house most of the MOTS components.

- The basement primary confinement exhaust (PCE) system charcoal adsorber room will house the new gas recirculation system hardware.

- The recirculation gas lines to the bubbler and wall will pass through the basement utility vault (BUV) and be routed up the south vertical chase through the shutter drive equipment room and cooling water delay tank cavity to the cooling water GLS tank cavity.

- Gas panels for the once-through gas supplies are in the target high bay above the cooling water GLS tank cavity.

On the diagram, black highlights represent equipment installed prior to the GI3 project.

The GI3 project provided the hardware highlighted in blue and credited the existing items shown in red. The gas supply hardware provided for the once-through GI3 gas supply to the target bubblers was installed in a new gas panel 9, located in the target high bay. A spare target shroud water line that is routed from the target water loop GLS tank cavity into and down the front face of the service bay was repurposed for use as a conduit for the helium supply lines for gas injection. The location of the once-through GI3 helium gas supply panel 9 in the target high bay provides an inherently safe configuration, since no source of pressure inside the service bay is sufficient to push mercury to the elevation of the penetration (~17 ft above the mercury pump discharge) during an unmitigated off-normal event. Therefore, both once-through and recirculating gas supplies for gas injection to the bubblers and the gas wall will take this route into the service bay.

Planned operational improvements to the gas injection process pre-PPU are represented as brown highlights in the diagram for gas panel 9, in the mercury loop target gas supply, and in MOTS.

The gas injection upgrades to be provided by PPU are highlighted in magenta and include the following:

- A new gas panel 10 will be located adjacent to GI3 gas panel 9 in the high bay and will supply up to 10 SLPM once-through helium to the target gas wall via the same pathway used for the bubbler helium supply from gas panel 9.

- New, ¼ in. bubbler and wall gas supply lines will be pulled into the repurposed conduit (the plan is to install this tubing in CY 2020).

- A recirculating gas injection system will supply helium to both the target bubbler and the target wall using separate compressors trains, each with an installed spare compressor.

- Modifications to the mercury process system (Section 3.3) will include running a new gas line from the conduit supply hose to the back of the carriage and adding a target jumper for the wall supply.

- Modifications to the MOTS will be made (Section 5.3.4).

The PCE system charcoal adsorber room was selected as the preferred location for the PPU gas recirculation system hardware after an evaluation of five target basement locations for factors including space availability, accessibility, maintainability, background dose rates during operation and maintenance, impacts of leaks, and availability of utilities.

A total of four (two operating and two spare) helium compressors will be installed. The compressors will share suction tie-ins, with two different suction tie-ins provided for operational flexibility (one upstream of the copper oxide bed in the MOTS room and one downstream of the cryogenic charcoal bed in the MOTS room). Each compressor will have its own tubing to supply helium to the target devices via the manifold in the cooling water GLS cavity (either the bubblers or the wall, depending on the compressor train being used). After passing through the target, the combined bubbler and wall helium flows pass into the new overflow tank and into the MOTS via the existing loop seal arrangement, and then through the GA room and back to the compressor suction tie-in being used.

Both positive displacement compressors will be reciprocating diaphragm-type devices. The compressors can develop discharge pressures up to 16 bar gauge when inlet pressure is near atmospheric and can also function with inlet pressure down to about 100 mBar while providing a lower discharge pressure. The actual operating discharge pressure of each compressor will be determined by the helium flow rate in conjunction with the resistance to flow developed by the process flow path selected. Nominal line size on each gas supply will be ½ in. tube.

Each of the two operating compressors has the physical capacity to supply about twice the 10 SLPM maximum flow at pressures of more than 100 psig. Instrumentation and controls will be used to modulate the operating helium flow and the pressure generated. For that purpose, each compressor will have a mass flow sensor/transmitter installed in its discharge path to measure the helium flow rate for use as an input to a proportional/integral/derivative (PID) flow controller. The PID flow controller will be configured in the Experimental Physics and Industrial Control System (EPICS) and will use either compressor speed or a suction-side control valve to regulate compressor flow rate. A combination of compressor speed control and suction throttling will be required to limit the flow to ≤10 SLPM in each train. The device not selected to meet the flow rate setpoint (either compressor speed or suction pressure control valve position) will be set at a fixed value by the operator by placing the device in manual and inputting the desired parameter (either percent of full speed for the compressor speed or percent open for the suction pressure control valve). Compressor suction pressure, discharge pressure, and discharge temperature will be monitored by the control system with inline instrumentation. Flow rate, pressure, and dewpoint of the gas travelling to the MOTS room equipment will be monitored, as well as the mercury pump tank pressure. Interlocks similar to those developed for once-through gas injection will be implemented for the recirculating system including those to

- prevent too much total helium flow to the target, either from once-through or recirculated helium flow,
- prevent simultaneous flow to the target from both the once-through and the recirculated helium flow, and
- shut off helium gas flow in case of high mercury levels in the mercury tank or overflow tank, as well as pump tank burst disk activation.

A bypass backpressure regulator and a pressure relief valve will help to manage flow when the active controls do not limit pump output to the actual gas demand and will provide protection against system overpressure.

A preliminary off-normal/hazard and operability (HAZOP) analysis was performed on the preliminary flowsheet represented in Figure 5.4 to inform flowsheet development, identify ways to improve reliability, and guide hazard analysis.

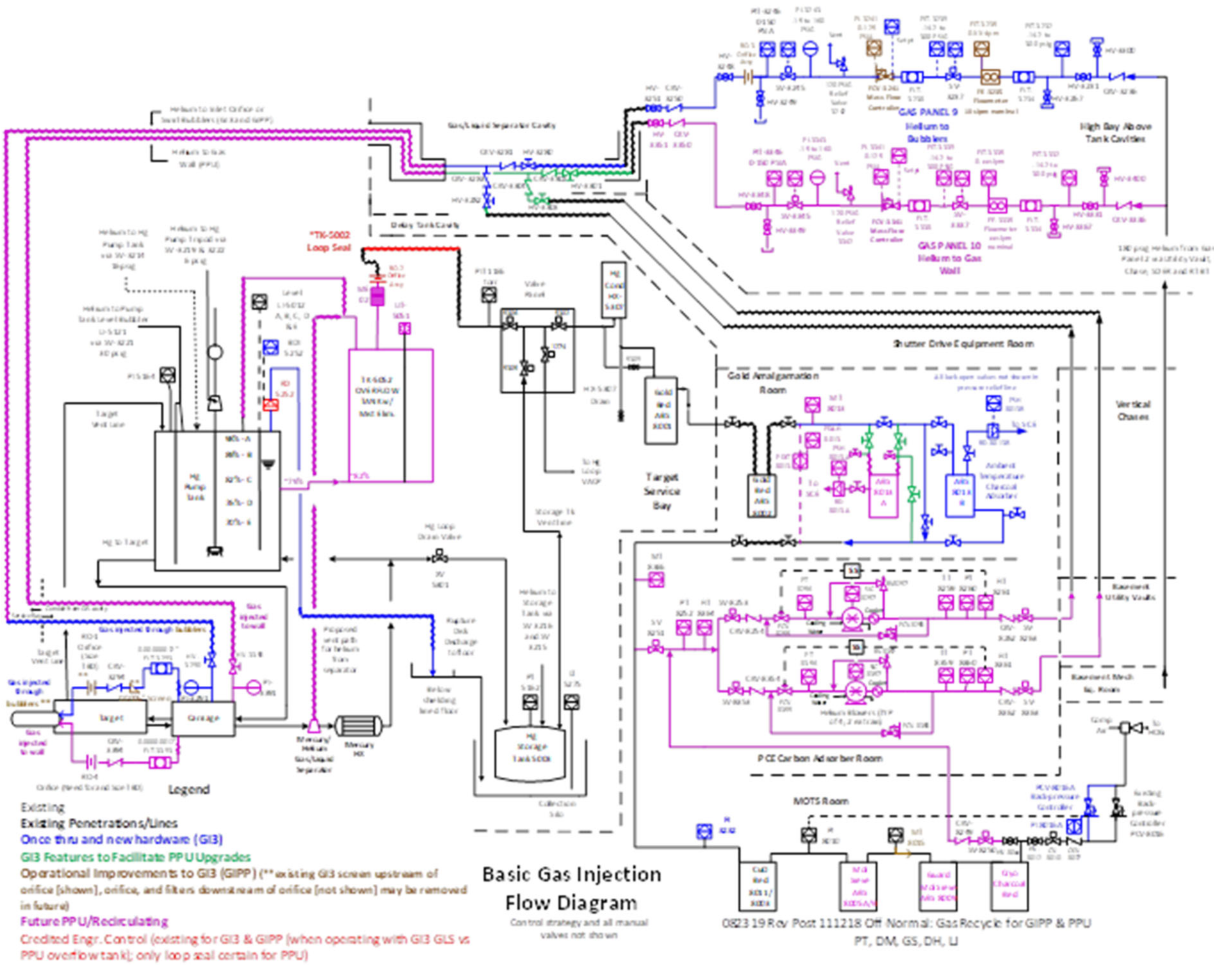

Figure 5.4. Schematic layout of mercury loop, helium gas supply, and MOTS.

5.3.2 Bubblers and Gas Wall Injector and Helium Supply Connections

The main flow of mercury through the mercury target module divides with approximately half flowing on each side to the module "nose," flowing across the inner wall of the nose, and combining and flowing away from the target nose in the center channel (see Figure 5.5). The PPU modifications will protect the stainless steel inner wall of the target nose by injecting helium into the flowing mercury in two different ways: bubbler injection and gas wall injection. An assembly of four swirl bubblers (e.g., see Figure 5.1) is provided in each target inlet flow path, roughly 30 cm upstream from the target nose. The swirl bubblers create a large number of small bubbles without the need for many, very small, orifices. The gas wall injection point is ~2 cm immediately upstream from the target nose inner wall and its purpose is to create larger pockets of gas by injecting up to 10 SLPM of helium in the immediate vicinity of the center portion of the inner wall that receives the greatest impact from the proton beam. For each injection path, gas inside the target module flows through firmly mounted tubes and machined passages to the final injection points.

Two helium supply lines are provided outside the target module, one for the bubblers and one for the gas wall. Remote disconnects allow retraction of the target carriage for target module replacement. The arrangement of the helium supply lines will be highly similar to the current gas injection system (i.e., with an additional line for the gas wall). Gas passes into the service bay through penetrations are routed to the target carriage and then supplied to the target module. Gas will be supplied from the high bay above the service bay, which provides protection against any mercury being driven out of the service bay. Each gas supply line is expected to have filters that have been shown to reduce backflow of mercury in the event of upstream breakage of a gas line. The lines are also expected to include flow control elements such as check valves and orifices. The filters and flow control elements are located outside the target module but inside the target module shielding.

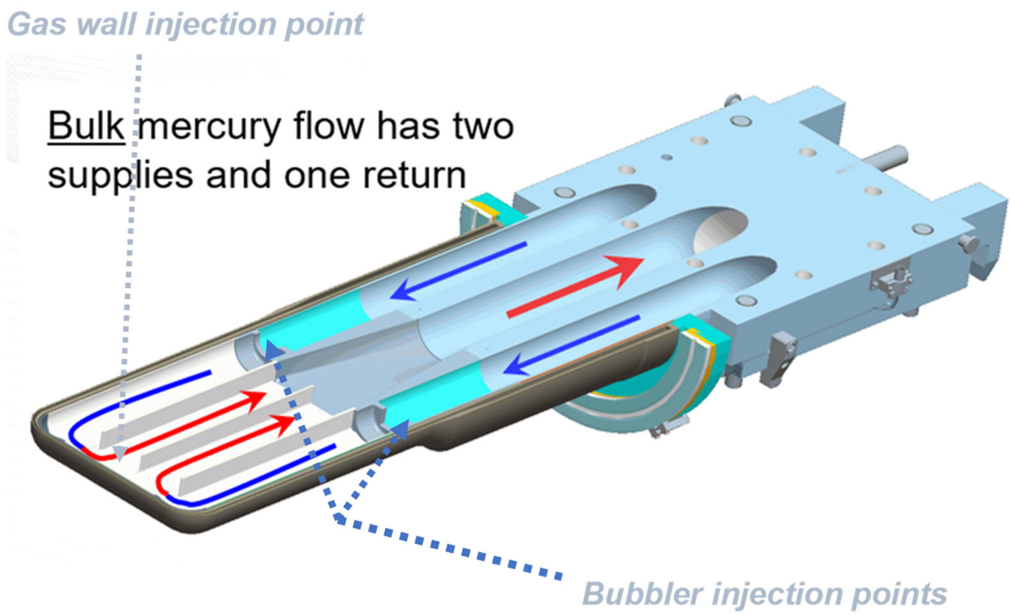

Figure 5.5. Schematic depiction of target gas bubbler and gas wall injection points.

5.3.3 Mercury Loop Modifications and Additions

PPU modifications to the mercury loop include an overflow tank (Figure 5.6), a helium-mercury GLS (Figure 5.7), and stainless steel tubing to connect the helium supply for the "gas wall" helium injection to the target module (tubing for the bubblers was installed as part of the GI3 pilot program). The overflow tank is sized to hold the maximum plausible transient surge of displaced mercury from the mercury loop (see safety analysis of Section 5.4.2). The mercury overflow tank is typically close to being largely void so it can, if needed, hold the displaced mercury from the pump tank and allow it to return to the mercury pump tank when the level in the pump tank recedes. The preliminary design for the overflow tank is a passive tank design that is located on top of the existing shielding, adjacent to the mercury pump, and connected to the pump overflow nozzle with a 1½ in. metal flex hose. The overflow tank functions as additional head space for the mercury pump tank. Excess mercury can flow freely between the pump tank and the overflow tank. If the mercury volume in the pump tank exceeds the "82% bubbler level," it flows into the overflow tank and rises to whatever level the volume requires. As the volume recedes in the pump tank, the mercury flows back into the pump tank from the overflow tank. The tank and associated piping will be shielded with 4.5 in. thick steel shielding consistent with other adjacent parts of the mercury loop. A float-type level instrument will provide a measurement of the mercury level in the overflow tank. The overflow tank is vented to the MOTS through the loop seal flexible metal hose. Additionally, vent hoses from the mercury pump tank and the return line GLS are connected to the top over the overflow tank.

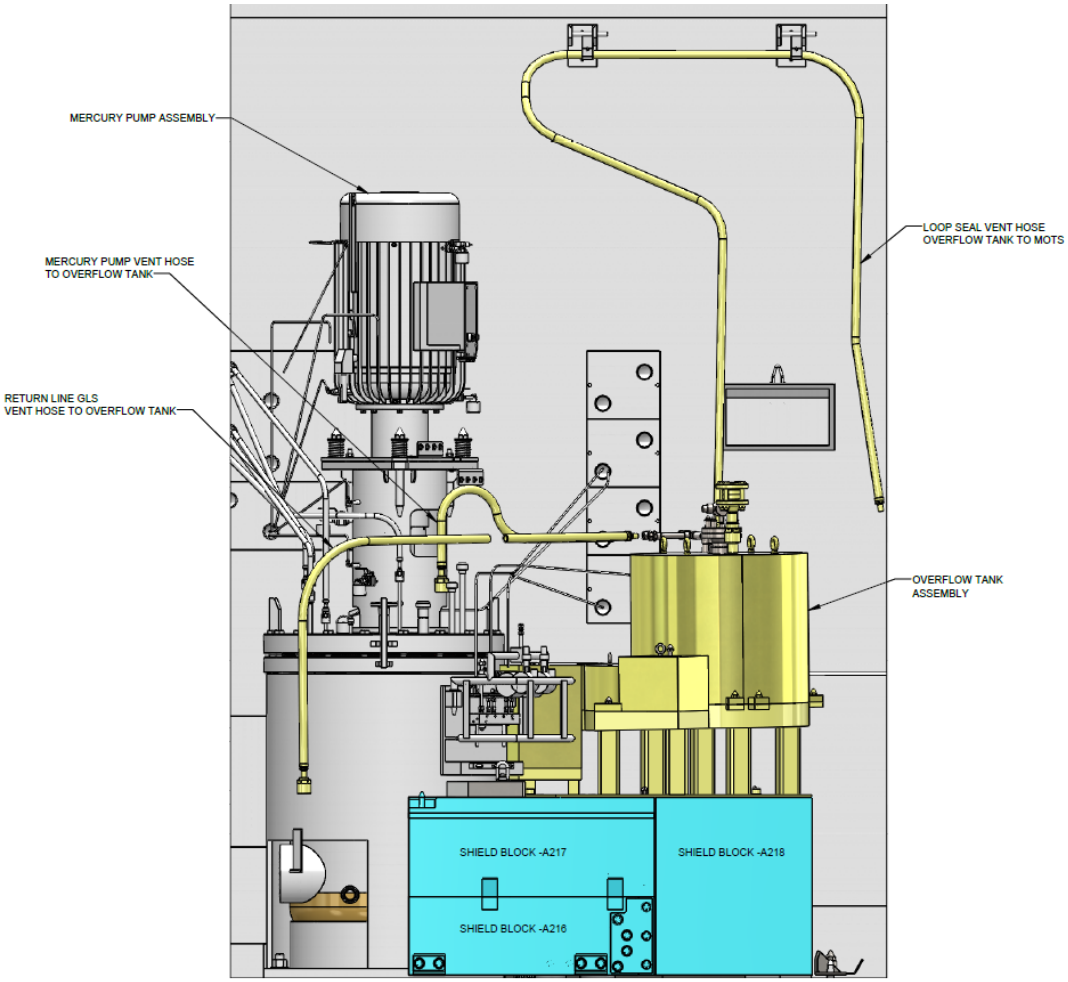

Figure 5.6. Mercury pump overflow tank assembly exterior view (with shielding in place).

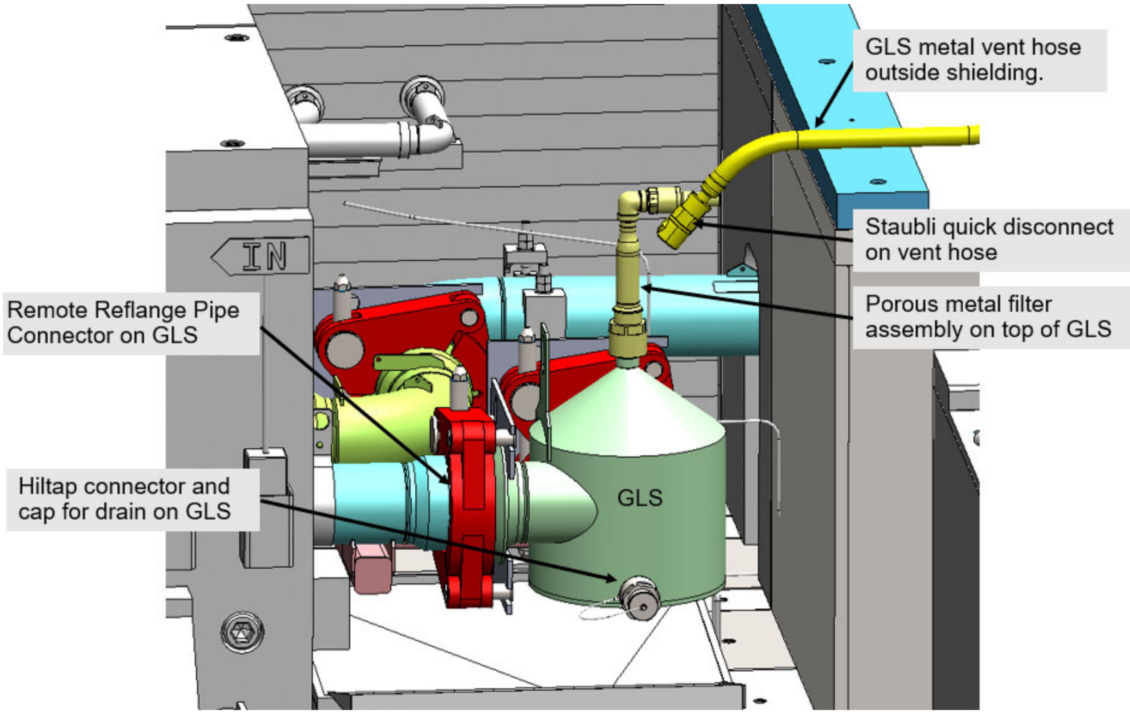

Figure 5.7. Mercury loop gas-liquid separator (GLS, shielding panels removed to allow visibility).

The purpose of the PPU mercury GLS is to remove helium gas from the mercury flowing in the return line before it descends to the heat exchanger. The GLS is designed to be installed in the 6 in. return line piping, inside the shielding at the location where the target carriage piping is disconnected for target change out. The 6 in. return line elbow will be removed from the target carriage, and the GLS will be installed in its place. The PPU GLS will stay with the target carriage during target replacement similar to how the carriage piping is currently disconnected for target replacement. The preliminary design includes a method to vent the helium gas from the top of the GLS to the overflow tank outside of the shielding. The method includes an internal perforated plate arrangement to prevent mercury from flowing with the helium into the vent line. The vent line for the helium from the GLS will be routed through the shielding by designing a new "spacer." The current geometry of the GLS design includes a "hold-up" volume, where approximately 10 L of liquid mercury would reside after the mercury loop is drained for target change-out.

5.3.4 MOTS Changes

The MOTS removes radioactivity and mercury vapor carried by the helium off-gas stream from the mercury loop and discharges the treated helium to the HOG system for filtration and discharge to the SNS 80 ft stack, as described in Section 3.3.9 of the *FSAD-NF* [5-2]. Locations of MOTS components are as indicated on Figure 5.6 and on Figure 5.8. The MOTS has been necessary from the inception of the SNS because small flows of inert gases have always been exhausted from the mercury loop—for example, the helium bubbler level measurement device in the mercury pump tank involves a steady helium flow of ~0.3 SLPM of helium. MOTS was upgraded prior to initiating the current (GI3) helium gas injection capability of up to 2 SLPM (once-through mode only), and further upgrades are included for PPU as needed to handle the 20 SLPM total design injection flow with ensured operational reliability and radioactivity removal effectiveness.

The PPU MOTS scope includes the addition of a second carbon delay bed (ABS-8013A on Fig. 5.8) and related shielding to be installed in the GA room. The first one was installed as part of the GI3 effort. The second delay bed will ensure dose rates to workers and equipment in the MOTS equipment room and nearby areas will be maintained at acceptable levels. It also provides the ability to swap out or regenerate one delay bed canister while maintaining MOTS operation. An additional cryogenic carbon adsorber (CA) assembly will be added to improve the reliability of MOTS. This component removes noble gases and spallation products from the off-gas stream, which reduces emissions. Overpressure protection will be provided by a rupture disk relieving to the PCE system.

The existing molecular sieve beds, which trap moisture to protect the cryogenic CA, will be replaced with larger units to provide the required residence time at 20 SLPM. A total of five molecular sieve bed units, including shielding, will be provided. The configuration will be two trains of two molecular sieve beds each for added reliability. These units will require heaters, temperature indications, and controls for regeneration of the media. The fifth bed will be used to capture the exhaust of the regenerated units and will be replaced periodically. Overpressure protection will be provided by a rupture disk relieving to PCE system.

Evaluations of the entire MOTS maximum flow capacity will be performed prior to post-PPU operation. The pressure profile up to 25 SLPM will be determined through functional testing during non-beam operations to establish a margin above the maximum envisioned steady 20 SLPM flow rate. MOTS set points, indications, and controls will be modified to incorporate operation of the gas injection recirculating gas compressors (described in Section 5.3.1). Connections and interfaces to the equipment will be accommodated in a modified MOTS configuration.

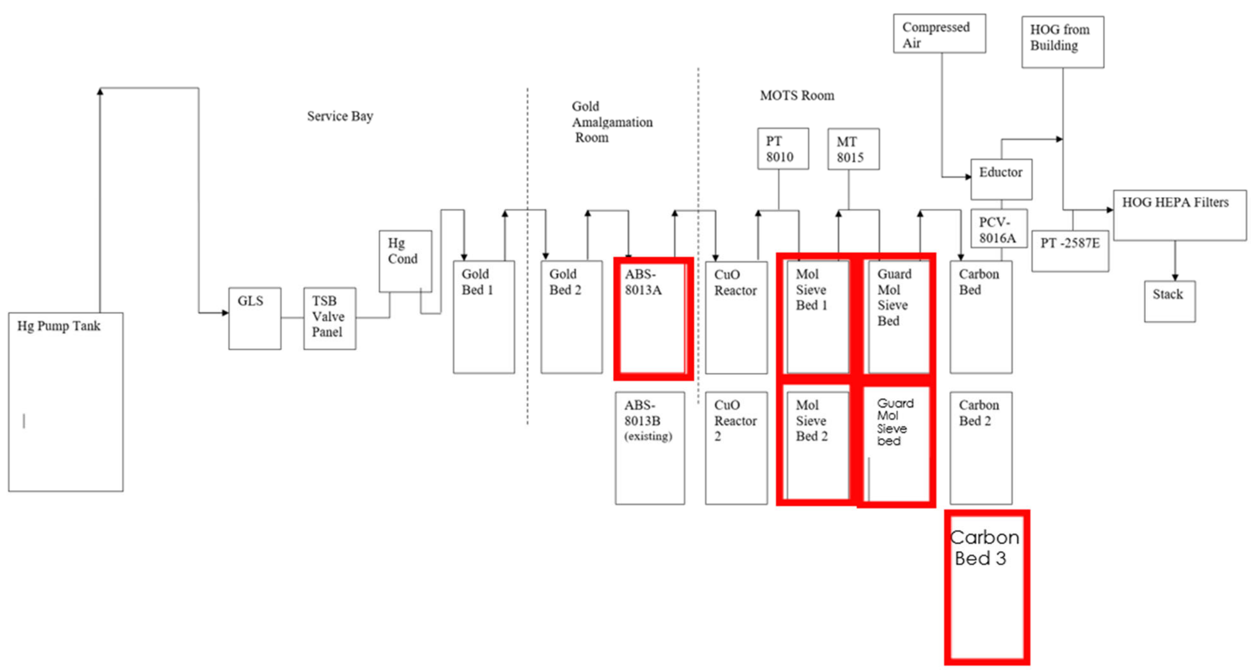

Figure 5.8. Simplified MOTS diagram showing location of components (PPU proposed modifications shown in red).

5.4 Safety Basis Evaluation of PPU Gas Injection Modifications

This section provides a comprehensive hazard analysis of the PPU modifications for gas injection (Section 5.4.1) and summarizes the results of analytical studies done to support the hazard analysis (Section 5.4.2). The evaluations in this section consider not only unique hazards of the gas injection modifications but also how the modifications could affect the existing hazard analysis as documented in the *FSAD-NF* [5-2].

The hazard analysis is organized around the most involved three systems:

- the helium system that can supply either fresh helium for once-through gas injection or purified helium from the MOTS for gas injection in the recycle mode,
- the MOTS, and
- the target system (i.e., mercury target, mercury loop, and associated components).

Prior to 2017, the helium supply system was essentially "screened out" of the hazard analysis because it supplied only a very low flow of fresh helium for the bubbler-type level sensor on the mercury pump tank and for the mercury pump shaft seal. It was considered to have no significant accident potential and so no events in the *FSAD-NF* [5-2] address gas supply system accidents. The SNS performed a hazard analysis of once-through gas injection in 2017 [5-6] as needed to obtain approval for once-through helium injection under the GI3 program. The hazard analysis presented here generally follows the approach in the GI3 hazard analysis and adds additional events as needed (e.g., for gas injection in the recycle mode).

5.4.1 Hazard Analysis

5.4.1.1 Hazard Analysis for Modifications to Helium Injection System

There are three different ways that failures of, or damage to the helium supply system could impact the mercury loop:

- Controller malfunction whereby either the bubbler or gas wall train supplies more helium flow than desired—see Tables 5.2 and 5.3 (note: malfunctions resulting in zero injection gas flow are bounded by helium supply line breaks)
- Helium supply line break outside the target service bay—see Tables 5.4 and 5.5
- Helium supply line break inside the target service bay—see Table 5.6

Each of these failures or damages is essentially a new event in SNS hazard analysis. As documented in the hazard analysis tables, the multiplicity and diversity of relevant design features of the helium supply system and its interface with the mercury loop serve to prevent worker consequences that might otherwise be significant enough to require mitigation by safety-related credited controls.

Table 5.2. Event GW-A_OT, excess gas injection flow during once-through injection mode.

Event Description: Gas injection controller provides more injection flow than desired, either gas wall or bubbler.

Assumptions and Initial Conditions:	**Causes**:	**Initiating Event Frequency**:
1. 2 MW beam on target continues until cutoff by operators, the PPS (the existing, safety-credited PPS), or MPS (the existing, non-safety-credited Machine Protection System). 2. The gas injection system is under automatic control in once-through mode. 3. The gas injection system can be run in either once-through or recycle modes, but not both at the same time 4. Up to 20 SLPM helium being injected into mercury flowing in the target module: ≤10 SLPM to the bubblers and ≤10 SLPM to the gas wall.	Either a random failure of the automatic controller (e.g., the gas flow sensor) or physical damage to the controller or control valve.	Anticipated

Unmitigated Impact on Systems:	**Unmitigated Consequences**	
	Radiological	**Chemical**
The increased injection gas flow could result in increased voiding inside the mercury loop and higher gas flow to MOTS. The higher gas flow to MOTS could result in slightly increased external radiation levels in the basement rooms.	Public: Negligible WG1: Negligible WG2: Negligible	Public: N/A WG1: N/A WG2: N/A

Safety Function: The mercury overflow tank has sufficient volume to accommodate plausible transient or steady-state surges due to voiding in the mercury loop caused by gas injection.

Method of Detection:	
Flows and pressures in the gas injection system and level sensors in the mercury pump tank and overflow tank allow detection of abnormal operation of the gas supply system.	
Preventive Features – Attributes:	**Credited**:
Design: Maximum flow physically possible is limited by the use of various flow control devices (e.g., orifices) and fittings. Multiple interlocks would stop the gas flow in the event of an upset such as controller failure including both interlocks that are based on gas injection system parameters such as gas flows or pressures in the supply train as well as interlocks based on level in the mercury overflow tank or pump tank. **Administrative**:. N/A	None.

Table 5.2. Event GW-A_OT (continued).

Mitigative Features – Attributes:	**Credited:**
Design: Assuming failure of active preventive features, the mercury overflow tank (that will be attached to the existing mercury pump tank) has sufficient volume to hold the mercury surge during the maximum plausible gas bubble shedding event that could accompany trip of the mercury pump. This prevents significant safety consequences due to transient or steady-state voiding. **Administrative**: N/A.	None

Planned Analysis, Assumption Validations, and Risks/Opportunities:	**Mitigated Consequences:**		
Functional testing will be conducted before operation as needed to verify system characteristics, performance of control elements ad interlocks and the void retention of the mercury loop as a function of gas injection rate.	**Radiological** Public: Negligible WG1: Negligible WG2: Negligible	**Chemical** Public: N/A WG1: N/A WG2: N/A	**Mitigated Frequency** <Extremely Unlikely (EU)
Notes:			

Table 5.3. Event GW-A_Re, excess gas injection flow during recycle injection mode.

Event Description: Recycle injection gas injection controller provides more injection flow than desired, either gas wall or bubbler.

Assumptions and Initial Conditions:	**Causes**:	**Initiating Event Frequency**:
1. 2 MW beam on target continues until cutoff by operators, PPS, or MPS. 2. Gas injection system under automatic control in recycle mode. 3. The gas injection system can be run in either once-through or recycle modes, and not both at the same time (e.g., gas wall in recycle and bubblers in once-through) 4. Up to 20 SLPM helium being injected into mercury flowing in the target module: ≤10 SLPM to the bubblers and ≤10 SLPM to the gas wall.	Either a random failure of the automatic controller—e.g., the gas flow sensor—or physical damage to the controller or control valve or recycle compressor.	Anticipated

Unmitigated Impact on Systems:	**Unmitigated Consequences**	
	Radiological	**Chemical**
The finite volume of helium in the MOTS and mercury loop make this event self limiting after the initial injection flow increase transient and subsequent decrease in helium pressures. The initially increased injection gas flow could result in increased voiding in the mercury loop and a temporary increase in gas flow to MOTS. The higher gas flow to MOTS could result in slightly increased radiation levels in the basement rooms.	Public: Negligible WG1: Negligible WG2: Negligible	Public: N/A WG1: N/A WG2: N/A

Safety Function: The mercury overflow tank has sufficient volume to accommodate plausible transient or steady-state surges in the pump tank.

Method of Detection:	
Flows and pressure sensors in the recycle mode gas injection system and the mercury pump tank and overflow tank level sensors allow detection of abnormal operation of the gas injection system.	
Preventive Features – Attributes:	**Credited**:
Design: Maximum flow physically possible is limited by the use of various flow control devices (orifices) and fittings. Two levels of interlocks would stop the gas flow in the event of an upset such as controller failure—the first level would be in the gas injection system itself based on gas flow or pressure in the supply train and the second level, based on indicated mercury level in the mercury pump tank and/or overflow tank. **Administrative**: N/A.	None.

<table>
<tr><th colspan="4">Table 5.3. Event GW-A_Re (continued).</th></tr>
<tr><td colspan="3">Mitigative Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="3">Design: The mercury overflow tank (that will be attached to the existing mercury pump tank) has sufficient volume to hold the mercury surge during the maximum plausible gas bubble shedding event that could accompany trip of the mercury pump. This prevents significant safety consequences due to transient or steady-state voiding.

Administrative: N/A</td><td>None.</td></tr>
<tr><td rowspan="2">Planned Analysis, Assumption Validations, and Risks/Opportunities:
Functional testing will be conducted before operation as needed to verify system characteristics, performance of control elements and interlocks and the void retention of the mercury loop as a function of gas injection rate.</td><td colspan="3">Mitigated Consequences:</td></tr>
<tr><td>Radiological
Public: Negligible
WG1: Negligible
WG2: Negligible</td><td>Chemical
Public: N/A
WG1: N/A
WG2: N/A</td><td>Mitigated Frequency
<EU</td></tr>
<tr><td colspan="3">Notes:</td><td></td></tr>
</table>

<table>
<tr><th colspan="5">Table 5.4. Event GW-B_OT, gas injection line breaks outside the target service bay during once-through injection.</th></tr>
<tr><td colspan="5">Event Description: Break in the helium supply tubing outside the target service bay, in either the cavity that holds the target cooling water GLS tanks, or further upstream at Gas Panel 9 or the adjacent Gas Panel 10, both of which are located in the high bay above the tank cavities.</td></tr>
<tr><td colspan="2">Assumptions and Initial Conditions:
1. 2 MW beam on target continues until cutoff by operators, PPS, or MPS.
2. Gas injection system under automatic control in once-through mode.
3. The gas injection system can be run in either once-through or recycle modes, and not both at the same time (e.g., gas wall in recycle and bubblers in once-through)
4. Up to 20 SLPM helium being injected into mercury flowing in the target module: ≤10 SLPM to the bubblers and ≤10 SLPM to the gas wall.</td><td colspan="2">Causes: Line breakage could be caused by physical damage, corrosion, or maintenance error.</td><td>Initiating Event Frequency:
Anticipated</td></tr>
<tr><td colspan="2" rowspan="2">Unmitigated Impact on Systems:
The supply of helium to either the bubblers or the gas wall would cease, allowing target module wear and corrosion cycles to intensify (an operational problem if not corrected). Mercury pressure in the module would attempt to force mercury backwards out the affected helium supply tube. Trace levels of contamination could diffuse backward through the supply line to the break.</td><td colspan="3">Unmitigated Consequences</td></tr>
<tr><td>Radiological
Public: Negligible
WG1: Negligible
WG2: Negligible</td><td colspan="2">Chemical
Public: N/A
WG1: N/A
WG2: N/A</td></tr>
<tr><td colspan="5">Safety Function: Gas supply tubing enters service bay at high elevation to prevent mercury escaping from the service bay by backflow through a broken supply tube.</td></tr>
<tr><td colspan="4">Method of Detection:</td><td></td></tr>
<tr><td colspan="4">Depending on location of the break, this could be difficult to detect. Indicated flow in the MOTS would decrease, which would be a clear sign.</td><td></td></tr>
<tr><td colspan="4">Preventive Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="4">Design: The supply tubing enters the service bay from the cooling water GLS tank cavity at an elevation of 205 in. above the pump tank; there is no source of pressure inside the service bay that could force liquid mercury to escape through the broken line.

Administrative: Exercise of care in conducting operations or maintenance in the High Bay area near the Gas Panels 9 and 10 (components in GLS tank cavity not accessible during operations). Post installation leak checking.</td><td></td></tr>
</table>

Table 5.4. GW-B_OT (continued).			
Mitigative Features – Attributes:			**Credited:**
Design: The final connection of each helium supply line to the target module includes a filter and a check valve, either of which would prevent significant amounts of mercury from flowing backwards into the unpressurized line. **Administrative**:			None.
Planned Analysis, Assumption Validations, and Risks/Opportunities:	**Mitigated Consequences:**		
	Radiological Public: Negligible WG1: Negligible WG2: Negligible	**Chemical** Public: N/A WG1: N/A WG2: N/A	**Mitigated Frequency** <EU
Notes:			

Table 5.5. Event GW-B_Re, gas injection line breaks outside the target service bay during recycle mode of injection.

Event Description: A break in helium supply tubing outside the target service bay in the cavity that holds the target cooling water GLS tanks. Breaks in recycle mode injection line further upstream are covered as a variety of MOTS line break event (see Tables 5.7 and 5.9).

Assumptions and Initial Conditions	Causes	Initiating Event Frequency
Assumptions and Initial Conditions: 1. 2 MW beam on target continues until cutoff by operators, PPS, or MPS. 2. Gas injection system under automatic control in recycle mode. 3. The gas injection system can be run in either once-through or recycle modes, and not both at the same time (e.g., gas wall in recycle and bubblers in once-through) 4. Up to 20 SLPM helium being injected into mercury flowing in the target module: ≤10 SLPM to the bubblers and ≤10 SLPM to the gas wall.	**Causes**: Line breakage could be caused by physical damage, corrosion, or maintenance error.	**Initiating Event Frequency**: Anticipated

Unmitigated Impact on Systems	Unmitigated Consequences: Radiological	Unmitigated Consequences: Chemical
Unmitigated Impact on Systems: The supply of helium to either the bubblers or the gas wall would cease, allowing target module wear and corrosion cycles to intensify (an operational problem if not corrected). Mercury pressure in the module would attempt to force mercury backwards out the broken helium supply tube. Trace levels of contamination could diffuse backward through the supply line to the break. The finite volume of helium in the MOTS and mercury loop limits the amount of recycle helium that can leak during this event. After the line break, the leakage flow would decrease and then cease after subsequent decrease in helium pressures. Flow of recycle helium out the break would release noble gas spallation products and increase radiation level in the cooling water GLS cavity but it is heavily shielded, not accessible during operation, and swept by the PCE system.	**Radiological** Public: Negligible WG1: Negligible WG2: Negligible	**Chemical** Public: N/A WG1: N/A WG2: N/A

Safety Function: Gas recycle tubing enters service bay at high elevation to prevent mercury escaping by backflow through a broken supply tube.

Method of Detection:

Sensors in the recycle supply train will detect low gas pressure. Indicated flow in the MOTS would decrease, which would be a clear sign. SNS main ventilation discharge stack monitor may alarm due to release of noble gases to the gas/water separator cavity (swept by PCE which discharges to the stack).

Preventive Features – Attributes	Credited
Design: The supply tubing enters the service bay from the GLS tank cavity at an elevation of 205 in. above the pump tank; there is no source of pressure inside the service bay that could force liquid mercury to escape through the broken line. **Administrative**: Post installation leak checking.	None.

Table 5.5. Event GW-B_Re (continued).			
Mitigative Features – Attributes:			**Credited:**
Design: Each of the two recycle gas supply trains has interlocks that would trip the compressors on abnormal indications (e.g., recycle helium pressure). **Administrative**: Alarm response procedures.			None.
Planned Analysis, Assumption Validations, and Risks/Opportunities:	**Mitigated Consequences:**		
	Radiological Public: Negligible WG1: Negligible WG2: Negligible	**Chemical** Public: N/A WG1: N/A WG2: N/A	**Mitigated Frequency** <EU
Notes:			

<table>
<tr><td colspan="4">Table 5.6. Event GW-C, gas injection line breaks inside the target service bay.</td></tr>
<tr><td colspan="4">Event Description: Break in the helium supply tubing inside the target service bay, upstream of the target module, in either the once-through or recycle injection mode. Breaks in the gas exhaust line inside the target service bay downstream of the mercury loop are covered under the existing hazard event GW3-2; the results summarized in the FSAD-NF [5-2] for GW3-2 apply to post-PPU operations.</td></tr>
<tr><td>Assumptions and Initial Conditions:
1. 2 MW beam on target continues until cutoff by operators, PPS, or MPS.
2. Gas injection system under automatic control in either mode.
3. Up to 20 SLPM helium being injected into mercury flowing in the target module: ≤10 SLPM to the bubblers and ≤10 SLPM to the gas wall.</td><td colspan="2">Causes: Line breakage could be caused by physical damage, corrosion, or maintenance error.</td><td>Initiating Event Frequency: Anticipated</td></tr>
<tr><td rowspan="2">Unmitigated Impact on Systems:

The supply of helium to either the bubblers or the gas wall would cease, allowing target module wear and corrosion cycles to intensify (an operational problem if not corrected). Mercury pressure in the module would attempt to force mercury backwards out the affected helium supply tube. Trace levels of contamination could diffuse backward through the supply line to the break. In the recycle mode, this break could result in the recycle compressors operating with a negative inlet pressure which could expose MOTS components in the GA room to subatmospheric pressure. Also, in recycle mode this break in either bubbler or gas wall line would ultimately result in loss of both injection flows when the recycle compressor inlet pressures stabilize at a subatmospheric pressure.</td><td colspan="3">Unmitigated Consequences</td></tr>
<tr><td>Radiological
Public: Negligible
WG1: Negligible
WG2: Negligible</td><td colspan="2">Chemical
Public: N/A
WG1: N/A
WG2: N/A</td></tr>
<tr><td colspan="4">Safety Function: Service bay confinement of spilled mercury is already a credited feature (stainless steel lined floor sloped to promote gravity drainage of spillage to collection basin,—see Section 5.2.9.2 of the FSAD-NF).</td></tr>
<tr><td colspan="3">Method of Detection:</td><td></td></tr>
<tr><td colspan="3">Indicated flow in the MOTS would decrease since these breaks are upstream of the injection point. In recycle mode, helium pressure in the mercury pump tank, overflow tank and MOTS components would decrease to subatmospheric and stack radiation alarms would sound.</td><td></td></tr>
<tr><td colspan="3">Preventive Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="3">Design: Gas injection tubing is wall mounted where practical and, otherwise, routed as far from known transit paths for crane or manipulators as practical.

Administrative: Exercise of care during remote operations inside the service bay when near gas injection tubing. Post installation leak checking.</td><td>Service bay confinement of mercury (existing credited control).</td></tr>
</table>

<table>
<tr><th colspan="4">Table 5.6. Event GW-C (continued).</th></tr>
<tr><td colspan="3">Mitigative Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="3">Design: The final connection of each helium supply line to the target module includes a filter and a check valve, either of which would prevent significant amounts of mercury from flowing backwards into the unpressurized gas injection tubing.

Administrative:</td><td>None.</td></tr>
<tr><td rowspan="2">Planned Analysis, Assumption Validations, and Risks/Opportunities:</td><td colspan="3">Mitigated Consequences:</td></tr>
<tr><td>Radiological
Public: Negligible
WG1: Negligible
WG2: Negligible</td><td>Chemical
Public: N/A
WG1: N/A
WG2: N/A</td><td>Mitigated Frequency
<EU</td></tr>
<tr><td colspan="3">Notes:</td><td></td></tr>
</table>

5.4.1.2 Modifications to the MOTS: Impact on Hazard Analysis

The PPU modifications to MOTS are intended to ensure reliable, efficient operation to remove essentially all radioactivity from the target off-gas stream at the design helium injection flow rates. In the once-through mode of helium injection, the 20 SLPM design injection flow rate requires about 20.3 SLPM of off-gas processing capability including the additional ~0.3 SLPM of helium injected for the bubbler-type mercury pump tank level sensor and the He provided to the mercury pump bearing seals. As described in Section 5.3.4, the MOTS upgrades include:

- a second ambient temperature charcoal delay bed,
- replacement of the existing sieve beds with a configuration of 5 molecular sieve beds, and
- an additional cryogenic charcoal adsorber.

The off-gas stream currently exits the mercury loop from the pump tank and the proposed design switches this to the planned adjacent overflow tank. The off-gas to MOTS consists primarily of the helium injected into the target module as well as smaller flows of (1) helium from the bubbler-type level sensor in the pump tank, (2) helium from the pump seal enclosure assembly, (3) a small flow of nitrogen that leaks in from the N2-pressurized target module knife edge seals, and (4) trace quantities of spallation product hydrogen (including heavy hydrogen and tritium). The temperature of helium flowing from the pump tank into MOTS could be ~60°C or less during operations and can safely be assumed to be saturated in mercury vapor. Taking the helium temperature at 60°C and assuming saturation of the mercury vapor, the transport of mercury vapor can be estimated at about 0.3 g Hg/h or 7.2 g Hg/day. Since the mercury is highly activated, treatment stages are provided in the existing MOTS to retain it in the target service bay by removing it from the off-gas stream. The first MOTS treatment stage, the cryogenic mercury condenser, removes most of the mercury vapor and the first stage GA treatment (in the service bay) removes most of the small amount that is not condensed.

The off-gas line exits the service bay and is routed to the second GA treatment stage in the basement room known as the GA room where remaining traces of mercury vapor are removed. The GA room contains the first ambient temperature charcoal adsorber bed (that was added in preparation for GI3 gas injection) and will also house the second ambient temperature charcoal bed to be added by PPU. The ambient temperature charcoal beds delay Xe and Kr noble gases to allow their decay and therefore reduce downstream radiation levels. The off-gas line leaves the GA room and is routed through the PCE charcoal adsorber room to the MOTS room which contains the final stages of treatment before discharge of the gas to the HOG system: the CuO bed that transforms the small quantities of spallation product hydrogen isotopes to water vapor, the molecular sieves that remove the water from the stream and the cryogenic charcoal adsorber units that essentially prevent any noble gases from being discharged to the HOG system.

The existing hazard analysis addresses the hazard of mercury vapor in the MOTS off-gas stream in Section 4.3.4 of the *FSAD-NF* [5-2]. For postulated breakage of the MOTS line in the target service bay (hazard event GW3-2) the *FSAD-NF* credits several controls with preventing worker exposure to the chemical hazard of mercury vapor: (1) administrative controls preventing worker access to the target service bay, (2) service bay differential pressure monitoring system, and (3) the PCE system charcoal adsorbers (in the *FSAD-NF* see Table A-1, SNS controls Matrix). Other MOTS events are noted in the *FSAD-NF*, basically involving failures of the mercury removal stages, which allows transport of mercury vapor into downstream stages of the MOTS and/or discharge to the environment. Consequences were found not to require credited controls and this conclusion would not change for post-PPU operations. Prototypic testing at Oak Ridge

National Laboratory's thermal hydraulic test facility has shown that the mercury condenser retains its mercury removal efficiency at helium flows up to 20 SLPM.

The hazard associated with the MOTS off-gas stream in the basement include the tritium hazard and the noble gas hazard, dominated by Xe, Kr, and Ar. The tritium hazard is addressed adequately in the *FSAD-NF* [5-2] as discussed in Section 4.3.4 for hazard events GW3-4, GW3-5, GW3-6 and GW3-8 and does not require any credited controls. Tritium is not addressed further is this hazard analysis.

The radiological hazard of noble gases in the MOTS off-gas stream has undergone an evolution that requires that it be addressed at this point. Whereas much of the spallation-born noble gases in past operations decayed while still in the mercury loop, they will in the future be more efficiently transported into the off-gas stream. According to the USI determination published in preparation for installation of the first ambient temperature charcoal adsorber [5-7],

> The Tritium Removal Room in the Target Building basement [Note: in line with current practice, this room is called the "MOTS room" throughout this report] has experienced a slow rise in general area radiation levels since operations at SNS commenced. Levels have now reached a point where the radiation area boundaries of the room are extending into the walkway outside the door and high radiation area postings are required within the Tritium Removal Room. Installation of the ambient temperature carbon adsorber is a step toward reducing radiation levels in the Tritium Removal Room area by delaying radioactive isotopes of noble gases in the heavily shielded Gold Amalgamation Room to allow decay before entering the MOTS components in the Tritium Removal Room.
>
> Operational experience indicates that injecting gas into the mercury loop will increase activity observed in MOTS. This is based on experience with in-leakage (about 7.9E-4 SLPM) of nitrogen gas into the mercury loop from pressurized target module knife edge seal which had detectable effects on the activity level observed in MOTS.… The increase in activity associated with the knife edge seal, above, and anticipated with gas injection is believed to be a result of better mass transfer to the gas phase of noble gases dissolved in the liquid mercury.

As anticipated, the installation of the first ambient temperature charcoal adsorber in the GA room was successful in reducing radiation levels in the MOTS room, including for the period during and after initiation of the GI3 gas injection flows of ~1 SLPM. The shielding provided for the various components (e.g., 6 in. of lead for the ambient temperature charcoal adsorber) helps keep routine operational radiation exposures ALARA. It was decided that the current hazard analysis update should address ways in which the noble gas might escape into the potentially occupied rooms, posing an external radiation hazard. This includes the GA room, the PCE charcoal adsorber room and the MOTS room. Three basic scenarios were considered:

- During either once-through or recycle mode of gas injection, the MOTS off-gas line fails in the GA room upstream of both of the ambient temperature charcoal adsorbers (see Table 5.7, Event GW3-2a).
- During once-through mode of gas injection, the MOTS off-gas line fails downstream of the ambient temperature charcoal adsorbers (see Table 5.8, Event GW3-2b).
- During recycle mode of gas injection, the MOTS off-gas line fails downstream of the ambient temperature charcoal adsorbers (see Table 5.9, Event GW3-2c).

The rationale for the event designations for the above three hazard events—GW3-2a, -2b, or -2c—is as follows: existing *FSAD-NF* event GW3-2 is for a break of the MOTS line inside the target service bay, and the new events summarize hazards for the MOTS line breaks that are outside the service bay. An analytical study was conducted to support the hazard analysis of noble gas release; it is discussed in Section 5.4.2. The conclusion from these events is that a MOTS line break in the GA room, upstream of the ambient temperature CAs, would have the potential to result in worker radiological exposure exceeding the criteria for identification of credited controls [5-3], necessitating a credited control for worker entry to this room. The access controls currently in effect for the GA room, put in place to ensure 10CFR835 compliance, are as follows:

- The GA room is required to be locked, with entry requiring approval of the SNS Radiation Safety Officer.
- Radiological control technician survey of the room is required before worker entry.
- An alarming area radiation sensor is installed in the GA room for information (although its usefulness is limited by the location of the read-out in a different area of the basement).

These controls have worked well since they were begun in 2017. The need to ensure future worker safety could be served by formally designating these controls to constitute a credited administrative control. In association with this process, there is a plan to move the read-out of the GA room radiation sensor to a location in the PCE charcoal adsorber room, where it will be adjacent to the entry door of the GA room and therefore most useful.

The one other accident that could result in an escape of noble gases from the MOTS components, especially the ambient temperature CAs, is fire. However, two existing controls, one credited and one not, ensure worker safety. First, the radiation shielding around these components (e.g., ~6 in. of lead around the ambient temperature charcoal adsorbers) provides some degree of noncredited inherent protection. Second, these rooms have National Fire Protection Association (NFPA) -compliant sprinkler systems that would act to limit the size of potential fires; and the target building combustible material control program limits the accumulation of extraneous flammable materials within the MOTS rooms. The basement fire sprinklers are already identified as credited engineered controls for event TS1-2, medium fire originating outside the target service bay and event BG1-1, facility-wide fire ([5-2], *FSAD-NF*, Table A-1, SNS Controls Matrix).

<table>
<tr><td colspan="6">Table 5.7. Event GW3-2a leak or breach of MOTS in the GA room, upstream of the ambient temperature charcoal adsorbers, applicable to either once-through or recycle mode of helium gas injection.</td></tr>
<tr><td colspan="6">Event Description: Release of target off-gas to GA room.</td></tr>
<tr><td colspan="2">Assumptions and Initial Conditions:
1. 2 MW beam on target continues until cutoff by operators, PPS, or MPS.
2. Upstream Hg condenser and gold adsorber stages remove Hg vapor from off-gas, so release is primarily noble gas spallation products carried out by continuing helium flow (20 L/min from bubblers and gas wall, 0.7 L/min from Hg level sensors).
3. Released MOTS helium (with noble gases) mixes with room air.
4. Bounding dose rate after 1 h of noble gas release into GA room >25 rem/h within 1 h with secondary confinement exhaust (SCE) system “on,” and >50 rem/h if SCE system “off.”
5. The normally running SCE system releases noble gases to the environment through the SNS stack.</td><td colspan="3">Causes:
MOTS piping material defect, corrosion, fatigue failure due to prolonged vibration or thermal cycles, impact from worker activity, incorrect alignment of valves on ABS8013A or 8013B, failed post-maintenance checks/tests, or actuation of AB8013A/B rupture disc due to MOTS line plugging.</td><td>Initiating Event Frequency:
Anticipated</td></tr>
<tr><td colspan="3" rowspan="2">Unmitigated Impact on Systems:
Potential for release of significant quantities of noble gas radionuclides to the environment through the SNS 80 ft stack;
If 100% of MOTS helium flow escapes to GA room, the continuing slight vacuum of the HOG system would draw air into the MOTS, which would then cause eventual ice accumulation in the cryogenic carbon adsorber (CA) stage (in the MOTS room). If operating in recycle mode, air instead of helium could be injected into the mercury loop through the bubblers and gas wall injection points. Ambient temperature charcoal would continue to adsorb noble gases during air operation.</td><td colspan="3">Unmitigated Consequences</td></tr>
<tr><td>Radiological
Public: Negligible
WG1: Moderate
WG2: Negligible</td><td colspan="2">Chemical
Public: N/A
WG1: N/A
WG2: N/A</td></tr>
<tr><td colspan="6">Safety Function: Control of access to GA room as needed to prevent excessive worker exposure to external radiation from postulated MOTS line break.</td></tr>
<tr><td colspan="6">Method of Detection:</td></tr>
<tr><td colspan="6">SNS site stack monitor will alarm and the area radiation monitor in the GA room will alarm. MOTS and/or gas injection systems operational parameters may alarm.</td></tr>
<tr><td colspan="5">Preventive Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="5">Design: Use of ASTM-rated stainless steel tubing and vessels. Locked, heavy steel personnel access door must be opened to allow worker entry to normally unattended GA room. 3 ft thick concrete walls and a 6 in. thick steel access door confine radiation to inside the GA room.
Administrative: Post–maintenance valve alignment checking and PM helium leak checking minimize the chance of a maintenance error causing a tubing connection failure. Access to the GA room is under a Radiation Work Permit, the room is locked, and unlocking/access requires Radiation Safety Officer (RSO) approval and Radiological Control Technician (RCT) radiation survey before entry.</td><td>Radiological Protection Program</td></tr>
</table>

Table 5.7. Event GW3-2a (continued).

Mitigative Features – Attributes:	Credited:
Design: Instrumentation system provides ample alarms to warn operators of this condition. The SCE system provides partial (but not totally adequate for the bounding break) mitigation of accident radiation levels maintaining a flow of air through the GA room and sweeping the contaminated air to the stack. The SCE system has proven very reliable and has a standby blower with automatic start in the event the operating blower fails (Ref: OPM 5.T-19.3 SCE Low/No Flow/VFD Alarm). **Administrative**: Emergency response procedures for the SNS stack monitor alarm requires prompt notification of the SNS RSO and the SNS Environmental Compliance Officer, which would lead to enhanced attention and response actions to an ongoing uncontrolled release of noble gas radionuclides inside the building and to the environment. Cutting off the proton beam stops the production of noble gases within the mercury target and thus leads to cessation of the buildup of noble gases in the GA room, as well as diminishes the release of noble gases to the environment.	N/A

Planned Analysis, Assumption Validations, and Risks/Opportunities:	Mitigated Consequences:		
Based on the SNS policy for designating safety-credited controls (SNS-102030100-ES00005-R00), this table indicates that a credited control is warranted. For example, the Radiological Protection program could become a credited administrative control for preventing excessive worker radiation exposure in the GA room in this event. The present system of having a locked door to the GA room with RSO approval and RCT survey required prior to any entry into the room provides adequate rigor for control of this hazard.	**Radiological** Public: Negligible WG1: Negligible WG2: Negligible	**Chemical** Public: N/A WG1: N/A WG2: N/A	**Mitigated Frequency** <extremely unlikely (EU)

Notes:

Table 5.8. Event GW3-2b, leak or breach of MOTS during once-through helium injection, downstream of the ambient temperature charcoal adsorbers.

<table>
<tr><td colspan="4">Event Description: Release of target off-gas helium flow at any point downstream of the ambient temperature charcoal adsorbers (ABS-8013A&B). Possible downstream line break points include GA room, PCE system charcoal adsorber room, and the MOTS room.</td></tr>
<tr><td>Assumptions and Initial Conditions:
1. 2 MW beam on target continues until cutoff by operators, PPS, or MPS.
2. Upstream Hg condenser and gold adsorber stages remove Hg vapor from off-gas, so release is primarily noble gas spallation products carried out by continuing helium flow (20 L/min from bubblers and gas wall, 0.7 L/min from Hg level sensors).
3. Upstream ambient temperature CAs reduce noble gases available for release.
4. Released MOTS helium (with noble gases) mixes with room air. The highest dose rates occur in the MOTS room (no potential to exceed 25 rem in PCE charcoal adsorber room; downstream release to GA room covered in GW3-2c).
5. Bounding dose rate after 1 h of noble gas release into MOTS room ~1.5 rem/h with SCE system “on,” and ~6 rem/h within 1 h if SCE system “off.”
6. Cases with SCE system running release noble gases to the environment through the SNS stack.</td><td colspan="2">Causes:
MOTS piping material defect, corrosion, fatigue failure due to prolonged vibration or thermal cycles, impact from worker activity, incorrect alignment of valves on ABS8013A or 8013B, failed post-maintenance checks/tests, or actuation of ABS-8013A/B rupture disc due to MOTS line plugging.</td><td>Initiating Event Frequency:
Anticipated</td></tr>
<tr><td rowspan="2">Unmitigated Impact on Systems:
Potential for release of significant quantities of noble gas radionuclides to the environment through the SNS 80 ft stack, primarily argons and kryptons due to long residence time of Xe on ambient CAs.
For double-ended break, the continuing slight vacuum of the HOG system would draw air into the MOTS, which would then cause eventual ice accumulation in the cryogenic CA stage (in the MOTS room).</td><td colspan="3">Unmitigated Consequences</td></tr>
<tr><td>Radiological
Public: Negligible
WG1: Low
WG2: Negligible</td><td colspan="2">Chemical
Public: N/A
WG1: N/A
WG2: N/A</td></tr>
<tr><td colspan="4">Safety Function: Prevent excessive worker exposure to external radiation.</td></tr>
<tr><td colspan="4">Method of Detection:</td></tr>
<tr><td colspan="4">SNS site stack monitor will alarm and the area radiation monitor in the MOTS room will alarm. MOTS operational parameters may alarm.</td></tr>
<tr><td colspan="3">Preventive Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="3">Design: Use of ASTM-rated stainless steel tubing and vessels. An RMS-3 area radiation detector is installed in the MOTS room. Its readout is in the vestibule outside the MOTS room and it has the High alarm at 100 mrem/h (audible plus red indicator).
Administrative: Post–maintenance valve alignment checking and PM helium leak checking minimize the chance of a maintenance error causing tubing a connection failure. Access to the MOTS room is under a Radiation Work Permit.</td><td>N/A</td></tr>
</table>

<table>
<tr><th colspan="4">Table 5.8. Event GW3-2b (continued).</th></tr>
<tr><td colspan="3">Mitigative Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="3">Design:
Instrumentation system provides ample alarms to warn operators of this condition. The normally running SCE system removes potential for worker dose to exceed 25 rem. This system has proven very reliable and has a standby blower with automatic start in the event the operating blower fails (Ref: OPM 5.T-19.3 “SCE Low/No Flow/VFD Alarm.”
Administrative:
Emergency response procedures for the SNS stack monitor alarm requires prompt notification of the SNS RSO and the SNS Environmental Compliance Officer, which would lead to enhanced attention and response actions to an ongoing uncontrolled release of noble gas radionuclides inside the building and to the environment. Cutting off the proton beam stops the production of noble gases within the mercury target and thus leads to cessation of the buildup of noble gases in the GA room, as well as diminishes the release of noble gases to the environment.</td><td>N/A</td></tr>
<tr><td rowspan="2">Planned Analysis, Assumption Validations, and Risks/Opportunities:
Based on the SNS policy for designating safety-credited controls (SNS-102030100-ES00005-R00), it could be argued that the Radiological Protection program should become a credited administrative control for preventing excessive worker radiation exposure in the MOTS room in this event. However, a credited control is not necessary for this event because at least three infrequent failures would have to occur simultaneously to allow an excessive exposure: (1) the line break itself, (2) failure of the very reliable SCE system, and (3) failure of all radiological control procedures that are in place to the extent of an hours-long occupancy in the MOTS room despite an alarming area radiation sensor adjacent to the entry door and the radiological work permit requirement for a current radiation survey at the time of entry.</td><td colspan="3">Mitigated Consequences:</td></tr>
<tr><td>Radiological
Public: Negligible
WG1: Negligible
WG2: Negligible</td><td>Chemical
Public: N/A
WG1: N/A
WG2: N/A</td><td>Mitigated Frequency
<EU</td></tr>
<tr><td colspan="4">Notes: One could postulate that the ambient temperature carbon adsorbers (ABS-8013A&B) could degrade over time and thus, that downstream leaks could have higher doses than indicated under “Design” above, possibly requiring a credited control for the line break event. Such an assumption would not be realistic because failure of ABS-8013A and B would cause an unexpected high radiation level in the MOTS room, which would be alarmed by the MOTS room RMS-3 area radiation monitor, leading to the detection and correction of the condition.
This event is for once-through helium injection, but the outcome would be the same if the helium injection system were operating in the recycle mode in which the recycle blowers are aligned to take suction from the line that carries MOTS exhaust to the HOG system.</td></tr>
</table>

<table>
<tr><th colspan="4">Table 5.9. Event GW3-2c, leak or breach of MOTS during recycle mode of helium injection, downstream of the ambient temperature charcoal adsorbers.</th></tr>
<tr><td colspan="4">Event Description: During recycle mode with mid-MOTS suction point through SV-8251 (see Figure 5.4), a release of target off-gas helium flow occurs at a point downstream of the ambient temperature charcoal adsorbers (ABS-8013A&B). For recycle blower suction side breaks, possible downstream line break points include the GA room and PCE charcoal adsorber room. For blower discharge side breaks, possible release points include the PCE charcoal adsorber room, basement utility vault, vertical pipe chase, shutter drive equipment room (SDER), and water system delay tank or gas-liquid separator cavities. MOTS room release is not considered because flow through the MOTS room to the HOG system is only ~0.3 L/min. Water system cavities are not considered because they have no access way except removing the thick concrete pit covers with the 50-ton crane. The basement utility vault and SDER are not considered because they are PPS access-controlled areas during beam operation. The pipe chase is not considered because it is accessed only through the SDER.</td></tr>
<tr><td>Assumptions and Initial Conditions:
1. 2 MW beam on target continues until cutoff by operators, PPS, or MPS.
2. Upstream Hg condenser and gold adsorber stages remove Hg vapor from off-gas, so release is primarily noble gas spallation products carried out by continuing helium flow (20 L/min from bubblers and gas wall, 0.7 L/min from Hg level sensors).
3. Upstream ambient CAs reduce noble gases available for release.
4. Released helium (with noble gases) mixes with room air. The highest dose rates occur in the GA room.
5. Dose rate after 1 h of noble gas release into GA room ~1.4 rem/h within 1 h with SCE system “on,” and ~2.9 rem/h within 1 h if SCE system “off.”
6. Case with SCE system “on” releases noble gases to the environment through the SNS stack.</td><td colspan="2">Causes:
MOTS piping material defect, corrosion, fatigue failure due to prolonged vibration or thermal cycles, impact from worker activity, incorrect alignment of valves on ABS8013A or 8013B, failed post-maintenance checks/tests, or actuation of ABS-8013A/B rupture disc due to MOTS line plugging.</td><td>Initiating Event Frequency:
Anticipated</td></tr>
<tr><td rowspan="2">Unmitigated Impact on Systems:
Potential for release of significant quantities of noble gas radionuclides to the environment through the SNS 80 ft stack, primarily argon and krypton due to long residence time of xenon on ambient CAs.
In double-ended breaks, the continuing slight vacuum of the HOG system would draw air into the MOTS, which would then cause eventual ice accumulation in the cryogenic CA stage (in the MOTS room).</td><td colspan="3">Unmitigated Consequences</td></tr>
<tr><td>Radiological
Public: Negligible
WG1: Low
WG2: Negligible</td><td colspan="2">Chemical
Public: N/A
WG1: N/A
WG2: N/A</td></tr>
<tr><td colspan="4">Safety Function: Prevent excessive worker exposure to external radiation.</td></tr>
<tr><td colspan="4">Method of Detection:</td></tr>
<tr><td colspan="4">SNS site stack monitor will alarm and the area radiation monitor in the GA room will alarm. MOTS operational parameters may alarm.</td></tr>
</table>

Table 5.9. Event GW3-2c (continued)

Preventive Features – Attributes:	**Credited**:
Design: Use of ASTM-rated stainless steel tubing and vessels. Preventive maintenance on recycle blowers. Locked, heavy steel personnel access door must be opened to allow worker entry to normally unattended GA room (likewise for the PCE charcoal adsorber room except not locked). 3 ft thick concrete walls and a 6 in. thick steel access door confine radiation to inside the GA room. **Administrative**: Post–maintenance valve alignment checking and helium leak checking minimize the chance of a maintenance error causing a tubing connection failure. Access to the GA room is under a Radiation Work Permit, the room is locked, and unlocking/access requires RSO approval and prior RCT radiation survey.	

Mitigative Features – Attributes:	**Credited:**
Design: Instrumentation system provides ample alarms to warn operators of this condition before the occurrence of excessive worker exposure. The normally running SCE system removes the potential for worker dose to exceed 25 rem. The SCE system has proven very reliable and has a standby blower with automatic start in the event the operating blower fails (Ref: OPM 5.T-19.3 "SCE Low/NO Flow/VFD Alarm." **Administrative**: Control room alarm response procedure (BEAST-based) for the SNS stack monitor alarm requires prompt notification of the SNS RSO and the SNS Environmental Compliance Officer, which would lead to enhanced attention and response actions to an ongoing uncontrolled release of noble gas radionuclides inside the building and to the environment. Cutting off the proton beam stops the production of noble gases within the mercury target and thus leads to cessation of the buildup of noble gases in the GA room, as well as diminishes the release of noble gases to the environment.	None.

Planned Analysis, Assumption Validations, and Risks/Opportunities:	**Mitigated Consequences:**		
The ~8 h occupancy time required in the GA room, given the unlikely coincident failure of the SCE system, for worker dose to exceed the 25 rem criterion of the SNS policy for designating safety-credited controls (SNS-102030100-ES00005-R00) and the alarms that would lead to termination of beam operation would make it unnecessary to designate a credited control for this event. However, a credited control will be designated for event GW3-2a (upstream release in GA room), making this consideration inapplicable. A credited control is not considered for the PCE charcoal adsorber room because an ~16 h exposure would be required given assumed coincident failure of the SCE flow.	**Radiological** Public: Negligible WG1: Negligible WG2: Negligible	**Chemical** Public: N/A WG1: N/A WG2: N/A	**Mitigated Frequency** <EU

Notes:

5.4.1.3 Impact of Gas Injection on Target System Hazard Analyses

The target system hazard analysis considers a wide range of mishaps with the potential to result in radiological consequences to workers. The *FSAD-NF* ([5-2], Section 4.3.1) addresses these under the "Target Systems (TS) Event" scenarios and includes the following categories: TS1 fire events, TS2 explosion events, TS3 loss of confinement events, and TS4 direct exposure events. Review of all these existing events has resulted in the conclusion that they remain bounding for post-PPU operations, with the following understandings:

- For event TS1-3, target service bay fire, the credited control is either the service bay water mist system or the shielding that surrounds the target loop components. The new components that the PPU scope add to the mercury loop are the overflow tank and the mercury GLS. Since they are both equipped with steel shielding consistent with that of the balance of the loop, the shielding is still a viable credited control for fire. The new gas injection lines (stainless steel tubing, one for the bubblers and one for the gas wall) that enter the target carriage for connection into the target module could be postulated to be broken outside the shielding in a fire and provide a pathway for mercury to flow onto the fire. However, this is not a realistic threat for the PPU because of two flow control devices that are installed in the tubing inside the target carriage shielding: a filter and a check valve. Only a trivial amount of mercury could leak backwards through these devices, so the target loop shielding would remain a valid control for preventing airborne release of mercury during hypothetical service bay fires.

- Several TS3 events (e.g., TS3-12, full loss of mercury flow [mercury pump trip or locked rotor]) require credited mitigation by the target protection system (TPS) that trips the proton beam–based on either abnormal pressure difference across the mercury pump or abnormal temperature in the exit pipe of the heat exchanger (cold leg). The PPU preliminary hazard analysis (PHAR, [5-1]) concluded that based on the design and placement of the sensors, the presence of a credible amount of helium voiding in the loop would not prevent the TPS from acting promptly when needed. This conclusion remains valid and has been strengthened by the safety evaluation for GI3 gas injection reaching the same conclusion and by monitoring of the performance of these instruments during actual gas injection.

The existing target system hazard analyses provide a range of fire-related events to cover routine operations and certain maintenance actions, but none of these adequately address the target module replacement operation which is expected to take place up to four times per year during post-PPU operations. During replacement, the current procedure is to drain all the mercury to the storage tank, which is at a low point with respect to the loop, under thick steel shielding and therefore protected against the effects of postulated fire in the service bay. Post-PPU target exchange will be the same except for about 10 L of mercury remaining at the bottom of the PPU mercury GLS component that cannot be totally drained without a particular time-consuming operation. The GLS will normally be inside the steel shielding that surrounds the mercury loop piping. However, during target replacement, it will be enclosed only partially because five shielding blocks must be removed prior to withdrawal of the target carriage to allow remote access to the disconnect joints for the mercury supply and return piping. Therefore, the mercury inside the GLS would be subject to possible vaporization by a locally intense fire if it were assumed that the fire was directly adjacent. This analysis adds a new hazard event, TS1-3a, for service bay fire during target exchange. The hazard analysis for TS1-3a is shown in Table 5.10 and is successfully mitigated by existing credited controls.

The PHAR [5-1] declared that the PPU-proposed helium injection was a USI for the following reason:

> Operating the mercury loop with continuous helium injection ***does introduce the possibility of a new type of accident*** associated with postulated uncontrolled helium void accumulation at one or more points within the loop to the extent that the mercury in the pump tank could overflow into the mercury off-gas treatment system. Part of the MOTS is located in basement rooms that are not designed (e.g., with regard to shielding) to accommodate safely the presence of liquid mercury. ***Therefore, by this criterion, the proposed helium injection should be a USI.***

Section 5.4.1.1 presents hazard analyses of helium system events GW-A_OT and GW-A_Re, which involve addition of helium at an excessive rate to the mercury loop bubbler or gas wall injection line (see Tables 5.2 and 5.3 for the associated hazard analyses). If such a mishap were to happen, a somewhat greater than normal amount of voiding could exist in the loop, held in place by the force of the flowing mercury and compressed by the hydrostatic pressure of mercury in the pump tank and loop. The helium supply system would cut off the helium flow based on the interlocks provided, and the excess helium voiding would slowly find its way back to the pump tank gas space. However, if the mercury pump tripped at this time (existing FSAD-NF hazard event TS3-12), the voids would be free to flow upward toward the pump tank. As the voids flow upward, they would expand and displace mercury upward in the pump tank and, post-PPU, into the overflow tank. The PPU designers have sized the overflow tank to be able to hold the worst case in a mercury surge event. In this way, the temporary surge in mercury level would be prevented from entering the off-gas line to the loop seal and downstream MOTS components. Therefore, the overflow tank will have a safety function and can be either designated to be a credited control or an inherent feature with a recognized safety function.

<table>
<tr><th colspan="4">Table 5.10. Event TS1-3a, fire in target service bay during target module removal or replacement.</th></tr>
<tr><td colspan="4">Event Description: Fire during the target module replacement operation.</td></tr>
<tr><td>Assumptions and Initial Conditions:
1. The mercury in the loop has been drained to the mercury storage tank. Approximately 10 L of Hg remains in the gas liquid separator, which limits the maximum possible source term to ~135 kg of Hg vapor.
2. Mercury loop components remain inside shielding except where shielding panels are removed to allow access to disconnect joints near the mercury gas liquid separator.
3. Fire assumed to be intense enough to breach any part of the mercury loop piping not inside the steel shielding.</td><td colspan="2">Causes:
Excessive accumulation of transient combustibles combined with electrical malfunction that provides a spark or heat for ignition.</td><td>Initiating Event Frequency:
Unlikely</td></tr>
<tr><td rowspan="2">Unmitigated Impact on Systems: Contamination spread inside service bay, especially if any mercury is vaporized by fire; thermal and smoke damage to components in target service bay.</td><td colspan="3">Unmitigated Consequences</td></tr>
<tr><td>Radiological
Public: Low
WG1: Low–Moderate
WG2: Low</td><td colspan="2">Chemical
Public: Below
WG1: Exceeds
WG2: Exceeds</td></tr>
<tr><td colspan="4">Safety Function: The following safety functions are provided by existing credited controls. Prevent accumulation of significant amounts of transient combustible material. Service bay differential pressure monitoring system (SBDPMS) warns workers if negative pressure not maintained inside the service bay. PCE system HEPA inlet dampers prevent backflow to occupied areas if service bay pressure goes positive. SBDPMS warns workers in adjacent spaces left if vacuum is lost inside the target service bay.</td></tr>
<tr><td colspan="4">Method of Detection:</td></tr>
<tr><td colspan="4">Target service bay smoke detector, view of service bay interior through the manipulator windows, various/random equipment or instrument failures indicated at control panel.</td></tr>
<tr><td colspan="3">Preventive Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="3">Design: Electrical codes and standards; mechanical design codes and standards; NFPA codes and standards.
Administrative: Operating procedures and training; surveillance and maintenance; combustible material control program; limited combustibles in mercury process piping encasements.</td><td>Service bay combustible material control program.</td></tr>
</table>

Table 5.10. Event TS1-3a (continued).			
Mitigative Features – Attributes:			**Credited:**
Design: Target service bay water mist system. Shielding surrounding mercury loop components, fire barrier enclosing target service bay and core vessel; PCE (including charcoal filter) system captures vaporized Hg; service bay confinement features that would enable spilled Hg to gravity drain to the collection basin (in protected location); PCE inlet HEPA filter and backdraft dampers; SBDPMS detection/alarm on loss of negative pressure between target service bay and adjacent areas. **Administrative**: Mercury drained to storage tank except for gas liquid separator residual volume; emergency response procedures.			SBDPMS, PCE system inlet dampers.
Planned Analysis, Assumption Validations, and Risks/Opportunities:	**Mitigated Consequences:**		
This hazard analysis has assumed that all of the 10 L residual inside the gas liquid separator could be vaporized if a locally intense safety basis fire were to occur during retargeting. Further accident analysis could provide estimate of how much of the 10 L residual inside the gas liquid separator could be vaporized by the postulated safety basis fire.	**Radiological** **Public**: Negligible **WG1**: Negligible **WG2:** Negligible	**Chemical** Public: N/A WG1: N/A WG2: N/A	**Mitigated Frequency** <EU
Notes:			

5.4.2 Analytical Studies

This section provides a brief summary of analytical studies conducted to support the design and/or inform the hazard analyses discussed in Section 5.4.1.

5.4.2.1 Maximum Void Accumulation in the Mercury Loop and Mercury Surge during Worst Case Bubble Shedding Transient

The safety evaluation of helium injection depends on the answer to the following question. Can the injected helium result either in a slow voiding build-up scenario or a transient bubble shedding event that could displace mercury upward to the extent that it would escape from the service bay through the MOTS line that connects to the mercury overflow tank? This section summarizes the results of analytical studies conducted to define a bounding answer to this question and to provide a firm basis for the required volume for the overflow tank.

The task of defining the maximum plausible mercury surge into the pump tank was divided into two parts. The first part [5-8] combines two-phase flow correlations, experimental data, and computational fluid dynamics to study how helium bubbles are transported under the two-phase flow conditions expected during loop operation and where the bubbles might coalesce and accumulate. The results show that a maximum of up to 67.9 L of helium could accumulate at various points in the mercury loop with the greatest single accumulation of 21.1 L in the heat exchanger. This estimate describes the maximum volume of gas at each location in which it may accumulate so that the bounding accumulation of 67.9 L would displace that volume of mercury in the pump tank. At this point, the level of mercury in the pump tank would be about 3/8 in. below the 93% high-level alarm that would trigger interlocks to discontinue gas injection flow. In addition to conservatisms used in estimating the maximum voiding at each location in the loop, an arbitrary safety factor of 50% was applied, bringing the bounding void estimate up to 102 L (i.e., well above the 93% high-level alarm but with combined head space of about 134 L left in the pump tank and overflow tank).

Since the target module outlet pipe is sloped downward in the direction of flow from the target module to the heat exchanger (necessary to allow proper drainage from the mercury loop to the mercury storage tank prior to the target module replacement activity), the natural upward direction for coalesced helium to take is counter to the flow direction (i.e., back toward the target module). The forward momentum of the flowing mercury in the outlet pipe would counterbalance the tendency of the bubbles to travel back toward the target module where they would be vented through the target module vent line to the pump tank gas space (this vent line is an existing part of the original design and not related to PPU scope). At the point where the target module outlet pipe undergoes a sharp bend to allow the mercury to descend vertically toward the heat exchanger inlet, the mercury velocity is sufficient to carry only very small bubbles downward toward the heat exchanger. If the maximum void accumulation were reached during operations by injecting excess helium, periodic shedding of helium would take place in which the bubbles would return to the pump tank and be vented out the off-gas line. If a pump trip were to occur at the time of maximum plausible void accumulation in the loop, a rapid rise of the bubbles would be triggered that would define the maximum plausible mercury surge event.

The second part [5-9] of the analytical study of voiding behavior in the mercury loop assumes the bounding 102 L void accumulation has occurred, followed by a triggering event such as a mercury pump trip, and tracks the expansion of the helium void as it moves upward toward the target module. As noted earlier, accumulating 102 L of void in the loop requires assuming failure of the pump tank high-level alarm that would discontinue helium injection flow. As a further conservatism, it is arbitrarily assumed that the entire 102 L of void has accumulated in the heat exchanger—the component with the lowest elevation—thereby maximizing the expansion of the void as it rises in the piping. The results of the calculation show that the original 102 L volume would expand to 193 L before the expansion is interrupted by venting that would occur through the existing target module vent line, leaving about 6 in. of headspace in the overflow tank. An additional similar calculation showed that it would take an initial void accumulation of 150 L in the heat exchanger (i.e., significantly more than plausible) to cause the mercury surge to entirely fill the overflow tank. Consequently, it is concluded that the volume of the overflow tank is adequate to hold the bounding void expansion event, and the goal of preventing overflow of mercury to the off-gas system is achieved.

5.4.2.2 Calculations of External Radiation Exposure Hazards for Evaluation of MOTS line breaks

To complete the hazard analysis of accidental noble gas releases in the MOTS rooms (discussed in Section 5.4.1.2), it was necessary to do calculations that bound the potential for external radiation exposure to workers who need to enter these rooms occasionally. A spreadsheet-based model was developed [5-10], with each MOTS basement room of interest defined as a control volume for calculation of radionuclide concentration following postulated line-break accidents. Noble gas radionuclide production rates at the 2 MW maximum beam on target and 1.3 GeV maximum proton energy were available from neutronics studies of the mercury target [5-11]. The spreadsheet mixing model was configured to allow the concentrations of escaped noble gases to be calculated with and without room ventilation flow. The following conservative assumptions were made to ensure the results would be bounding:

- All the line breaks are taken to be guillotine breaks that would release the entire helium off-gas flow into the room.

- The break flow is assumed to continue unabated with assumed failure of all operator action, interlocks, or inherent features that would limit or terminate helium injection and thus, the release.

- The proton beam is assumed not to be tripped so that the release of radioactive noble gases into the affected MOTS room would continue indefinitely.

- External radiation dose rate in each room is calculated using dose conversion coefficients applicable to larger room size (i.e., at the same concentration, thus calculating dose rate for an artificially increased source size).

- Complete mixing of room air and helium released from MOTS line breaks is assumed. This is bounding because the released gas is mostly helium (the volume fraction of the heavier noble gas nuclides is small), which is very buoyant in air and would rise rapidly to the ceiling, resulting in a lower dose rate for a worker standing on the floor in the room than would a uniform mixture because of the high ceiling in the GA room (~12 ft).

- Radioactive argon and neon isotopes are assumed not to adsorb onto the ambient temperature charcoal adsorbers, although argon is known to be adsorbed to some extent (both are removed by the cryogenic charcoal adsorbers downstream from the recycle compressors).

An example of the calculation results is shown in Figure 5.9 for the worst case line break in the GA room, upstream from the ambient temperature charcoal adsorbers. This example shows that even with the room ventilation "on," the GA room could become very hazardous in a short period of time if the helium flow to the MOTS were not stopped or the proton beam tripped. Similar MOTS line breaks downstream of the ambient temperature charcoal adsorbers would result in fewer releasable radionuclides by at least an order of magnitude, resulting in the conclusion of the hazard analysis in Section 4.1.2 that identification of additional credited controls would be warranted only for the GA room—the only room in which a break upstream of the ambient adsorbers could occur.

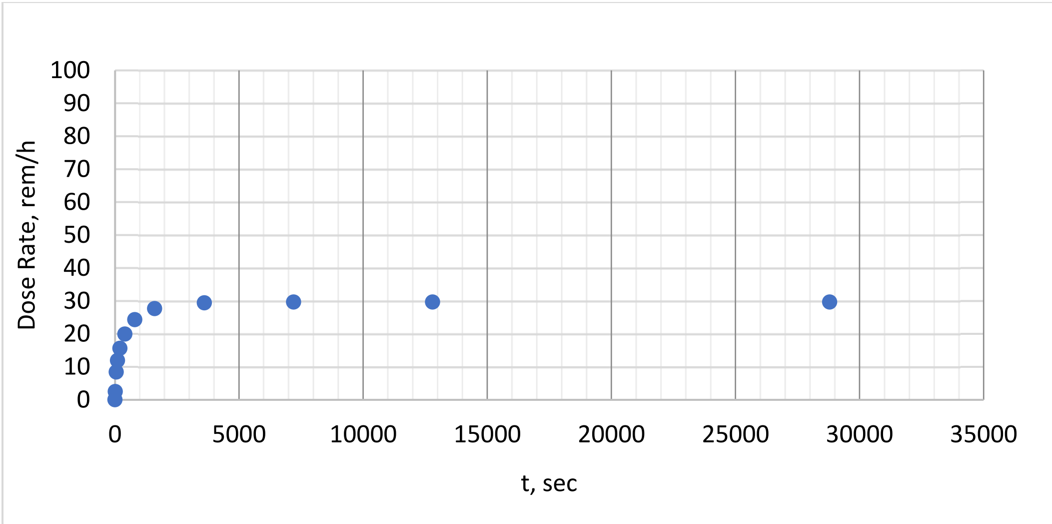

Figure 5.9. Bounding external radiation level in GA room for guillotine line break upstream of ambient temperature charcoal adsorbers (case with room ventilation).

5.4.3 Selection of Safety-related Credited Controls

The main point of current CD-2 hazard analysis update is to document the determination of whether PPU-related hazards are significant enough to require safety-related credited controls that are not presently identified in the current safety basis for the target station, as documented in Chapter 5 of the *FSAD-NF* [5-2]. The analyses presented above (Section 5.4.2.1) show that the PPU design has obviated the need for specific designated safety-credited controls by providing a new component, the overflow tank attached to the mercury pump tank that has volume sufficient to hold the maximum plausible void shedding event. The volume and presence of the overflow tank can be considered to be a credited control or else recognized as a safety-related characteristic. In either case, the main benefit of such a designation will be in configuration control to make sure that the overflow tank remains in place in the loop and thus able to receive a mercury surge from a helium bubble shedding event.

The hazard analysis of MOTS line breaks in the GA room has indicated the need for a safety-credited control. The existing access controls for entry to the GA room are adequate but should be formally designated as safety-credited mainly for configuration control purposes. In conjunction with this, the read-out panel for the area radiation monitor in the GA room should be moved to the PCE charcoal adsorber room for more convenient use by workers during the entry process.

5.5 Preoperational Testing to Verify Gas Injection Characteristics

Both mission-related and safety-related goals will be served by testing of helium gas injection to be conducted before beam on target operation with PPU gas injection. Plans for functional testing before and after proton beam on target will be addressed at the accelerator readiness reviews that will be required before operations following installation of the proposed PPU gas injection modifications.

The safety analysis of bounding loop void accumulation will be substantiated by functional testing prior to beam on target operation. The maximum plausible void accumulation in the mercury loop was estimated by ref. [5-8] to be 67.9 L, which was multiplied by a factor of 1.5 to yield the 102 L initial void volume of the transient analysis of a mercury pump tank level surge event [5-9]. The pre-beam functional testing will verify the loop void retention characteristics as a function of helium injection flow rate.

Another safety-related characteristic that will need to be addressed in pre- as well as post-beam functional testing is performance of the safety signals that the TPS depends on to shut down the proton beam when mercury loop flow or cooling is not adequate. Therefore, the performance of the TPS pump pressure difference sensors and the heat exchanger outlet temperature sensors will be verified during pre- and post-beam operations. The pump pressure difference signal can be tested before beam on target operation, but the response of the mercury temperature sensors cannot be completed until beam on target provides enough energy to result in significant change in mercury temperature.

The SNS plans to progress to higher gas injection flows prior to PPU installation, and a goal of 5 SLPM has been adopted to be achieved under operational funding. Therefore, data will be available to partially validate the void retention characteristics of the mercury loop and the TPS sensor performance. The partial validation will inform planning for the full validation under full PPU design conditions.

5.6 Conclusions

The safety evaluations and analyses of this section show that installation and operation of PPU helium injection at 20 SLPM can be achieved safely. Development of the preliminary design has identified safety features that address foreseeable hazards. The helium gas is supplied at an elevation far enough above the target module that the gas lines cannot become pathways for mercury to escape the target service bay. The addition of the new mercury overflow tank provides a normally empty volume that can mitigate any plausible mercury voiding event. The present stringent controls on GA room access can be designated as a credited control to ensure worker protection in the event of postulated MOTS line break events.

5.7 References

5-1 R. M. Harrington and S. M. Trotter, *Preliminary Hazard Analysis in Support of the Proton Power Upgrade Project*, PPU-P01-ES0001-R00, May 2017.

5-2 *Spallation Neutron Source Final Safety Assessment Document For Neutron Facilities*, 102030102-ES0016-R03, September 2011.

5-3 *Spallation Neutron Source Policy for Selection of Safety Related Credited Controls*, 102030100-ES0005-R00, March 2005.

5-4 *Spallation Neutron Source Final Safety Assessment Document for Proton Facilities*, 102030103-ES0018-R02, September 2010.

5-5 S. M. Trotter, J. R. DeVore, et al., *Radiological Emissions Associated with the PPU Project at the Spallation Neutron Source*, PPU-103-ES0003-R00.

5-6 *GI3 report: Safety Assessment Supplement for Target Gas Injection Initial Implementation (GI3)*, 102030102-ES0094-R00.

5-7 Jacob Platfoot, *USI Evaluation for Addition of Ambient Temperature Carbon Adsorber to Mercury Offgas Treatment System (MOTS)*, SNS-102030102-ES0090-R00, December 2016.

5-8 Charlotte Barbier, *Estimation of the Maximum Gas Accumulation Volume in the SNS Mercury Loop*, SNS-10610200-TR0007-R00, January 19, 2019.

5-9 Charlotte Barbier, *Helium bubble transients: Mercury Process System Safety Scenario Evaluations within the Proton Power Upgrade (PPU) Project*, SNS-10601200, January 25, 2019.

5-10 J. R. Devore and R. M. Harrington, *Radiological Exposure Potential for Post-PPU Accidental Release of Noble Gas Radionuclides in MOTS Rooms*, SNS PPUP-103-TR0001-R00

5-11 F. X. Gallmeier, *Mercury Radionuclide Production Rates*, email dated 4/24/2019.

6. Safety Evaluation of Addition of the Catalytic Converter to Each Cryogenic Moderator System Loop

6.1 Introduction

The PHAR [6-2] concluded that the addition of catalytic converters met the criteria to be a USI for two reasons: (1) the increase in hydrogen inventory and (2) the addition of a granular catalyst material that could become activated. This section provides a safety evaluation of the effect of the proposed modification to the CMS.

Each of the three separate cryogenic hydrogen moderator loops that form the CMS will be modified by installation of a catalytic conversion stage to convert hydrogen from the ortho to the para form. This conversion will be done in the hydrogen utility room (HUR), which contains the three helium-cooled heat exchangers, circulators, and other components. As shown schematically in Figure 6.1, a full-flow catalytic converter unit will be installed between each loop's accumulator and heat exchanger. Each catalytic converter is a 6 in. diameter stainless steel vessel that holds the granular catalyst material. The catalyst is a 30–50 mesh paramagnetic hydrous ferric oxide (Fe_2O_3) powder. Although many different catalysts have been developed, Ionex was chosen because it is readily available, safe to handle, and cost-effective. The catalyst manufacturer screens the catalyst during production to ensure >90% of the catalyst granules are nominally specified to be between 30 and 50 mesh size with less than 5% either above or below the desired mesh size range. A screen/filter assembly is placed at the inlet (top) and outlet (bottom) of each converter vessel to securely confine the catalyst within the converter vessel. Each screen assembly (one at the top/inlet of the converter vessel and one at the bottom/outlet) sandwiches fibrous ceramic (Al_2O_3+SiO_2) felt filter material (called Cerafelt by the manufacturer) between discs of woven stainless steel mesh backed up by perforated stainless steel discs.

The SNS catalytic converter design is based on the design, installation, and successful use of catalytic converters at the Japan Proton Accelerator Research Complex to convert ortho-hydrogen to para-hydrogen during accelerator operation. Prior to being used in accelerator-based scattering applications, ortho-para catalysts have been used in research and industrial applications involving storage of hydrogen under cryogenic conditions.

The addition of the catalytic converter vessel and tubing to each CMS loop increases the total hydrogen inventory of the CMS from 6.8 kg (rounded to 7 kg in previous safety analyses) to 8 kg. A more complete description is provided in the CMS section of the CDR.

6.2 Potential Impacts of Catalytic Converters on SNS Safety Basis

As documented in the *FSAD-NF* [6-1], the focus of the existing safety basis evaluation of the CMS is whether credible accidents exist in which hydrogen could undergo combustion in the presence of target mercury, (i.e. inside the core vessel or target service bay). As explained in the *FSAD-NF* (Section 3.3.3.2 Hydrogen Utility Room), preventing hydrogen combustion elsewhere in the target building is a priority that, is achieved by application of Oak Ridge National Laboratory standards for conventional and fire safety.

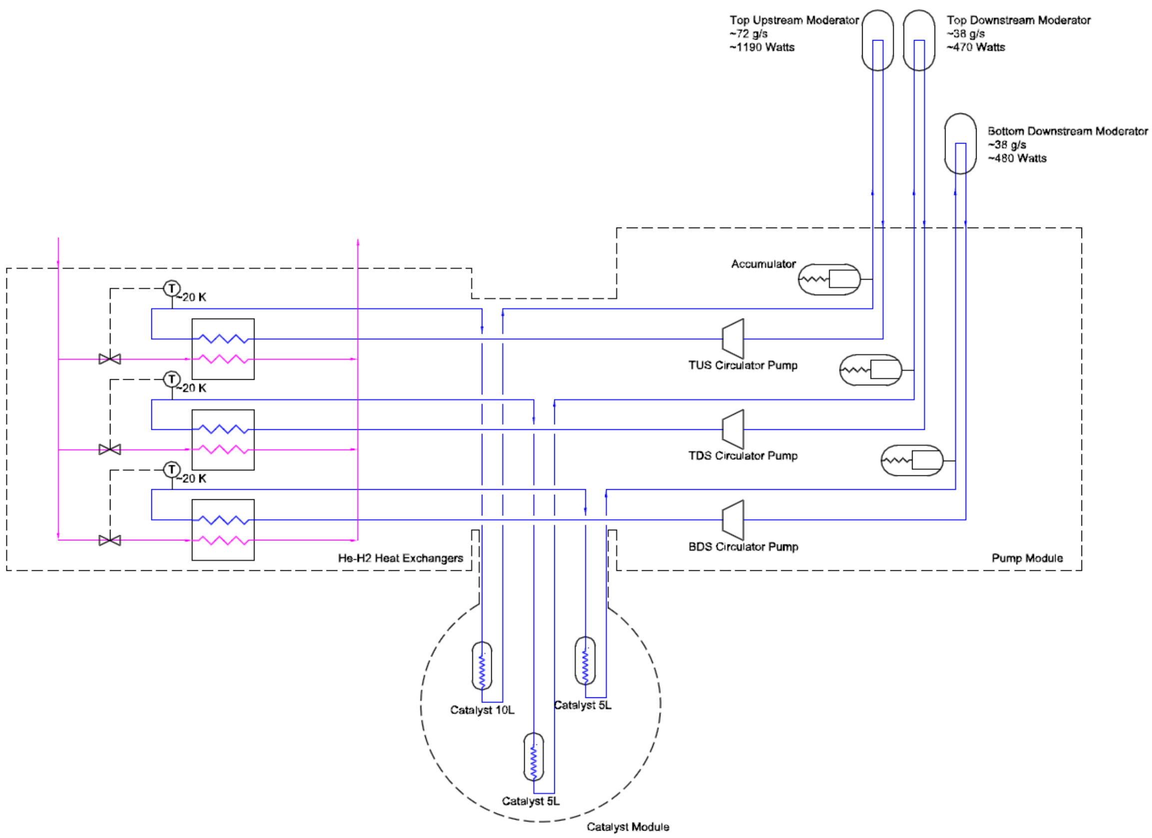

Figure 6.1. Schematic diagram showing catalytic converters inside the new catalyst module in the three CMS loops (all components shown are in the HUR except the moderators, which are in the core vessel, and transfer line between core vessel and HUR).

The CD-1 preliminary hazard evaluation of the proposed PPU changes to the CMS [6-2] identifies three safety basis concerns for evaluation at the present CD-2 stage:

- Does the catalyst held within the converter vessel affect the safety-credited vent path? Or, could catalyst granules escape from the converter vessel and interfere with the function of the safety-credited hydrogen pressure relief path or rupture disc?

- Does the presence of the catalyst material introduce a previously unidentified radiological hazard?

- Does the additional hydrogen in the CMS increase the consequences of hypothetical accidents sufficiently to require additional LOCs to prevent or mitigate accident consequences?

The first concern would affect the safety basis if the catalyst granules could interfere with the safety-credited hydrogen pressure relief function. The catalyst is held in the converter vessel; and if granules escaped from there, they could presumably be transported into the existing CMS piping or components and form a blockage in the credited relief paths to the rupture discs. If the catalyst remains in the converter vessel, it cannot interfere with venting of hydrogen through the 18-bar (261 psid) rupture discs because there are two relief paths in the existing system, with one connecting downstream of the catalytic converter and the other to the upstream side. In the event of failure of the hydrogen boundary, the hydrogen is vented through the 2-bar vacuum barrier rupture discs. Installation of the new catalytic converter vessels does not affect the vacuum vent path, so the existing venting calculations [6-3] will not need to be modified to show that the PPU modifications to the CMS provide adequate venting.

The second safety basis concern is whether ferric oxide catalyst particles might escape from the converter vessel and be circulated in the CMS—from the HUR and down into the neutron field adjacent to the mercury target and then back to or toward the HUR. This circulation would potentially create excessive radiation levels near the unshielded CMS cryogenic transport lines or near the components in the HUR, none of which have radiation shielding. In almost 15 years of operation of the three CMS loops, experience has shown that the hydrogen does not become significantly radioactive. Hazard analysis was performed to determine if the potential exists for activation of the catalyst to result in a significant hazard to workers [6-4].

Two scenarios were considered as potential paths for exposure: direct exposure nearby the hydrogen transfer lines (CM4-1) and airborne exposure following venting of hydrogen through over-pressure protection devices (CM3-9). Analysis identified the direct exposure pathway to pose a significant risk to workers with a "Moderate" consequence, and the airborne exposure pathway was determined to have "Negligible" consequences. As such, a credited layer of control was identified for the direct exposure pathway. The retention elements in the catalytic converters were credited with retaining at least 95% of the catalyst media, consistent with the specified mesh size of the wire mesh screens on the retention elements and the specified size distribution of the catalyst granules. This also serves to further reduce the consequences of the airborne pathway and prevent the possibility of vent path blockage discussed above, though neither of these requires the control to be credited. See Tables 6.1 and 6.2 for a summary of hazard analysis of these events. A detailed description of the functional requirements, appropriate for incorporation into the FSAD-NF, is provided in Reference [6-4].

<table>
<tr><td colspan="4">Table 6.1. Event CM4-1, exposure to activated catalyst media in RTBT</td></tr>
<tr><td colspan="4">Event Description: o-p catalyst media circulates in the moderator loop, becomes activated, exposes personnel working in RTBT</td></tr>
<tr><td>Assumptions and Initial Conditions:
1. The Top Downstream moderator loop provides the bounding case for activation and exposure.
2. The catalyst is distributed homogenously throughout the moderator loop.
3. Activation is based on the maximum lifetime of an Inner Reflector Plug, 4 years at 2 MW for 5000 hours = 40 GW-hours of exposure.</td><td colspan="2">Causes:
Material failure of retention element. Fabrication error in retention elements or module assembly.</td><td>Initiating Event Frequency:
Anticipated</td></tr>
<tr><td rowspan="2">Unmitigated Impact on Systems: Internals of hydrogen transfer lines become contaminated with activated catalyst. Potential damage to components, especially where catalyst granules could interfere with moving parts, such as circulator impeller.
Degradation of neutron spectra at instruments.</td><td colspan="3">Unmitigated Consequences</td></tr>
<tr><td>Radiological
Public: N/A
WG1: Moderate
WG2: N/A</td><td colspan="2">Chemical
Public: N/A
WG1: N/A
WG2: N/A</td></tr>
<tr><td colspan="4">Safety Function: Retain at least 95% of the catalyst granules inside the catalyst module.</td></tr>
<tr><td colspan="4">Method of Detection:</td></tr>
<tr><td colspan="4">Reduced thermal-hydraulic performance of the moderator loop, premature failure of circulator, perturbations of neutronic performance of associated moderator, rising radiation levels in HUR, High Bay, RTBT, and/or Shutter Drive Equipment Room.</td></tr>
<tr><td colspan="3">Preventive Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="3">Design: ASME B31.3, welded construction
Administrative: Periodic radiation surveys in affected areas, monitoring and trending of worker dose by radiological protection program, surveillance and maintenance of moderator loop performance, observation of shift in neutronic profile by instruments.</td><td>Robust design and fabrication of catalytic converter retention elements to prevent catalyst escape.</td></tr>
</table>

Table 6.1. Event CM4-1, exposure to activated catalyst media in RTBT (cont.)			
Mitigative Features – Attributes: **Design**: Seismic shielding around HTLs **Administrative**: Efficient work planning would typically reduce residence time and employ worker in activities in other areas.			**Credited:** None.
Planned Analysis, Assumption Validations, and Risks/Opportunities: This hazard analysis only takes advantages of the wire mesh screens of the retention elements because they are specified consistent with the granule size distribution, but the Cerafelt elements are expected to provide a much higher degree of retention. Testing or other means of demonstrating Cerafelt's effectiveness could provide further reduction in consequences.	**Mitigated Consequences:** **Radiological** **Public**: N/A **WG1**: Negligible **WG2:** N/A	**Chemical** Public: N/A WG1: N/A WG2: N/A	**Mitigated Frequency** Extremely Unlikely
Notes:			

<table>
<tr><th colspan="4">Table 6.2. Event CM3-9, activated catalyst media dispersed by venting hydrogen via overpressure device</th></tr>
<tr><td colspan="4">Event Description: o-p catalyst media circulates in the moderator loop, becomes activated. Overpressure in CMS loop vents hydrogen, dispersing activated media, potential for exposure (inhalation and immersion) by outside receptor (WG2 at 100-m)</td></tr>
<tr><td>Assumptions and Initial Conditions:
1. Catalyst activation consistent with CM4-1 assumptions.
2. Overpressure event occurs at the end of IRP life when catalyst is at peak radioactivity.
3. Atmospheric dispersion conservatively estimated by using the ground level release for a receptor at 100 meters.
4. The FSAD-NF approach to conservatively estimate dose due to inhalation from mercury spallation products, including an uncertainty factor of 1.575, is also applicable to the activated catalyst.</td><td colspan="2">Causes: As CM4-1, with the addition of an overpressure event in the CMS loop causing pressure relief actuation.</td><td>Initiating Event Frequency: Unlikely</td></tr>
<tr><td rowspan="2">Unmitigated Impact on Systems:
Contamination of the hydrogen venting header, vent stack, and roof of Target Facility.
Atmospheric release of radionuclides into the environment.</td><td colspan="3">Unmitigated Consequences</td></tr>
<tr><td>Radiological
Public: Negligible
WG1: N/A
WG2: Negligible</td><td colspan="2">Chemical
Public: N/A
WG1: N/A
WG2: N/A</td></tr>
<tr><td colspan="4">Safety Function: Not required.</td></tr>
<tr><td colspan="4">Method of Detection:</td></tr>
<tr><td colspan="4">As CM4-1 with the addition of CMS loop indications of relief actuation: alarms, interlocks including beam trip</td></tr>
<tr><td colspan="3">Preventive Features – Attributes:</td><td>Credited:</td></tr>
<tr><td colspan="3">Design: ASME B31.3, welded construction, robust design and fabrication of catalytic converter retention elements to prevent catalyst escape
Administrative: Periodic radiation surveys in affected areas, surveillance and maintenance of moderator loop performance.</td><td>N/A</td></tr>
</table>

Table 6.2. Event CM3-9, activated catalyst media dispersed by venting hydrogen via overpressure device (continued).

Mitigative Features – Attributes:	**Credited:**
Design: Vent path features (e.g. elbows) promoting fallout, vent stack shroud turns momentum down **Administrative**: Procedures and training make overpressure event less likely.	N/A

Planned Analysis, Assumption Validations, and Risks/Opportunities:	**Mitigated Consequences:**		
Consequences assessed above assume all material was respirable. Estimation of respirable fraction was not pursued due to low unmitigated consequences. A respirable particle is generally defined as having an aerodynamic diameter of 300 µm which is much smaller than most catalyst particles (US Standard sieve of 50 has an opening size of 297 µm). Consequences could be further reduced by characterizing the respirable fraction of the catalyst by evaluating the aerodynamic diameter distribution based on the geometric diameter distribution resulting from the sieving process.	**Radiological** **Public**: Negligible **WG1**: N/A **WG2:** Negligible	**Chemical** Public: N/A WG1: N/A WG2: N/A	**Mitigated Frequency** <EU

Notes:

The third safety basis concern that must be evaluated at the present CD-2/3 stage is whether additional hydrogen inventory could increase the assumed bounding consequences of previously evaluated hydrogen combustion accidents. If the effect were large enough to require additional credited engineered controls, they would have to be selected and evaluated. The modified CMS will have a total of 8 kg of H_2 (i.e., the sum total of H_2 held in all three CMS loops is ≤8 kg), compared with the previous total of 7 kg. The bounding consequences of postulated hydrogen explosion events are conservatively computed in the existing SNS safety basis accident analysis [6-5]. The entire inventory of H_2 is assumed to escape and mix in stoichiometric concentration with air over a pool of mercury (assumed to have spilled to maximize the source term) and to combust rapidly (i.e. by either deflagration or detonation). The source term released by the accident is directly proportional to the amount of hydrogen that undergoes the postulated rapid combustion. Thus, the new bounding consequences would increase by a factor of 8/7, or 1.143. This increase in consequences will need to be considered cumulatively with the increased spallation product inventory brought about by the higher proton beam energy that is part of the PPU project. For safety basis evaluations, the spallation product concentration is conservatively calculated at the end of the 40 years of operational life expected after initiation of post-PPU operations (which are scheduled to begin in about 2025). The two factors, taken cumulatively, will cause the consequences of the bounding unmitigated hydrogen combustion accidents to increase, with the greater amount of hydrogen increasing the amount of mercury made airborne, and the higher proton energy (after a lifetime of irradiation) increasing the amount of radioactive spallation products carried in or along with the airborne mercury.

The SNS policy for selection of safety-related credited controls [6-6] is used to determine how many credited LOCs are required for any particular postulated unmitigated accident, based on the bounding consequences. In safety basis terminology, an unmitigated accident is one in which control devices/features—either safety or non-safety—are assumed to not function (fail to function). Each required LOC must be able to mitigate consequences or prevent occurrence of the accident. As explained in the *FSAD-NF* [6-1], the SNS policy implements the graded approach to safety assurance in that the required number of LOCs depends not only on the consequence but also the frequency of the accident. The policy [6-6] can be summarized as follows:

- Public:
  - If unmitigated off-site radiological dose is between 5 rem and 25 rem, one LOC is required (accident frequency > 10^{-4}/year).
  - If unmitigated airborne concentration of chemically toxic substance (e.g., mercury vapor) exceeds the ERPG-2 level, one LOC is required.
  - If unmitigated off-site radiological dose exceeds 25 rem, two LOCs are required.
- Worker:
  - If unmitigated dose exceeds 25 rem anywhere on-site, one LOC is required.
  - If unmitigated airborne chemical toxicity exceeds ERPG-3 anywhere on-site, one LOC is required.
  - If unmitigated on-site dose outside the target building at 100-m exceeds 25 rem, two LOCs are required (frequency >10^{-4}/year).

A LOC required for any one of the policy elements is recognized as providing prevention/mitigation for all the policy elements. Therefore, for example, no more than two LOCs will be required for any given accident. Each LOC must be capable of providing the required mitigation or prevention.

As documented in the *FSAD-NF* [6-1], the first LOC for CMS safety basis accidents is the hydrogen boundary. The hydrogen boundary itself, the rupture disc, and the relief path leading to the rupture disc are safety-credited (i.e., in each of the three CMS loops). As part of that first hydrogen boundary LOC, the transfer line between the CMS cryostat (inside the core vessel) and the rupture disc (in the HUR) must be seismically qualified and protected against heavy objects falling onto it. Additionally, the relief line between the HUR and the roof-top discharge device is inert gas purged to further protect the relief function. All these elements complete the first LOC and ensure that the rupture disc can provide the credited relief function even in an earthquake. The second LOC for the CMS safety basis accidents is the vacuum layer boundary that surrounds the hydrogen boundary. The vacuum boundary LOC is analogous to the hydrogen boundary; its safety function is to provide a secondary path for controlled relief of hydrogen in the event of loss of the hydrogen boundary integrity. As explained in the *FSAD-NF* [6-1], the mission fulfillment (non-safety) function of the vacuum boundary is to thermally insulate the hydrogen so that it can be kept in the operationally required supercritical cryogenic state, at approximately 20 K. The very high vacuum that must be maintained in the vacuum layer provides an additional degree of safety because even very small through-wall failures of the hydrogen boundary would be detected. Any hydrogen gas in the vacuum layer would degrade the thermal insulation provided by the vacuum layer.

The current baseline consequences of postulated unmitigated accidents involving CMS hydrogen combustion are now compared against the post-PPU consequences considering the greater (7 versus 8 kg) hydrogen inventory and the higher post-PPU concentration of spallation products. Five hypothetical events involving hydrogen combustion are listed in the SNS safety basis:

- Hydrogen combustion without follow-on fire (CM2-1b)
- Hydrogen combustion with follow-on fire (CM2-1a)
- Crane load drop with hydrogen combustion (HB2-2)
- Seismic event with follow-on hydrogen combustion (no fire) (BG7-3)
- Seismic event with follow-on hydrogen combustion and fire (BG7-1)

Consequences are calculated and reported in [6-5] only for the first (CM2-1b) and last (BG7-1) events. Other events are listed as having consequences bounded by those of event BG7-1. Thus, for the present purposes, Table 6.3 addresses consequences of unmitigated hydrogen combustion (CM2-1b) and for a seismic event with follow-on explosion and fire (BG7-1), considering the cumulative effect of greater hydrogen inventory and greater spallation product concentration. The results reported in the table were calculated by multiplying the results computed for the greater spallation product concentration [6-6] by the hydrogen inventory increase factor of 8/7. Table 6.3 does not show the mercury vapor chemical toxicity numbers associated with hypothetical release because radiological consequences require more stringent controls.

As can be seen from Table 6.3, the consequence increases associated with the PPU modifications (8 kg versus 7 kg of H_2 inventory and worst-case mercury spallation product concentration taken at end of facility life about 46 years in the future) are numerically significant, with an 88% increase to the hydrogen combustion radiological consequences and a 64% increase in seismic event consequences. Nevertheless, per [6-6], these increases do not require any additional credited controls over the two LOCs described above, the H_2 boundary and the vacuum boundary (including associated relief paths and rupture discs with seismic qualification, and so on). This result supports the conclusion that the SNS safety basis is not adversely affected.

Furthermore, one could consider whether additional safety-credited mitigations besides the two LOCs identified and discussed above might be warranted. This is examined below for each of the two bounding accidents.

For the postulated H_2 combustion event CM2-1b, the following factors weigh against requiring additional means of prevention or mitigation.

- H_2 detonation or deflagration in the presence of spilled mercury is an unlikely event. Both credited LOCs are reliable, passive features that would function to prevent H_2 from escaping into the core vessel with possible combustion in the presence of mercury. Thus, both credited LOCs prevent, rather than reduce or minimize, the hypothetical consequences.

- The fact (not credited in the safety analysis) that the core vessel is maintained under a helium atmosphere during routine operation means that hydrogen escaping from the CMS into the core vessel would vent through the initially inerted core vessel vent path to outside the building, where any subsequent combustion would be far away from any target mercury and thus not a safety basis concern. This and other conservatisms in the unmitigated consequence calculations mean that the stated consequences are greatly exaggerated above realistically achievable values.

- The low-temperature cryogenic operation required for CMS operation provides inherent passive protection against boundary failure. The CMS cannot operate with a significant H_2 leak because of the necessity of maintaining an effective vacuum layer for thermal insulation of the H_2 at 20 K. Furthermore, in the event that the vacuum were spoiled, the system is designed such that increasing hydrogen pressure would deploy the rupture disc and be vented outside the building (above roof level) without the need for any automatic or human actions.

For the postulated seismic event (BG7-1) with follow-on H_2 explosion and fire, the following factors weigh against requiring additional means of prevention of mitigation.

- The frequency of the SDC-3 level seismic event [6-8] is, by definition, on the order of 1 per 2,000 years. Furthermore, the SNS safety basis makes no attempt to show that the assumed occurrence of follow-on H_2 combustion and fire would drive the frequency even lower.

- The helium atmosphere maintained in the core vessel (not credited in the consequence calculation) during routine operation would cause any hydrogen that escapes into the core vessel during a seismic event to either vent from the core vessel away from any target mercury (which would not be a safety basis concern), or vent to the target service bay because of seismic failure of the core vessel seals (which would result in less efficient combustion if ignited). Any H_2 remaining in the core vessel would not be combustible until air had a chance to diffuse back into the core vessel. Thus, possible subsequent H_2 combustion would involve a much smaller amount of H_2 (i.e., much smaller than 8 kg). This and other conservatisms made in the unmitigated consequence calculations means that the stated consequences are greatly exaggerated above realistically achievable values.

- As with the CM2-1b combustion event, the credited LOCs are preventive in nature and therefore would function to prevent any H_2 combustion that might occur during or following a severe seismic event.

Table 6.3. Unmitigated bounding radiological consequences of safety basis hydrogen combustion events: current FSAD-NF (pre-PPU) baseline versus post-PPU values.

Accident (frequency)	Radiological consequences (rem), Pre→Post PPU		Required Mitigation, Pre→Post PPU
	Public (MOI[a])	Worker @ 100 m	
CM2-1b: H_2 deflagration or detonation (Unlikely Event: 10^{-2}/y<frequency<10^{-4}/y)	2.1→3.9 (88% increase)	42→79 (88% increase)	2 LOCs, due to worker dose@100 m (2 LOCs = H_2 boundary + vacuum boundary) → same for post PPU
BG7-1: seismic event with follow-on H_2 explosion and fire (Unlikely Event: 10^{-2}/y<frequency<10^{-4}/y)	3.9→6.4 (64% increase)	79→130 (64% increase)	2 LOCs, due to worker dose@100 m (2 LOCs = H_2 boundary + vacuum boundary, also seismic qualification of same and of building structures) →same for post PPU

[a]MOI is most affected off-site individual at or beyond site boundary.

6.3 Conclusions

The risks associated with installation and operation of the described catalytic converters can be safely managed by using the existing layers of control, including the credited hydrogen and vacuum boundaries, and by crediting the retention elements in the catalytic converters.

Because of the multiple layers of both credited and noncredited layers of safety listed above for previously analyzed accidents, it is concluded that the two credited LOCs described are adequate to prevent consequences following the safety basis accidents in the CMS during post-PPU operation. Additional credited controls are not needed or warranted for events postulating a hydrogen explosion and would not provide significant risk reduction.

Robust design and quality fabrication of the retention elements in the catalytic converters provides assurance that no significant quantity of catalyst will escape, potentially affecting proper operation of the cryogenic hydrogen loop or leading to radiological dose to on-site workers.

6.4 References

6-1 *Spallation Neutron Source Final Safety Assessment Document For Neutron Facilities*, 102030102-ES0016-R03, September 2011.

6-2 R. M. Harrington and S. M. Trotter, *Preliminary Hazard Analysis in Support of the Proton Power Upgrade Project*, PPU-P01-ES0001-R00, May 2017.

6-3 *Vacuum Vessel Venting Analysis following Hydrogen Moderator Failure*, 1066020200-DA0002-R01, July 2003

6-4 *Hazard Analysis for Loss of Confinement of o-p Catalyst in Cryogenic Hydrogen Loop*, PPUP-103-TR0002-R00, June 2020.

6-5 *Master Engineering Calculation for SNS Target Facility Accident Analyses Supporting the Final SAD for Neutron Facilities*, SNS-102030103-CA0005-R01, April 2006.

6-6 *Spallation Neutron Source Policy for Selection of Safety Related Credited Controls*, 102030100-ES0005-R00, March 2005.

6-7 R. M. Harrington and S. M. Trotter, *Effect of PPU Increased End-of-life Spallation Product Inventory on Radiological Consequences of Hypothetical SNS Accidents*, PPUP-103-ES0002-R00, September 2018.

6-8 *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, DOE STD-1020-2002, US Department of Energy, January 2002.

7. Unreviewed Safety Issue Determination and Preliminary Safety Evaluation of Inadvertent Application of Excessive Power onto the SNS Mercury Target

7.1 Introduction

The PPU PHAR [7-1] addresses operation of the accelerator with sustained beam on the first target at up to 2 MW and states that operation at 2.8 MW will not take place until after the installation of the proposed STS (currently in conceptual design) and only after the completion and approval of additional safety documentation (i.e., for the STS, for any additional accelerator ring or transport line modifications, and for safety considerations of coordination between target stations). It was assumed during PHAR development that noncredited controls would make it implausible for the first target to receive a 2.8 MW sustained beam. As a result of an internal review held in February 2019, it was decided that the possibility of inadvertently exposing the SNS FTS mercury target to the full proton beam capability needed to be included in the CD-2 hazard analysis report. Therefore, this section provides a USI determination and CD-2 level safety evaluation for a hypothetical accident in which it is assumed that the maximum possible sustained post-PPU proton beam power of 2.8 MW is directed onto the mercury target of the FTS. The maximum beam power specified in the *FSAD-NF* [7-2] is 2.0 MW and the maximum proton energy is 1 GeV. The approved SNS Accelerator Safety Envelope (ASE) requires that the proton beam power stay within the following limitation: "When beam is directed to the Target, beam power shall not exceed the nominal 2MW limit by more than 10%, averaged over any 1 minute period."

The ASE limit allows temporary beam powers above 2 MW provided that the integrated energy deposition does not exceed 132 MW-s (MJ). For example, a beam power of up to 2.2 MW would be acceptable for up to 60 sec. Similarly, a beam power of 2.8 MW would be acceptable for as long as 47 sec.

Currently, the accelerator cannot physically produce a beam of time-average power significantly in excess of 2 MW. Moreover, a proton energy significantly exceeding 1 GeV is not possible without installation of at least some of the additional seven cryomodules planned as part of the PPU project. The PPU project will upgrade the accelerator power production capability from 2 MW to 2.8 MW and the particle energy from 1 GeV to 1.3 GeV. Since the post-PPU accelerator will be able to produce a 2.8 MW beam, this is a new situation that needs to be evaluated for PPU safety documentation to determine whether it is a USI. Before making the determination using the six USI screening questions, the potential causes and ramifications of a proton beam greater than 2 MW impacting the FTS are described.

As part of the PPU project scope, the FTS is being analyzed to ensure it can withstand loads (temperatures, thermal stresses, etc.) associated with an incident proton beam of 2 MW and proton energy of 1.3 GeV. This is the steady-state, pre-accident operating condition for this USI determination. Until the Second Target Station (STS) is completed, this will be the steady, pre-accident operating beam power for the accelerator, as well.

For the post-PPU beam on the FTS to exceed 2 MW, the average current of pulses from the accelerator front end would have to undergo a net increase, and the fractional increase in current would have to be sustained through the length of the accelerator. The front end average current demand would have to be set above the level consistent with the desired 2 MW operating level, and all automatic and administrative controls intended to prevent excessive beam on target would have to fail. These conditions would involve more than a single failure and thus not be a very likely event. After the STS becomes operational, the likelihood of inadvertently impacting the FTS with a 2.8 MW beam would increase because a single, sudden failure of the kicker that extracts pulses for the STS would place the entire 2.8 MW onto the FTS.

Chief among the ramifications of excess power up to 2.8 MW on the FTS would be the greater heating rates into the target module and other structures not separated by shielding from the primary and secondary radiation cascade of the proton beam as it interacts with the target. An increase in energy per pulse on target would immediately increase the transient peak thermal and pressure stress levels in the walls of the target module. Inadvertently directing a higher frequency of pulses onto the target (e.g., as could be possible, though unlikely, in the future after the STS is built and begins operating) would increase the heat load and the rate of buildup of stress cycles. Premature failure of the target module would be likely in this circumstance without mitigation. However, neither the target module nor the water-cooled shroud are defined as safety-credited systems. If accompanied by simultaneous failure of the water-cooled shroud, mercury leaking from the module could fall into the core vessel. As documented in the current *FSAD-NF* [7-2], the core vessel, including the core vessel inserts and neutron beam windows, has the safety-credited mission of protecting workers by confining mercury that might leak or spill into it. Therefore, workers would be protected by existing credited controls.

Bounding thermal analyses to check for coolant boiling with steady 2.8 MW beam operation onto the FTS were performed for key components of the target station, including the core vessel, the core vessel inserts that house the neutron beam windows, the outer reflector plug, the proton beam window (aluminum design), the target module water-cooled shroud, and the water-cooled portion of the CMS vacuum boundary [7-3],[7-4]. Only the first (core vessel including inserts and neutron beam windows) and the last (CMS vacuum boundary) are safety-credited engineered controls within the FTS. Adequate margin against coolant boiling at 2.8 MW was determined in all cases for time periods of 1 min or less. Boiling could occur after longer periods if the temperature of cooled surfaces should exceed the local boiling point of the cooling water. Except for the proton beam window, analyses were done with heating power based on 1.3 GeV proton energy. The proton beam window analysis was done with an energy deposition rate consistent with overall 2.8 MW beam power and 1.0 GeV protons, which is higher than what it would be with 1.3 GeV protons for that component. These preliminary analyses show that the safety-credited components would continue to be adequately cooled in the immediate period after an inadvertent increase in beam power to 2.8 MW, but continuing this level of beam on target could allow boiling to begin as the various components begin to heat up. The occurrence of boiling would be a beyond-design basis condition since the flow paths with boiling could experience flow starvation and unpredictable flow and temperature swings. Moreover, the thermal stresses on these safety-credited structures have not been evaluated for a 2.8 MW beam on target, so the intermediate and long-term effects remain uncertain. As part of the PPU scope, beam power measurement capability is being developed for the PPS that will allow it to monitor power to the FTS and trip the beam if power exceeds the setpoint. Machine protection setpoints will be implemented to ensure margin to coolant boiling is maintained in the credited systems.

7.2 USI Determination

As used in each of the following USI determination questions, the "change" means the PPU modifications that make it possible for a proton beam of up to 2.8 MW in thermal power to be inadvertently directed onto the FTS.

Question 1. Could the change significantly increase the probability of occurrence of an accident previously evaluated in the FSADs? Yes __ No _X_

Justification: The *FSAD-NF* evaluates several accidents with potential consequences similar to excessive beam power. The following event descriptions are from the SNS hazard analysis report ([7-5], as referenced in the *FSAD-NF*):

> **TS3-1**, frequency A (anticipated event)→ Beam Misalignment (Focused Beam): Release of radioactive Cooling Water from Proton Beam Window due to overheating of the Proton Beam Window caused by a partially expanded beam or a focused beam. Release of cooling water into RTBT Line and Core Vessel. Assumes that the Proton Beam Window would fail before Target fails.) Causes: Malfunction in the Beam Expander mechanism
>
> **TS3-2**, frequency A→Description: Beam Misalignment (Focused Beam): Release of radioactive Hg from Target and activated water from shroud cooling and window cooling systems due to overheating caused by a partially expanded beam or a focused beam. Proton Beam Window and Target Module are assumed damaged due to a focused beam. Causes: Malfunction in the Beam Expander mechanism.
>
> **TS3-4**, frequency U (unlikely event)→ Description: Release of Hg and activated shroud cooling water into Core Vessel due to catastrophic failure of target module caused by loss of material integrity. Causes: Loss of material integrity; Manufacturing error; High Coolant Pressure; Material fatigue caused by thermal cycles.

The event descriptions show that the current FTS safety analyses consider an event similar to accidental increase in total beam power on target (i.e., failure to expand the beam with an increase in areal density of the beam impacting the nose of the target module) so that some of the effects of excess beam power would be experienced without an increase in total beam power. For the nose of the target module, local stresses associated with the failure to expand the proton beam could equal or exceed those of the postulated 40% increase in total beam power. For this evaluation, a 2.8 MW beam incident upon the FTS is assumed to cause failure of target module boundaries—the target water-cooled shroud boundary, which holds the cooling water, and the target module mercury boundary. For mercury to leak into the core vessel, both the mercury and the water boundaries would have to fail. As stated in Section 7.1, neither of these boundaries is safety-credited. The definitions of events TS3-1 and TS3-2 express that each of these is already assumed to be in the highest event frequency category and thus, their frequency would not significantly increase by the postulated inadvertent 2 MW to 2.8 MW increase in beam power. The answer to this question is “No” for accidents TS3-1 and TS3-2.

Event TS3-4 is rated as an unlikely event. During post-PPU but pre-STS operations, the routine operating power of the accelerator will be 2 MW, so there is no single likely failure that could cause the accelerator to put more than 2 MW onto the FTS for an extended period of time and thus cause premature failure of the target module or other components. Thus, event TS3-4 remains in the “U” category and the answer to this question is “No.”

Another previously evaluated accident whose frequency could be affected is event TS4-1.

> **TS4-1** (Unlikely Event), Description: Inadvertent actuation (or routing) of beam to the Target Service Bay when the Target carriage has been withdrawn from the Core Vessel for maintenance or retargeting. Causes: Failure of interlock, Operator Error.

In the future, TS4-1 is a potential concern in that the STS could likely be operated routinely while the FTS is down for maintenance. The *FSAD-NF* places TS4-1 in the Unlikely category, so while it is possible such an operating mode would make beam incident on the FTS with carriage withdrawn more likely to occur, it is beyond the scope of this USI determination because this evaluation addresses post-PPU operation of the accelerator STS during the period before the STS becomes operational. Thus, the answer is also "No" concerning event TS4-1.

Question 2. Could the change significantly increase the consequences of an accident previously evaluated in the FSADs? Yes __ No _X_

Justification: The consequences of most of the FTS accidents documented in the *FSAD-NF* depend largely on the amount of spallation products that become airborne, and the radiological toxicity of the spallation products is dominated by the following four spallation products: Hg-197, Hg-203, Gd-148, and I-125. All these dominant radionuclides have half-lives much greater than 24 h. The target would not credibly be operated at much higher than nominal maximum beam power level for a long enough period (i.e. days) to significantly impact the inventory of dominant radionuclides. Therefore, this question is answered "No" regarding impact on spallation product activity and thus radiological consequences of mercury release accidents.

Of the hazard events addressed in the *FSAD-NF*, only one would have a consequence directly related to the proton beam power: TS4-1. Since the *FSAD-NF* already places the unmitigated onsite consequences of this event in the High category (radiological exposure > 100 rem), the question would be answered "No" regarding this accident.

Question 3. Could the change significantly increase the probability of occurrence of a malfunction of equipment important to safety previously evaluated in the FSADs? Yes _X_ No __

Justification: Safety-credited systems of the FTS that could conceivably be affected by the imposition of a 2.8 MW beam would include the following:

- Neutron beam windows: The safety-credited neutron beam windows are limited to an operating temperature of 130°C. Calculations have shown [7-4] that their temperature would not exceed that limit even for steady operation at 2.8 MW. Similarly, the core vessel inserts (which are part of the core vessel boundary and hold the neutron beam windows in place and are thus also safety-credited) are water-cooled and the same calculations have shown that they do not experience excessive temperatures in steady operation at 2.8 MW.

- The CMS hydrogen boundary: The safety-credited boundary is cooled by the supercritical H2 circulating inside it. If the CMS cooling system were not able to maintain the desired 20 K operating temperature because of the imposition of a 40% greater heat load, hydrogen temperature could increase. If hydrogen temperature increases significantly, the system is designed to automatically vent the H2 pressure (through a passive rupture disc) to the outdoors. Thus, the credited H2 boundary would not experience excessive temperature or pressure. The CMS vacuum boundary would also receive up to about 40% greater heat load in this postulated accident. It is cooled by water and a preliminary evaluation has shown that the cooling water would not boil for a heat load consistent with a 2.8 MW incident on the mercury target. However, accompanying thermal stresses and other factors have not been evaluated. Thus, degradation or failure is a possibility.

Since one of the above safety-credited components could experience degradation or failure due to excessive proton beam power, the probability of malfunction of a safety-credited system could increase as a result of excessive beam power on the FTS. Thus, based on currently available information, the answer to this question is "Yes."

Question 4. Could the change significantly increase the consequences of a malfunction of equipment important to safety previously evaluated in the FSADs? Yes __ No _X_

Justification: This postulated accident does not affect unmitigated accident consequences of failure of safety-credited equipment, so the answer is “No.”

Question 5. Could the change create the possibility of a different type of accident than any previously evaluated in the FSADs that would have potentially significant safety consequences? Yes _X_ No __

Justification: Impacting the target with significantly greater proton beam power than it has been evaluated and authorized for could be considered a new type of accident, so the answer to this question is “Yes.”

Question 6. Could the change increase the possibility of a different type of malfunction of equipment important to safety than any previously evaluated in the FSADs? Yes __ No _X_

Justification: Inadvertent excessive proton beam power on target is a USI because of its possible effect on safety-credited equipment, but postulated failure modes are the same as previously considered, so the answer to this question is “No.”

7.3 Safety Evaluation

It is concluded in Section 7.2 (Questions 3 and 5) that accidentally directing the full 2.8 MW post-PPS proton beam capability onto the FTS is a USI. Any potential excessive safety consequences will be prevented by the additional protective function being added to the PPS as part of the PPU project.

The existing power limitation in the SNS ASE [7-6] gives provision for exceedance of 2 MW by up to 10% averaged across one minute. Evaluation was performed to determine if this provision would remain acceptable if 2.8 MW were applied to the target for a duration such that delivered power would be equivalent to this limit (i.e. 132 MJ) [7-7]. This evaluation demonstrated that the existing limitation in the ASE is acceptable. A requirement document was written to reflect this decision and provide specific requirements for the Beam Power Limiting System (BPLS) to ensure the control prevents conditions from exceeding those evaluated [7-8].

Design of the BPLS is underway with a plan to validate its operational characteristics and provide proof of concept before it is needed as a credited control. The design will use Fast Current Transformers to measure beam current and monitor current to the windings of the DH-13 magnet to measure particle energy. These values will be combined to determine beam power. Integral beam power in a 1-minute rolling window will be compared against a setpoint consistent with the requirements of [7-8]. If integral power exceeds the setpoint, the BPLS will send a signal to the RTBT segment of the PPS to initiate a trip of the proton beam. Because the standard microprocessors associated with a PLC cannot process the beam current signal quickly enough, the BPLS will use redundant µTCA-based processing crates to calculate the integral power and determine the need for a beam trip. The beam trip signal will be passed to a safety PLC that will then communicate with the PPS RTBT PLC. The BPLS PLC may also provide monitoring for the µTCA processor and pass information to EPICS.

As described in the [7-9], the PPS is a credited engineered control that has proven to be a highly reliable system. The µTCA portion of the BPLS is being designed using a consensus standard from the aviation industry, DO-254 [7-10], where FPGA components, such as the µTCA crate, are used to provide safety functions. This standard provides guidance to ensure the FPGA-based components will be designed, manufactured, installed, and maintained using a level of rigor consistent with the existing parts of the PPS. The new trip function will meet the existing requirements (specified in the SNS ASE) for surveillance of the PPS. Therefore, the same high degree of safety associated with SNS operations will be ensured for post-PPU operations.

7.4 References

7-1 R. M. Harrington and S. M. Trotter, P*reliminary Hazard Analysis in Support of the Proton Power Upgrade Project*, PPU-P01-ES0001-R00, May 2017.

7-2 *Spallation Neutron Source Final Safety Assessment Document For Neutron Facilities*, 102030102-ES0016-R03, September 2011.

7-3 Barbier, C., *Evaluation of key FTS components at 2.8MW*, PPUP-500-TR0002-R00, under preparation.

7-4 Martinez, O., *Core Vessel Insert Thermal Structural Analysis with PPU Beam Operation*, PPUP-507-DA0001-R00, August 2019.

7-5 *Spallation Neutron Source Target Facility Hazard Identification and Evaluation,* SNS 102030102-ES0017-R00, Oak Ridge National Laboratory, Oak Ridge, TN, October 2005.

7-6 *SNS Accelerator Safety Envelope (ASE): for Full Power Operations of the Front End, Linac, Ring, Transport Lines, Beam Dumps, and Target*, 102030103-ES0016-R05, May 2007.

7-7 Barbier, C., *Evaluation of key FTS components at 2.8MW*, PPUP-500-RE002, R00, November 2019.

7-8 *Requirements for Limiting Power to the FTS after PPU Accelerator Upgrades*, PPUP-500-TS0001, R00, August 2019.

7-9 *Spallation Neutron Source Final Safety Assessment Document for Proton Facilities*, 102030103-ES0018-R02, December 2010.

7-10 RTCA, *DO-254/EuroCAE ED-80 Design Assurance Guidance for Airborne Electronic Hardware,* Washington, D.C.: RTCA SC-180, 2000.

8. Overall Conclusions

This report updates the hazard analyses of the USIs identified in the PPU PHAR report, plus one other USI identified during the CD-2 design activities. The level of detail is consistent with the current CD-2/3 design stage of the project. The safety evaluations presented in this report conclude that the proposed PPU modifications are accommodated largely within the safety basis of the SNS, as supplemented by a small number of additional safety-credited controls. These are listed as follows.

For the capability to inject up to 20 SLPM of helium into the target module:

- Designating the existing administrative controls on access to the GA room as safety-credited administrative controls will prevent worker entry in the event of MOTS off-gas line breakage upstream of the ambient temperature CAs.

- Adding passive design features as described in Section 5 eliminates the need for additional engineered controls. For example, the proposed overflow tank has the capacity to accommodate credible void shedding events. The routing of the helium supply tubing from high above the target module eliminates the possibility that mercury could escape from the target service bay by backflow.

For the addition of catalytic converters into the CMSs:

- Incorporating a robust screen/filtration arrangement will ensure retention of at least 95% of the granular catalyst material within the catalytic converter vessel preventing worker exposure to activated catalyst media.

For operation of the mercury target at 2 MW with a 2.8 MW-capable accelerator:

- Adding an additional beam power sensing and cut-off feature to the PPS that will terminate the proton beam in the event of excessive beam power on target.

It is expected that the design of the PPU modifications will continue to evolve during subsequent stages of the PPU project. The safety evaluations presented in this report will be refined and possibly changed as necessary to assess safety impacts of design evolution. Finally, the existing SNS safety assessment documents [8-1, 8-2] and accelerator safety envelope [8-3] will be modified to incorporate the PPU modifications.

8.1 References

8-1 *Spallation Neutron Source Final Safety Assessment Document for Neutron Facilities*, 102030102-ES0016-R03, September 2011.

8-2 *Spallation Neutron Source Final Safety Assessment Document for Proton Facilities*, 102030103-ES0018-R02, December 2010.

8-3 *SNS Accelerator Safety Envelope (ASE): for Full Power Operations of the Front End, Linac, Ring, Transport Lines, Beam Dumps, and Target*, 102030103-ES0016-R05, May 2007.