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Preliminary Hazard Analysis in Support of the Proton Power Upgrade Project

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OAK RIDGE NATIONAL LABORATORY
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1. INTRODUCTION

This preliminary hazard analysis report (PHAR) has been prepared as part of the Critical Decision 1 (CD-1) process for the Spallation Neutron Source (SNS) Proton Power Upgrade (PPU) Project. It will be updated at appropriate stages as the project proceeds. Descriptions of specific upgrades proposed as part of the PPU Project are provided in the PPU Conceptual Design Report (CDR) [1].

The SNS is an existing Department of Energy (DOE) accelerator facility that has been operating since 2006, compiling a record of safe operations in full compliance with DOE and Oak Ridge National Laboratory (ORNL) requirements. The safety of the SNS was reviewed and operations authorized in accordance with the Accelerator Safety Order, DOE O 420.2C. The SNS safety assessment document (SAD) comprises two volumes. The *SNS Final SAD* [FSAD] *for Proton Facilities* [2] addresses operations from the ion source (front end) through the ring-to-target beam tube, including ancillary support facilities. The *SNS Final SAD for Neutron Facilities* [3] covers all operations in the target building: target, target support systems, and the neutron instruments. The SAD describes safety management of the SNS and provides hazard analyses for significant and unique accelerator hazards. As explained in the SAD, standard industrial or common research laboratory hazards are controlled under the Oak Ridge National Laboratory (ORNL) integrated safety management program including promulgation of environment, safety, and health requirements through the ORNL Standards Based Management System (SBMS).

The preliminary hazards analysis requirement of DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets*, for the proposed SNS PPU project is fulfilled in this document using the approach outlined in the *Accelerator Facility Safety Implementation Guide for DOE O 420.2C, SAFETY OF ACCELERATOR FACILITIES* (DOE G 420.2-1A). Specifically, in Section 2.1 of the guide,

> "Accelerator projects at existing accelerators that require formal project management would follow a similar approach; however, in this instance, the SAD and ASE will already be in place. The SAD and USI process may be used to address 413.3B hazard assessment requirements as appropriate. A project-specific HA may still be developed to meet the needs for project management, and the USI process could be used to determine if the new project potentially introduces significant safety consequences or risk beyond those already addressed in the facility's SAD."

Therefore, this hazard analysis focuses on significant changes proposed as part of the PPU project and whether any of them constitutes an unreviewed safety issue (USI). Detailed analyses of the hazards that are USIs will be submitted for DOE approval at the appropriate stage of PPU project authorization and construction. As explained in the existing SNS SAD [2, 3], hazard and accident analyses for both proton facilities and neutron facilities were conducted assuming 2 MW proton beam power and 1.0 GeV maximum beam particle energy. SNS shielding was designed to accommodate beam power of 2 MW or higher and particle energy of 1.0 GeV. The SNS Accelerator Safety Envelope (ASE) authorizes operation at a beam power of 2 MW.

Although authorized to operate with a proton beam power of 2 MW, the SNS has been operating routinely at about 1 MW to provide extended life of the periodically replaced target modules, the walls of which are subject to cavitation erosion by mercury. A major aim of the PPU is to modify the target to allow injection of helium bubbles into the flowing mercury in the target module, and therefore allow the target to operate with a 2 MW proton beam on target with an acceptable target module service life. Another major target modification is the proposed incorporation of a catalytic converter in each of the three cryogenic moderator systems to allow control of the isomeric composition of the hydrogen moderators by conversion of ortho-hydrogen into para-hydrogen.

The other major aim of the PPU Project is to make the accelerator capable of producing a 2.8 MW beam. This requires an increase in beam particle energy from 1.0 GeV to 1.3 GeV and an increase in beam ion current capability. The specific modifications needed to do this are described in Chapters 2 through 7 of the PPU CDR [1]. Although PPU upgrades involve the physical capability to operate with a 2.8 MW proton beam, the SNS will—after completion of the PPU modifications—continue to operate within the current nominal 2 MW power limitation as specified in the DOE approved SNS Accelerator Safety Envelope (*SNS Accelerator Safety Envelope (ASE) for Full Power Operations of the Front End, Linac, Ring, Transport Lines, Beam Dumps and Target*, SNS-102030103-ES0016-R05, May 31, 2007). The 2.8 MW beam power capability will not be needed until after installation of a second target station (i.e., a new target building with included target systems and associated research instrument facilities). Thus, the safety of routine accelerator operation to 2.8 MW and the safety of the possible second target will be evaluated later as part of the second target station project. With an estimated PPU project completion date in 2025, the PPU project will have the effect of extending the nominal life of the first target facility to 60 years since target operations commenced in year 2006.

Except for the specific potential unreviewed issues (USIs) evaluated below, the PPU modifications have been screened and determined to come under the category of new equipment that can be installed and operated in accordance with ORNL SBMS and the existing SNS FSAD. Specific proposed PPU modifications that are deemed to justify evaluation to see if they are USIs, as defined in DOE O 420.2C, are listed below. For any that are determined to constitute a USI, a safety evaluation will be prepared to address the adequacy of the existing safety credited controls and define any additional necessary safety credited controls. Based on the guidance of DOE G 420.2-1A, this safety evaluation will undergo contractor internal independent review and DOE review leading to accelerator readiness review before operations are commenced with the PPU upgrades in place.

- Increased beam particle energy from 1.0 GeV to 1.3 GeV—effect on beam spill accidents
- Increased beam particle energy from 1.0 GeV to 1.3 GeV—effect on target spallation product inventory considering increased particle energy as well as longer (60 y) nominal target facility lifetime
- Increased beam particle energy from 1.0 GeV to 1.3 GeV—effect on target core vessel component heat deposition distribution
- Increased helium inventory in the superconducting linac
- Increased activation inside the proton beam enclosures
- Increased maximum sustained beam to the ring injection dump from 150 to 200 kW.
- Possible need for additional personnel protection system (PPS) interlocked area radiation monitor coverage in area of the ring-to-target beam-transport (RTBT) tunnel second target station tunnel stub-out
- Injecting helium into the circulating target mercury in the target module to reduce the rate of cavitation erosion of the target module and increase fatigue life margin
- Increased hydrogen inventory of the target cryogenic moderator system due to the proposed installation of a catalytic conversion stage to convert ortho-hydrogen into para-hydrogen.

2. EVALUATION OF POTENTIAL USIS

Each of the potential USIs identified above is evaluated in this section to determine whether it introduces significant safety consequences or risks beyond or different from those already addressed in the SNS SAD. There are seven ways in which a proposed modification can be an unreviewed safety issue:

1. Could the change significantly increase the probability of occurrence of an accident previously evaluated in the authorization basis?

2. Could the change significantly increase the consequences of an accident previously evaluated in the authorization basis?

3. Could the change significantly increase the probability of occurrence of a malfunction of equipment important to safety previously evaluated in the authorization basis?

4. Could the change significantly increase the consequences of a malfunction of equipment important to safety previously evaluated in the authorization basis?

5. Could the change create the possibility of a different type of accident other than any previously evaluated in the authorization basis that would have potentially significant safety consequences?

6. Could the change increase the possibility of a different type of malfunction of equipment important to safety other than any previously evaluated in the authorization basis?

7. Could the change significantly reduce the margin of safety as defined in the ASE (list any affected part(s) of ASE in the Justification)?

2.1 INCREASED BEAM ENERGY FROM 1 GEV TO 1.3 GEV: EFFECT ON BEAM SPILL ACCIDENTS IN ACCELERATOR TUNNEL

The potential hazard of prompt radiation outside beam enclosures during beam spill accidents is evaluated for 2 MW/1.0 GeV beams in Sections 4.3.1 and 4.4.1.2 of the *SNS FSAD for Proton* Facilities [2]. The installed passive shielding, the automatic machine protection system (MPS), and the safety credited automatic Personnel Protection System (PPS) ensure risk is extremely low. Installation of the proposed seven additional cryomodules in the space previously reserved for them at the high energy end of the linac allows the particle energy to reach 1.3 GeV. This increase in energy coupled with a modest increase in ion current (i.e., ~10% over the beam current maximum previously reached under 1.4 MW/1.0 GeV conditions) will bring the post-PPU beam power to 2 MW. If the dose rate outside the tunnel shielding berm following a beam loss (mis-steering, etc.) accident were substantially larger for a 2 MW/1.3 GeV beam versus the present maximum design 2 MW/1.0 GeV beam, this would constitute a USI due to possible increased accident consequences. This question has been investigated using the Sullivan method. The results [4] show that the estimated difference in the most crucial (shortest distance through the shielding) 90-degree direction for unmitigated beam loss accidents is small – approximately one percent. The difference is greater in the forward direction but it would be compensated by the greater distance of shielding through which a mis-steered beam would have to travel. This small increase in unmitigated dose consequence is not significant because the mitigation by shielding, the MPS, and the PPS ensure the overall mitigated risk remains in the extremely low category. Therefore, the beam loss accident analysis presented in the *SNS FSAD for Proton Facilities* [2] is still valid and the increased beam energy is, from the perspective of beam loss accidents, not an unreviewed safety issue.

Operating the SNS with 1.3 GeV beam particles does not constitute a USI with regard to beam spill accidents for the following reasons.

- Effect on accident consequences: the 1.3 GeV beam can increase possible radiation dose rate outside the beam enclosures in the event of a beam loss accident but the increase is on the order of 1%--a negligible amount from a hazard analysis perspective.

- Accident probability of occurrence: there is no known mechanism through which the higher energy particles will lead to more frequent beam loss accidents.

- Effect on credited safety systems: 1.3 GeV versus 1.0 GeV energy is not expected to have a detrimental effect on relevant safety systems. For example, the PPS interlocked area radiation monitors that the PPS utilizes work as well on 1.3 GeV particles as they do on 1.0 GeV ones.

- Ability to cause different kind of accidents: Higher energy particles have no way to enable a different kind of accident than previously evaluated since the beam is produced and utilized in the same way at both energies, both before and after the PPU upgrades.

- The current ASE beam power limit of 2 MW will not change for operation after installation of the PPU upgrades.

2.2 INCREASED BEAM ENERGY FROM 1 GEV TO 1.3 GEV: EFFECT ON TARGET MERCURY SPALLATION PRODUCT RADIONUCLIDE INVENTORY

The hazard and accident analyses of the mercury target in the *SNS FSAD for Neutron Facilities* [3] present source terms for hypothetical unmitigated airborne mercury release accidents in terms of fractional release of groups of radionuclides in the spallation product inventory. Depending on physical stresses and energy sources that occur in each accident, the hypothetical fractional release of different groups of spallation products differs. The groups of spallation products range from gaseous nuclides to non-volatile solids to mercury which is semi-volatile.

Although there are literally hundreds of spallation products, the accident consequences (radiation doses to persons) are dominated by a small handful of radionuclides. Foremost of these is gadolinium-148 (Gd-148), with mercury-197 and mercury-203 (Hg-197, Hg-203) following closely. Although the element gadolinium is a non-volatile solid, its isotope, Gd-148, dominates accident consequences because Gd-148 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.

The most recent calculations [5] of long term target operation after 60 years (i.e., operations under current limitations beginning in 2006 and extending to 2025, followed by 40 years at 2 MW/1.3 GeV after completion of PPU modifications) show that the Gd-148 activity reaches a level about twice that of earlier predictions for 40 years of operation. Much of this increase is due to the longer 60-year time period now involved versus the previous 40-year period—which is important for Gd-148 with its 74-year half-life—but the higher-energy protons and other factors affect the spallation product yields as well. This end-of-facility-life doubling of the most dominant radionuclide is estimated to increase the predicted doses for hypothetical unmitigated accidents, with increases ranging from less than 3% up to about 60%, depending on the type of accident involved. ***The top end of this range of increase is significant so this concern is defined to be a USI.*** Therefore, the *SNS FSAD for Neutron Facilities* will need to be modified to restate the increased unmitigated accident dose consequences with the 60-year, end of facility life spallation product inventory in order to ensure that safety credited features provide adequate prevention or mitigation. The evaluations will be submitted to DOE for review before post-PPU operations. The higher end-of-life spallation product inventory is not expected to constitute a safety problem for two reasons: (1) the projected end-of-life consequences for unmitigated accidents do not exceed thresholds that would require additional safety credited controls, and; (2) the mitigated consequences of accident initiators are made negligible by several layers of protection that exist for each accident to eliminate or greatly diminish the potential for airborne release.

2.3 INCREASED BEAM ENERGY FROM 1 GEV TO 1.3 GEV: EFFECT ON TARGET CORE VESSEL COMPONENT HEAT DEPOSITION DISTRIBUTION

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.***

2.4 INCREASED HELIUM INVENTORY IN THE SUPERCONDUCTING LINAC

The installation of the proposed seven additional cryomodules in the space previously reserved for them at the high energy end of the linac will bring the inventory of cryogenic helium in the tunnel from 19,000 liters to about 23,200 liters (about 600 liters per new cryomodule), an increase of about 22%. As discussed in Section 3.3 of the PPU CDR [1], the existing cryoplant has excess capacity to handle the additional heat load added by the seven new modules.

The hazard analysis in Appendix F of the *SNS FSAD for Proton Facilities* [2] presents two different hypothetical accident scenarios bounding helium release events in the tunnel. The first is a hypothetical large scale helium boundary failure of one cryomodule. Since this existing analysis assumed rapid release of about 1000 liters of helium, it is bounding with respect to the 600-liter inventory of each of the seven new cryomodules. The second accident scenario is a 4-hour-long release of cryogenic helium from the transfer line from the cryoplant into the tunnel at an assumed rate limited by piping size and plant capacity. Since the transfer lines and cryoplant are not being increased in size this accident is also bounding with respect to the installation of the seven new cryomodules.

The bounding nature of the helium release accidents considered in the existing SNS SAD, and the answers to the other USI criteria as listed below show that the ***installation and operation of the seven new cryomodules does not constitute a USI***:

- Effect on accident consequences: no effect since the existing analyses are bounding as discussed above.
- Probability of occurrence: helium release accidents are not more likely to occur due to incremental improvements incorporated into the helium and vacuum pressure boundaries. For example, the new cryomodules have ASME code–compliant pressure boundary and relief devices.

- Effect on credited safety systems: The existing credited safety features and systems—in their present configuration—are more than adequate to ensure oxygen deficiency hazard (ODH) safety of workers in the linac tunnel or connected structures such as the front end or high energy beam transport (HEBT) areas. These include the 2.5-ft deep ceiling lintels at either end of the superconducting segment that are passive design features designed to impede the flow of escaped helium out of the linac tunnel and facilitate its removal to the outdoors by the emergency ventilation system. Neither the lintels nor the emergency ventilation intakes need to be moved because of installation of the new cryomodules in the previously designated space. The ODH safety system includes multiple oxygen sensors near ceiling level in the tunnel at locations adjacent to, and between, the lintels. Since the lintel at the high energy end of the linac is already positioned at what will be the high energy end of the superconducting segment, the currently installed safety system will accommodate the additional cryomodules without needing to be moved or changed.

- Ability to cause different kind of accidents: No new types of inert gas release accidents are anticipated because the new cryomodules are designed to operate analogously to the existing ones and the cryogenic refrigeration plant does not need to be upgraded for operation with the additional cryomodules.

- The current version of the SNS ASE specifies operability requirements for the credited ODH alarm system and the emergency tunnel ventilation system; it will not need to be changed to limit operations with the higher tunnel helium inventory introduced by the new cryomodules.

2.5 INCREASED ACTIVATION IN ACCELERATOR PROTON BEAM ENCLOSURES

Activation of structures in the accelerator proton beam enclosures is an expected and normal condition in a high power proton accelerator. High energy protons are very penetrating and any proton that escapes from the beam interacts with the beam tube and with surrounding structural materials, making them radioactive. The degree of activation that builds up in structures and equipment that surround the beam determines the residual radiation field present inside the tunnel after the beam cut off. The level of radiation within the tunnel has a large effect on the maintainability of the accelerator due to the need to keep worker radiation exposure as low as reasonably achievable (ALARA) while allowing a significant amount of hands-on maintenance.

The essential need to keep activation levels low was recognized during design of the SNS accelerator proton beam enclosures and continues to be a central theme of accelerator operations at SNS. The need is met through continuous improvement in operation and tuning of the accelerator. The beam loss feature of the MPS detects incipient beam loss and can automatically react in time to truncate the pulse train in mid pulse. The first 10 years of SNS operation have yielded activation levels in the tunnel whereby maximum residual radiation levels are, with a few exceptions, within the 100 mrem/h (at 30 cm) limiting “rule-of-thumb” for hands on maintenance activities (see Figure 2.10 of the CDR [1]). The pedestrian aisle of the tunnel generally does not exceed 0.1 to 0.2 mrem/h during periods when the tunnel is opened for general access by trained workers under the applicable radiation safety work permit. Specific equipment items in the ring injection area have typically had radiation levels as much as a factor of ten above the 100 mrem/h rule-of-thumb at certain point locations. The higher residual radiation levels in the ring injection area have necessitated additional posting and additional work controls such as radiation control technician consultation for any work in the area, and job specific radiation work permits in some cases in order to keep exposures ALARA.

SNS operations, maintenance, and radiation safety staff have cooperated in the diligent application of the ALARA principle to all operations and maintenance work, as required by the 10 CFR 835 compliant ORNL Radiation Safety Program. The cumulative total annual radiation exposure–summed for the entire

SNS work force—has averaged below 2 person*rems/year for the ~10 years of SNS operation. This is much less than the 5 rem/y regulatory limit for a single person. By a wide margin, no single SNS worker has ever exceeded the ORNL SBMS administrative limit of 0.6 rem/year.

Beam loss and residual activation/radiation are considered in Section 2.3 of the PPU CDR [1]. Hand calculation methods applicable to the physical mechanisms of beam loss are applied to estimate the extent to which losses and thus residual activity would increase if the accelerator were operated at 2.8 MW with 1.3 GeV protons versus the present maximum operations at 1.4 MW with 1.0 GeV protons. The results show that the tendency toward beam loss would approximately double the 1.4 MW/1.0 GeV levels. Although the PPS accelerator upgrades will provide a *capability* to achieve maximum beam power of 2.8 MW/1.3 GeV, the maximum sustained beam power achieved after installation of the PPU modifications will not exceed 2 MW/1.3 GeV. Interpolating the numbers from the discussion in CDR Section 2.3 [1] supports the conclusion that residual activity under the proposed post-PPU operations at 2 MW/1.3 GeV would be about 50% higher than those for 1.4 MW/1 GeV. This increase can be accommodated within the framework of the ORNL radiological protection program requirements by continued application of the operational improvement and radiation control practices that have been demonstrated during more than a decade of operations at SNS.

The possible increased levels of activation anticipated in the accelerator tunnel after installation of the PPU upgrades do not constitute an unreviewed safety issue because the potential increase is incremental and because of the demonstrated ability of the SNS to apply ALARA principles to accelerator operations and maintenance.

2.6 INCREASING THE MAXIMUM SUSTAINED BEAM TO THE RING INJECTION DUMP FROM 150 TO 200 KW

This proposed change does not meet any of the first five USI criteria because the water-cooled ring injection dump was originally designed to operate at steady state with a beam input power of 200 kW. Hazard evaluations were performed assuming this incident beam power, and there are no other significant changes to the injection dump proposed as part of the PPU project. The maximum steady state limit on operating power was decreased from 200 kW to 150 kW when conservative heat transfer studies showed that the temperature of the concrete structure surrounding the shielding blocks could exceed the design temperature of the concrete for long term 200 kW operation. This downgrading was done before the dump was operated with significant incident beam. It has not been a serious limitation for operations to date at beam powers below 1.5 MW because the fraction of beam sent to the ring injection dump is typically below 10% of the incident beam power. For the projected post-PPU beam power of 2 MW, it would be desirable if the limit could be increased to 200 kW (i.e., 10% of the expected 2 MW beam power).

Thermocouples installed in the beam dump have provided operational data that will allow the original thermal model to be benchmarked against actual operational data. The PPU engineering work scope includes improvement of the thermal model of the dump enclosure to ensure that the model is consistent with measured temperature data while retaining an appropriate degree of conservatism. If the improved thermal model predicts significantly lower concrete temperatures, then the calculations will be documented to provide the basis for increasing the ASE limit on incident beam power to the injection dump from the current 150 kW limit to something higher, with a goal of reestablishing a limit of 200 kW if justified. ***Reestablishing a 200 kW ASE power limit for the injection dump is a USI because it requires modification of the current SNS ASE***. DOE approval is required for all ASE changes.

2.7 POSSIBLE NEED FOR ADDITIONAL PPS INTERLOCKED AREA RADIATION MONITOR COVERAGE IN AREA OF THE RTBT TUNNEL SECOND TARGET STATION TUNNEL STUB-OUT

The PPU project includes the construction of a truncated section of new tunnel (the "stub-out") leading from the current RTBT tunnel for a relatively short distance toward where it could eventually be extended to a second SNS target station. The stub-out will be covered with earth berm shielding on its top and sides and its interior cross sectional area blocked with concrete or steel shielding blocks. This block shielding will be subject to the system of physical features and administrative controls that protect against unauthorized removal of shielding as described in the SNS FSAD for Proton Facilities (FSAD-PF, see Sections 4.2.1.2 and Table 4.3.1-6 [2]). Although the stub-out will be shielded in accordance with the SNS Shielding Policy, it is a penetration in the earth berm shielding and an additional area radiation monitor (ARM) (referred to in the FSAD-PF [2] as a "chipmunk" style monitor, meaning one that has been demonstrated to have appropriate sensitivity to both gamma and neutron radiations, two-channel interlock capability, fail-safe operational features, and robust failure-checking features) interlocked with the Personnel Protection System (PPS) may be required to provide assurance of worker safety consistent with the existing configuration of the accelerator.

The need for the additional PPS interlocked ARM will be confirmed after the completion of the PPU Project tunnel stub-out design and related shielding calculations. The SNS Radiation Safety Officer, subject to review by the SNS Radiation Safety Committee, "determines the location and the number of Chipmunks" (i.e., PPS ARMs--see FSAD-PF [2], Section 4.2.2.2 Real Time Radiation Monitors). The current number of PPS ARMs is 47 and they are spread from the front end to the target, as needed to perform their safety mission of maintaining the integrity of radiation area classifications. The 1.3 GeV particle energy provided by the PPU modifications is well within the detection capability of the SNS PPS ARMs which are of the type originally developed by Fermilab and utilized at other high energy accelerator facilities. However, it is possible that repositioning of some of the PPS ARMs in the high energy segments of the accelerator may be needed. The configuration of PPS ARMs will be optimized as needed for post-PPU conditions. ***The addition of one or more ARMs (or repositioning of one or more) would not be a USI because it does not meet any of the criteria for a USI***:

- The PPS, with interlocked ARMs, provides credited mitigation of accidents but has no impact on the frequency of occurrence of accidents or their unmitigated consequences.

- Adding another ARM interlocked with the PPS would not increase the likelihood of PPS failure because the additional ARM installation would meet the existing, proven design requirements and because post-maintenance testing and certification would ensure that the installation is done correctly. For the same reason, it is not considered credible that new types of PPS failure would be associated with installation of an additional ARM.

- Installing an additional ARM would not increase the consequences of PPS failure because the shielding provided in the second target station stub-out will be consistent with shielding of other openings in the SNS beam enclosures.

- The existence of an additional PPS-interlocked ARM cannot cause a different type of beam spill accident or other radiation related accident.

- The installation of the additional ARM and operation of the SNS with the additional ARM can be accomplished within the existing SNS ASE.

2.8 INJECTING HELIUM INTO THE CIRCULATING TARGET MERCURY—POTENTIAL EFFECTS ON PERFORMANCE OF TARGET PROTECTION SYSTEM INSTRUMENTATION AND POTENTIAL EFFECTS ON CONFINEMENT OF MERCURY WITHIN THE TARGET SERVICE BAY.

SNS has determined that acceptable target module service life at beam powers above 1.4 MW will require injection of helium bubbles directly into the target module near the point where the proton beams impact mercury in the nose of the target module.

Helium is currently injected into the mercury process loop at the mercury pump tank, a location that is well removed from the target module. Operation of the current SNS mercury loop involves the flow of helium into mercury in the pump tank for two purposes: (1) the mercury level sensor mechanism injects a low flow of helium bubbles into the pump tank, and (2) the mercury circulation pump seal injects a low flow of helium into the pump tank. These low flows of helium accumulate in the pump tank gas space and flow to the mercury off-gas treatment system (MOTS) via a loop seal—an elevated section of pipe high enough above the pump tank to prevent the possibility of inadvertent flow of liquid mercury into the downstream MOTS components. Most of the stages of the MOTS are in two rooms in the basement and are not shielded sufficiently to ensure safety in the event of uncontrolled escape of liquid mercury from the target service bay. The off-gas line loop seal is a safety credited passive engineered feature that prevents escape of liquid mercury from the target service bay in the event of overfill of the mercury pump tank.

The proposed injection of helium for pressure pulsation attenuation differs from the existing helium injection in that the helium for pressure pulsation must be injected near the target nose where the pressure pulses are created. The target module is a local high point of the mercury loop. The existing vent line in the target module is designed to vent minor amounts of gas back to gas space in the upper part of the mercury pump tank but it is not thought to be adequate to vent all the helium proposed to be injected directly into the target module back to the pump tank.

The accomplishment of helium injection at the SNS will take place in two stages. The first stage—not part of the PPU project—is a pilot program scheduled for implementation in 2017 to install modifications that will inject a low flow of small helium bubbles (up to about 2 standard liters per minute(SLPM)) into the flowing mercury near the nose of the target module. As indicated below, this first stage of helium injection will be extensively documented and must be approved by DOE before operation. The second stage comprises the PPU-funded modifications necessary to enable the injection of a larger flow of helium bubbles (<25 standard liters/minute). Even though the pilot program modifications are less extensive than those planned for PPU, the safety considerations are analogous: the helium gas must be injected in such a way that the escape of mercury out of the target service bay is prevented, the presence of helium in the loop must not interfere with the safety credited pump delta-P and mercury temperature instruments (part of the Target Protection System), and the helium must be collected and piped to the MOTS system in such a way that liquid mercury cannot escape from the target service bay into other spaces.

A supplemental safety evaluation for pilot program modifications and operation is being prepared to establish whether additional safety credited features are required. Successful review and approval of the supplemental safety evaluation will be required before initiation of operations with the pilot helium injection. Any additional required safety credited features will be incorporated into supplemental ASE requirements, which will require DOE approval prior to pilot program helium injection. Experience gained from the pilot program will inform the design and operation of the more extensive changes necessary for the PPU helium injection.

Long-term target gas injection plans that are part of the PPU scope include consideration of the following (see Section 6 of the CDR [1]:

1. A recirculating gas compressor and injected gas rates no more than 25 SLPM while limiting helium consumption;

2. Swirl bubblers that can produce smaller size bubble distributions in greater volume fractions compared to orifice bubblers, thus providing more effective pressure wave and erosion mitigation;

3. Targets designed to provide protective gas walls in addition to large volume fraction of small gas bubbles;

4. Local system venting in the mercury process piping (i.e., downstream of the target module return) to mitigate gas hold-up issues on process loop functionality;

5. A second carbon delay bed in the mercury off-gas treatment system to increase radioactive gas delay and capability to swap out a carbon canister when needed;

6. Other measures – to be developed – to mitigate excessive mercury displacement in the process system and prevent liquid mercury from leaving the service bay via MOTS.

Adding a significant flow of helium into the mercury loop via the PPU scope is a USI because it meets at least two of the USI criteria.

- Injecting helium into the flowing mercury inside a target module does not increase probability of occurrence or consequences of previously identified accident initiators because it has no effect on failures occurring/initiated outside the mercury loop and because injecting the helium is expected to decrease stresses on the target module and cavitation erosion damage.

- If injecting helium into the mercury loop could have a deleterious effect on the target protection system (TPS) sensors that are in contact with the mercury inside the loop, it would have the effect of increasing the failure probability of the TPS. The mercury pump pressure difference sensors are connected to pressure tap tubes that connect to the loop in such a manner that gas bubbles could not enter the small pressure tap tubes. The resistance temperature detector (RTD) thermowells protrude a short way into the pipe that returns mercury from the heat exchanger to the pump tank. The thermowells are sufficiently robust to withstand forces associated with the passage of helium bubbles, and the geometry of the pipe they are installed in is such that it could not accumulate enough helium to blanket the thermowell in helium and thereby deprive it of contact with the flowing mercury. Therefore it is concluded that injecting helium into the mercury loop would not significantly increase the failure rate of the TPS pressure or temperature sensors.

- The consequences of failure of the TPS are not increased by the injection of helium into the mercury loop because helium is an inert gas and because the presence of helium has no way to cause additional barrier or safety system failures.

- 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.***

- Operation of the mercury loop with continuous helium injection ***may require modification of the SNS ASE*** because one or more safety credited engineered safety features may be needed to prevent and/or manage the possible accumulation of helium in undesired locations in the loop.

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. For example, safety evaluations for the pilot helium injection have concluded that flow of mercury from the target loop to the MOTS system can be positively prevented by changing an existing rupture disc atop the mercury pump tank to one with a lower relief pressure. The existing pump tank rupture disc is not currently a safety credited feature but will become one for helium injection. The safety evaluation of the PPU helium injection modifications will evaluate the adequacy of the rupture disc for PPU helium injection conditions.

2.9 INCREASED HYDROGEN INVENTORY OF THE TARGET CRYOGENIC MODERATOR SYSTEM DUE TO THE PROPOSED INSTALLATION OF A CATALYTIC CONVERSION STAGE

The PPU project includes provisions to design and install—in each of the three existing SNS cryogenic moderator loops—a catalytic converter designed to facilitate conversion of ortho-hydrogen to para-hydrogen during loop cooldown and operation. This change is desired to improve research characteristics of the cold neutrons produced by the cryogenic moderators. Each catalytic converter consists of a vessel with internal structure holding sufficient granular catalyst material (possibly ferric oxide granules). Since each converter will add volume to the total loop, hydrogen inventory will increase. The amount of hydrogen in the cryogenic moderator system is a determinant in the potential for creation of an airborne source term in certain postulated unmitigated accidents of the mercury target assembly. ***This proposed change to the cryogenic moderator systems is an unreviewed safety issue because it meets two of the USI criteria***.

- The addition of catalytic converters would not be expected to increase the frequency of any previously identified accident because the addition of a passive component to each of the cryogenic moderator systems combined with post installation surveillance and testing, ensure that the modified systems have the same operational characteristics.

- The addition of catalytic converters ***will increase the calculated consequences of certain postulated accidents*** involving release of hydrogen into the core vessel and the increase would be in proportion to the increased inventory of hydrogen, which has been estimated at approximately 20%. This modest increase is not significant because it would not raise consequences into higher categories and because the safety credited boundaries, relief devices and inherent system characteristics prevent these accident initiators from resulting in airborne source terms. However, the actual detailed design of the converters will not be done until after CD-1 so it is prudent to declare a USI based on the increase in hydrogen inventory.

- The addition of catalytic converters ***will have the potential to affect performance of the safety credited relief devices*** if flow resistance in the relief path is affected. This could be due either to the presence of the converter in a relief path or due to postulated escape of the granular catalyst material from the converter vessel. This issue will need to be addressed in both design and hazard analyses. Consequences of failure of these safety accredited features are affected only to the extent that this change increases the hydrogen inventory.

- The addition of a catalytic converter holding a granular ***substance will introduce the possibility of different types of accidents***. This would primarily include flow blockage accidents anywhere in the cryogenic loop (at least in the hypothetical unmitigated sense). In addition, it could be postulated that escape of small particles of ferric oxide from the installed granules could circulate into the high neutron flux zone inside the core vessel, becoming activated and presenting the possibility of direct radiation exposure events during maintenance or other worker activity. This potential for mishap is amenable to prevention by the incorporation of robust screens or filters into the design of the catalytic converter.

- The installation of the catalytic converters can be accomplished within the existing SNS ASE.

A safety evaluation of this change will be prepared and presented to the DOE for review and approval well before the cryogenic moderator systems are operated with PPU installed catalytic converters. Barring a significantly greater increase than 20%, the increase in hydrogen inventory is not expected to require any additional safety credited engineered features. New accident initiators associated with the addition of granular catalyst material into the cryogenic moderator loops will be mitigated or prevented by the incorporation of appropriate screens and/or filtration stage(s). An outcome of the planned safety evaluation will be the determination of whether the screening/filtration stages are required to be designated as safety credited features.

3. SUMMARY AND CONCLUSIONS

Per the guidance of the DOE G 420.2-1A, *Accelerator Facility Safety Implementation Guide for DOE O 420.2C, SAFETY OF ACCELERATOR FACILITIES*, this preliminary hazard analysis has reviewed nine potential USIs associated with the PPU proposed changes and determined that five of the nine constitute USIs:

- Increased beam particle energy from 1.0 GeV to 1.3 GeV—effect on target spallation product inventory

- Increased beam particle energy from 1.0 GeV to 1.3 GeV—effect on target core vessel component heat distribution

- Increased maximum sustained beam to the ring injection dump from 150 to 200 kW.

- Injection of helium into the circulating target mercury in the target module to control the rate of cavitation erosion of the target module

- Increased hydrogen inventory of the target cryogenic moderator system due to the proposed installation of a catalytic conversion stage to convert ortho-hydrogen into para-hydrogen.

The evaluations in the preceding sections explain why each of these five items is a USI. A safety evaluation for each of the above will be prepared in concert with advancing available design detail. These safety evaluations will be issued for review during the CD-2 project design stage (approve performance baseline) and will be updated as required at the CD-3 stage (approve start of construction or execution). Prior to the CD-4 stage (approve start of operations or project completion), the safety evaluations will be incorporated in a general updating of the SNS FSADs.

At least one of the PPU changes, increased beam power limit to 200 kW for the ring injection dump, will require modification to the SNS ASE. If the safety evaluations for PPU identify the need for any additional safety credited engineered or administrative controls, modification of the SNS ASE will be required to include those and will need to be approved by DOE before operation of the facility after installation of the PPU upgrades and modification.

Except for the unreviewed issues addressed above, the PPU upgrades come under the category of new or modified equipment that can be installed and operated under the auspices of the existing SNS FSADs. All PPU modifications will be constructed, installed, tested and operated in accordance with the integrated safety management requirements of the ORNL SBMS.

4. CONSTRUCTION SAFETY

The hazard evaluations discussed in the preceding sections refer to operation of the SNS after installation of the proposed PPU upgrades. Construction safety, including the management of worker radiological safety during construction and installation activities, is addressed in the ORNL policy procedure document that specifies the integrated safety management program that contractors must follow to perform work on the SNS site [6].

Since the SNS is a major scientific facility in the United States, the impact of PPU construction and installation activities on SNS operations will be minimized by careful scheduling of construction and installation outages. Certain PPU project installation activities will be able to be done during facility operations but only to the extent that they can be done without compromising safety requirements of the SNS SADs or ORNL SBMS requirements. The PPU Project Execution Plan [7] outlines the overall approach to scheduling and managing construction activities and the interfaces between construction/installation and operations.

5. REFERENCES

1. *Conceptual Design Report Proton Power Upgrade Project*, ORNL/TM-2016/672, PPU-P01-PD0001, May 2017.
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3. *SNS Final SAD for Neutron Facilities,* SNS-102030102-ES0016-Rev03, September 2011.
4. I. I. Popova, *Influence on radiation levels inside the klystron gallery with beam energy increase from 1 GeV to 1.3 GeV,* PUP0-342-TR0001-R00.
5. I. I. Popova, Radionuclide Inventory for Mercury in the SNS Target Loop for PPU Conditions at 2 MW, SNS-10610200-DA0077-R00, September 2016.
6. *ORNL/Chestnut Ridge Facilities Project Environmental, Safety, and Health Plan*, SNS 102030000-ES0007-R06, March 2015.
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