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Initial implementation of helium Gas into the SNS mercury target for mitigation of fatigue and cavitation damage

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Abstract. The short-pulse, 60 Hz beam used at the Spallation Neutron Source (SNS) initiates pressure waves in the mercury target with each pulse that 1) lead to huge numbers of fatigue stress cycles in the target vessel, and 2) pitting / erosion damage to the target vessel caused by mercury cavitation. Both phenomena can lead to target leaks and interruption of neutron production.

The number of beam pulses expected over a successful target life is on the order of 10^9; the number of response stress cycles at a vessel position can exceed 1 per pulse. This number is even beyond the regime typical of high-cycle fatigue. It is important to be aware that contemporary knowledge fatigue damage includes probabilistic behavior for many materials, and that for many materials a true endurance limit does not exist. Obtaining data in the giga-cycle regime is difficult, particularly repeatable data. In this regime, the effects of very small material defects, inclusions and inhomogeneity become relevant as their size approaches that of the material microstructure. Detecting and controlling such defect sizes is problematic in the SNS mercury target module weld assembly.

While considerable efforts are being made to improve the robustness of the SNS target, one thing that can be assuredly stated is that reducing high-cycle fatigue stress magnitude will add margin to its fatigue life. Injecting gas into the target mercury is one way to accomplish this. The degree of pulse stress reduction to be expected from a given gas condition is difficult to predict. There are SNS experimental data and JPARC target gas injection experience to expect stress reduction to ½ ~ ¼ of that without gas throughout much of the target mercury vessel.

As a first step towards reduction of cyclic stresses and mitigation of cavitation damage, SNS will implement gas injection in its mercury target module beginning in the fall of 2018. The project is known as Gas Injection Initial Implementation, or GI3. GI3 will comprise of a once-through system. That is, the injected helium will be processed through the Mercury Off-gas Treatment System (MOTS) rather than recycled for re-injection. GI3 will employ relatively low flow rate of up to 1 slpm of helium gas through a total of sixty orifices, each with a diameter of 8 microns. The upstream supply pressure will be approximately 6.9 atm.

GI3 in envisioned as a first step towards a more complete and complex gas injection system that would include much higher flow rates, gas re-circulation, and the potential combination of small gas bubble and gas wall supplies. Despite this reduced scope, there are significant design,

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installation, operational, and safety related challenges associated with the project. This paper and presentation will describe these challenges and the strategies employed to overcome them.

1. Introduction and Scope

This paper describes the system configuration for the Gas Injection Initial Implementation (GI3) project, which is a hardware and operational modification to the Spallation Neutron Source (SNS) mercury target system.

The short-pulse, 60 Hz beam used at SNS initiates pressure waves in the mercury target with each pulse that (1) lead to huge numbers of fatigue stress cycles in the target vessel, and (2) pitting / erosion damage to the target vessel caused by mercury cavitation. Both phenomena can lead to target leaks and interruption of neutron production. The injection of helium gas within the mercury target could mitigate both phenomena.

The first phase of mercury target gas injection at the SNS is known as GI3. The general parameters and requirements of GI3 are:

- The system shall allow continued neutron production in the event that gas injection is disabled or turned off.
- The system shall prevent backflow of mercury and spallation products out of the service bay via the helium supply line.
- Helium gas shall be injected into the target module at flow rates up to 1 slpm, total, which is an injected mass fraction of 0.1% compared to the mercury flow rate at a pump speed of 350 rpm. The injected volume fraction of helium in the mercury vessel is less than 0.1% because the mercury is under pressure greater than one atmosphere.
- Helium gas bubbles shall be as small as reasonably achievable within the constraints of existing target designs, which is likely to be an average diameter of 150 microns or less.
- The helium gas supply pressure shall be controlled and measured continuously.
- The helium gas flow rate shall be measured continuously.
- The system shall not allow liquid mercury to enter the mercury off-gas treatment system (MOTS) such that it either disables the operation of MOTS or leads to a loss of mercury from the service bay.
- The system shall not negatively impact the ability of the flowing mercury to remove heat from the system.

Following the implementation of GI3, it is anticipated that further upgrades will be made to the gas injection system allowing higher gas flow rates, smaller gas bubbles, and an additional target gas supply dedicated to protective gas wall. The scope of this document is limited to the GI3 phase only.

2. Gas Injection Initial Implementation (GI3) System Overview

The system is shown on the GI3 schematic diagram, which is shown in Figure 1. The schematic diagram shows the three main subsystems that comprise GI3, which are the helium supply system, modifications to the existing mercury loop system, and modifications to the existing mercury off-gas treatment system (MOTS). In addition to equipment necessary for GI3, some equipment will be installed with GI3 that will allow for future upgrades of the gas injection system. Fundamentally, GI3 involves the transport of helium gas through the following chain:

1. A new helium supply system located in the target building high bay, which is fed by the existing building helium system, which is fed by a helium bottle truck located outside the building
2. Through a GI3 gas panel located in the target building high bay
3. Through the a spare penetration of the water system gas liquid separator (GLS) cavity located adjacent to the High Bay
4. Through an existing 2-inch pipe that runs from the GLS cavity to the west end of the target process bay, which houses the mercury process system

5. Through a flexible hose from the 2-inch pipe to the rear (east end) of the target carriage
6. Through an existing gas line running from the rear to the front of the target carriage
7. Into the mercury target where it is injected into the flowing mercury through inlet orifice bubblers (IOB)
8. Through the mercury loop itself until the gas reaches the free surface at the top of the mercury pump sump tank or in the target mercury vent
9. Through MOTS
10. Through the Hot Off-Gas treatment system (HOG)
11. And finally, out of the building stack to the atmosphere

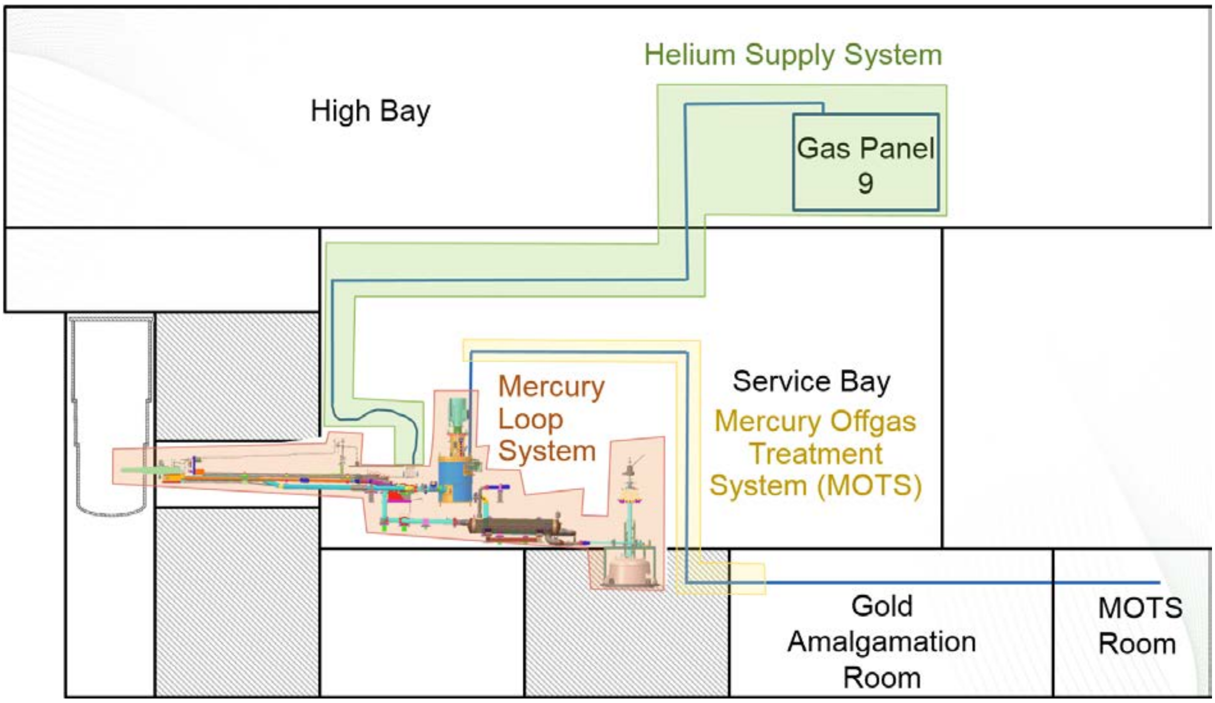

Figure 1 - GI3 Schematic Diagram

3. System Details and Specific Challenges

3.1. Gas Supply System

The most significant feature of the gas supply system is its location. Because the system requires a gas line to enter the high-pressure portion of the mercury loop downstream of the pump discharge, there is a potential safety accident in which mercury and spallation products back flow through the supply line. Because the gas panel is located in the high bay and the supply line enters the service bay from above, there is not enough pressure (even in off-normal cases) to push mercury out of the service bay, which results in an inherently safe design.

The panel for the gas supply system is a relatively standard design. It consists of valves, filters, a flow meter, a pressure regulator a pressure relief valve, and a pressure gauge. The system is designed to maintain a steady helium gas pressure from 0 to 100 psig at all times. From the gas panel, the helium is transported into an existing cavity which contains water system GLS and then into the mercury service bay through an existing 2-inch pipe. Transporting the helium through this pipe, which is about 80 feet long and has five 90 degree bends is particularly challenging. The pipe is used as a conduit through which two flexible hoses will be routed. Only one supply hose is used for GI3, but the second, separate hose is required for future upgrades to gas injection that will require an independent gas supply at a different pressure and flow rate.

The 2-inch pipe terminates along the north end of the service bay, which is closest to the monolith. From here, another flexible hose will transport the helium to an existing connection on the back of the target carriage. An existing gas line transports the helium to the target location and a new jumper brings the helium to the target module itself. The jumper is fitted with an additional check valve and filter. The filter prevents contamination of the small injection orifices and prevents backflow of mercury to the supply line.

3.2. Helium Gas Introduction to the Target Module

Helium is introduced to the mercury loop through new hardware added to target modules. The initial target modules have a retrofit design as shown in Figure 2.

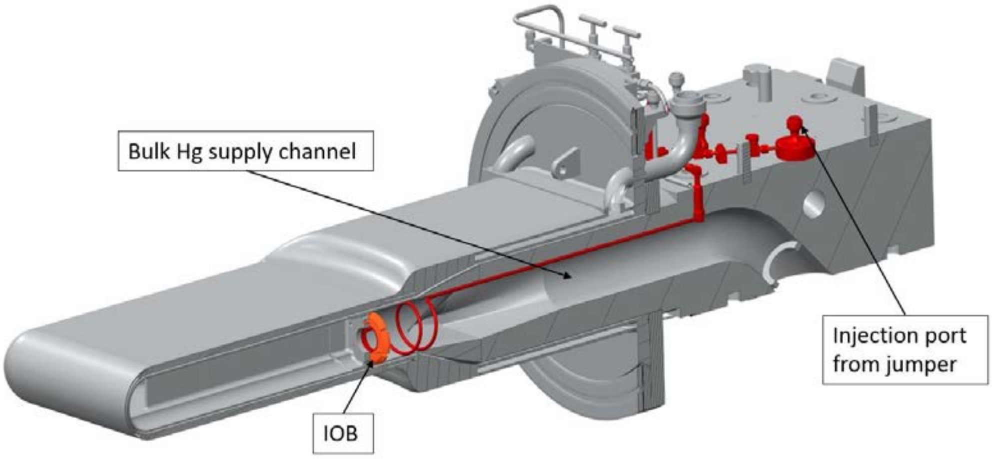

Figure 2 - GI3 Configuration at Mercury Target Module

On the target module, the gas supply is split into two paths feeding an inlet orifice bubbler (IOB) installed in each of the two bulk mercury supply flow paths. Each IOB has a circular array of 30 orifices oriented radially. Each orifice has a diameter of 8 microns (.0003 inches). At 100 psig supply pressure upstream of the IOBs and the mercury pump operating at 350 rpm, the flow is choked and the nominal total flow is 0.7 slpm.

3.3. Helium Gas within the Mercury Loop

Once injected, the helium bubbles interact with the turbulent mercury flow, where they may coalesce and/or be temporarily held up in low-pressure zones within the mercury. Some of the gas exits the target module through the vent line, and some of the gas is swept through the mercury loop, (Figure 3), but eventually, the gas reaches the pump tank and rises to the surface due to buoyancy. From the pump tank, the injected helium joins with the sweeping cover gas flow and is then drawn through the MOTS.

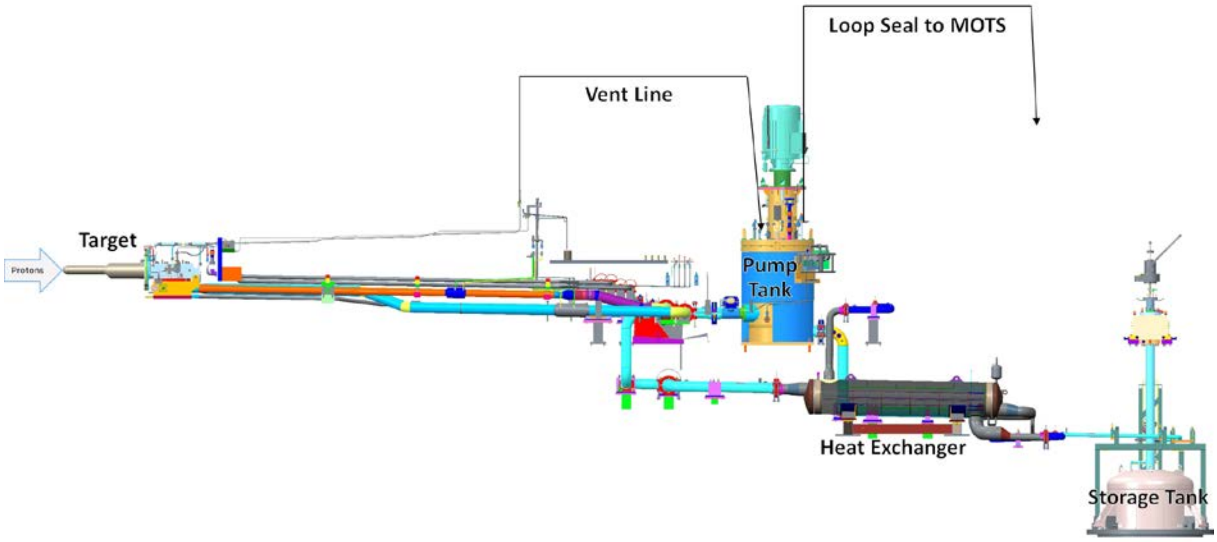

Figure 3 - Mercury Loop with Major Components

Figure 4 highlights potential collection points for gas, which are either local high points or downward turns in the flow path. Gas that is held up in the mercury flow causes the combined fluid volume in the mercury loop to increase, raising the mercury level in the pump tank. The trapped gas is eventually vented when the Hg pump is stopped or when the Hg is drained from the loop.

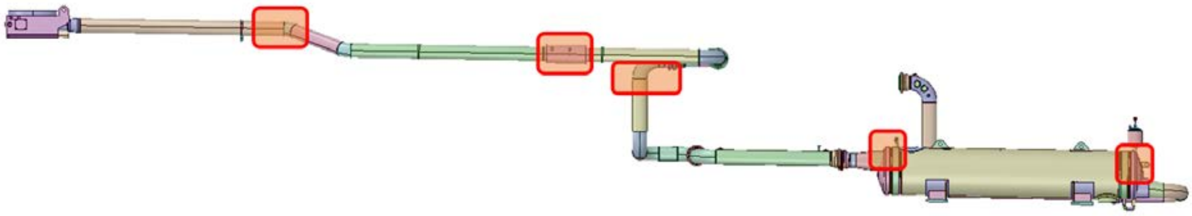

Figure 4 - Likely Collection Points for Injected Helium

3.4. Mercury Off-gas Treatment System (MOTS) modifications

3.4.1. Prevention of liquid Hg flow through MOTS. Figure 3 shows the loop seal, which is the beginning of MOTS. It is paramount to the successful operation of SNS that liquid mercury does not pass through MOTS. A runaway event caused by higher than expected gas injection rate or unexpected transients of capture and release of gas within the loop could conceivably send mercury over the loop seal and towards MOTS. Therefore, GI3 adds two features to protect against these potentials.

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First, the set point for the existing burst disk atop the pump sump tank will be lowered so that a static column of mercury will burst the disk before its height could exceed the elevation of the loop seal.

Second, a gas liquid separator (GLS) has been added downstream of the loop seal. The GLS protects against an event in which a pocket of trapped gas is released and moves through the mercury loop towards the pump tank. As the gas rises, it is subject to lower and lower pressure, which allows it to expand. This expansion raises the mercury level in the pump tank, which could occur relatively quickly. If the rising gas pocket pushes the free surface of the mercury against the top of the tank before breaking the surface, then some amount of mercury might be trapped inside the line leading to the loop seal. If the (3/4-inch) line is not large enough to allow the gas to flow past the mercury during this dynamic event, the buoyant gas pocket could push the trapped mercury up the loop seal line and potentially over the loop seal. In effect, the mercury loop would "burp" some volume of mercury. Figure 5 shows a conceptual representation of the GLS. If mercury collects in the GLS, it can be collected and returned to the mercury loop (not shown).

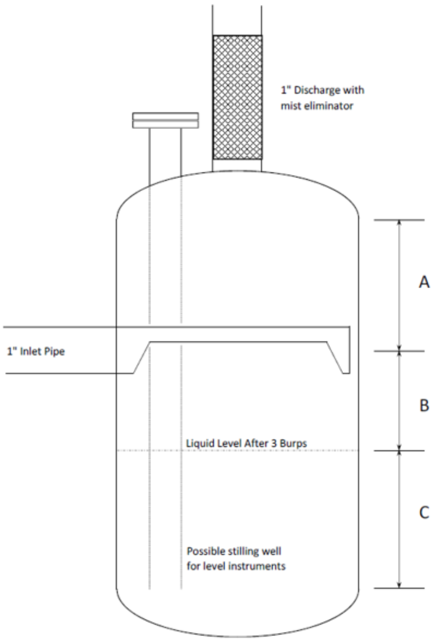

Figure 5 - Conceptual representation of MOTS GLS

3.4.2. Additional Carbon Adsorber

SNS operational experience has demonstrated that gas flow through the mercury loop causes accelerated shedding of radioactive spallation product noble gases from the liquid mercury. This has occurred when the gas leakage rate of the seal between the target module and the target carriage has significantly increased during operation. The fast shedding of noble gases leads to high dose rates adjacent to the MOTS components in the target building basement. As GI3 will be intentionally injecting gas, this phenomenon is expected. Therefore, an additional shielded carbon adsorber is to be installed in MOTS. The purpose of the device is not to add additional absorption capacity. Rather, it provides a simple delay tank so that the radioactive noble gases can decay before reaching downstream MOTS components for which the high does rates are not acceptable due to operational limitations.

4. Schedule

GI3 is planned to be commissioned in October, 2017. However, this completion date will be challenging. In addition to the hardware engineering and installations, extensive controls programing and modifications are required. These systems must be integrated with operations procedures and training. Finally, the system and readiness will undergo significant internal and external review prior to approval.

5. Summary

A comprehensive system for the initial implementation of gas injection into the SNS mercury target has been designed. The primary goal is to increase target module lifetime and reliability by (1) reducing the amplitude of cyclic loading and (2) reducing the damaging effects of cavitation bubbles within the mercury vessel structure. GI3 is expected to provide appreciable improvements and support the near-term goal of reliable 1.4 MW operation. In addition, GI3 provides the first step towards full scale deployment of gas injection.