SNS-OPM-ATT 2.B-10.a
Unreviewed Safety Issue (USI) Evaluation Form

I. Title of USI Evaluation

USI Evaluation for Increasing the Allowable Target Gas Injection Rate to 2 SLPM

II. Description of Proposed Activity (or discovered condition) (use attachments if necessary):

This USI Evaluation is being performed to evaluate a proposed increase in the gas injection rate to the target module up to 2 SLPM. The current limit of 1.2 SLPM is established in the SNS Operations Envelope [1] and is based on evaluations provided in References [2 and 3]. The drive to increase gas injection rates is planned to occur in a stepwise fashion, with the next two targets being capable of delivering about 1.4 SLPM.

The proposed changes to the gas injection system are intended to allow an increased rate of gas injection into the mercury target system. Gas injection was first introduced in target T18 and has been operated in three subsequent targets with gas injection rates ranging from about 0.3 SLPM to about 1 SLPM. Examination of these targets has shown that gas injection has been successful in reducing the cavitation damage inside the target modules [4]. In addition, measurements of the strain response of the target modules indicate that additional gas injection can be expected to lead to reduced strain of the target module and therefore higher reliability [5].

As stated in the *Safety Assessment Supplement for Target Gas Injection Initial Implementation* [2], the bubbler design is expected to evolve over time. These changes are part of that evolution.

II.A Gas Injection System Hardware Modifications

The proposed increase in gas injection rate will be achieved with the following hardware changes:

- Increase in the flow area of target bubblers from ~ 5.9 x 10^{-6} in² (sixty 9-micron orifices, see Appendix 1) to any combination of size and quantity of holes with a flow area less than 5.8 x 10^{-5} in².
- Increase in the diameter of the flow restricting orifice located in the gas supply pathway on the target module from 0.0051-inch to 0.0102-inch diameter.

The change in bubbler flow area will allow flexibility in the number and size of the bubbler orifice holes with a limit on the total area being less than 5.8 x 10^{-5} in². The existing bubbler orifice design provides a limiting flow (choked flow) of about 1.2 SLPM at the nominal injection pressure of 100 psig (see Appendix 1 for supporting calculations). The proposed increase in bubbler flow area would increase the limiting choked flow rate to about 10 SLPM at 100 psig; however, other components in the system would limit flow to the bubblers as described below.

Regardless of the bubbler flow area, the maximum sustained flow through the bubbler orifices remains limited by the pressure controller PCV-3241 as evaluated in Reference 2 and as verified by system testing [6]. As evaluated in Reference 2, PCV-3241 inherently and passively limits flow to 2.1 SLPM at 180 psig, 2.8 SLPM at 250 psig, or 3.1 SLPM at 275 psig. Normally the downstream pressure is maintained below 120 psig and the upstream pressure at the controller is 180 psig [2].

The increase in diameter of the gas supply flow restricting orifice located on the target module is desired to reduce the pressure drop in the system. The purpose of the restricting orifice is to reduce the maximum transient flow rate of gas that would occur in the event of a break in the gas line located in the mercury flow passages [2]. While the pressure controller described above limits the steady state flow, a flow transient could occur if the bubbler tubing within the module breaks causing the stored pressure in the supply line downstream of the PCV to be released into the mercury. The existing 0.0051-inch orifice limits the peak transient gas flow rate into the loop to 3.5 SLPM [2 and Appendix 1]. The increase in orifice diameter to 0.0102-inch will increase the maximum transient flow rate to about 14 SLPM (Appendix 1).

The potential thermal and mechanical impacts associated with the transient gas surge were evaluated without considering any reduction in flow capability of the orifice and were determined to be negligible [2 and 8]. Therefore, the increase in orifice diameter is acceptable.

Reference 2 evaluated the potential for mercury to backflow out of the loop system and into the process bay portion of the Service Bay, potentially leading to some puddling of liquid mercury on top of the steel shielding of the Process Bay should the helium supply line to the target module be breached. Reference 2 concluded that amount of potential puddling would be limited not only by the bubbler orifice size but also by in-line components located on the target module including a check valve and stainless-steel media high purity gas filter. While the larger bubbler flow area could also allow a greater backflow past these restrictions, the design still includes the check-valve and high purity gas filter, each of which were tested with mercury and shown to have no significant (less than 0.25 mL/min) backflow [2 and 9].

None of the identified changes above are associated with Credited Engineering Controls (CECs). These changes likewise do not interfere with any CEC's ability to meet their performance requirements. The changes do differ from the configuration described in the *Safety Assessment Supplement for Target Gas Injection Initial Implementation* [7], but the changes do not alter the conclusions of that document.

II.B Increased OE Limit on Gas Injection Flow Rate

The increase in the flow area of the bubblers will provide the capability of injecting greater amounts of gas flow into the mercury loop, up to 2.1 SLPM as limited by the Pressure Control Valve, PCV-3241. The operations envelope imposes a limit on the normal operating value of gas injection rate and requires execution of a procedure to increase the allowed rate. The existing process for increasing the gas flow uses the *Procedure to Modify Normal Operating Values of Target Gas Injection Parameters in the Operating Envelope* [10]. This will continue to be used to verify the mercury loop and credited Target Protection System (TPS) sensors continue to operate successfully with increased gas rates.

Analysis supporting the *Safety Assessment Supplement for Target Gas Injection Initial Implementation* [7] estimated the potential consequences of helium accumulation in the mercury process loop by conservatively assuming that 100% of the injected gas would become trapped within the loop. This provided an easily defendable upper bound for assumed accumulation in the absence of actual experience of how injected gas would behave within the loop. One of the biggest uncertainties with predicting how gas might accumulate within the loop dealt with potential accumulation in the heat exchanger. Testing with gas injection at the ORNL Target Test Facility (*TTF Gas Holdup Experiments* [11]) demonstrated only small amounts of gas accumulation occurred in the gas injection flow regimes envisioned for GI3. While the TTF is mostly prototypical of the SNS mercury loop, the TTF does not have features that accurately model the SNS loop heat exchanger.

However, experience gained at SNS with injection rates of up to about 1 SLPM also indicate that only a small fraction of injected gas becomes trapped in the loop and that gas accumulation reaches a steady state in less than an hour with a total displacement of less than about 2% (1 inch) in indicated pump tank level. The accumulation behavior for injection rates up to 2.1 SLPM is expected to increase somewhat but is expected to be of similar magnitude as that observed with injection rates of ~ 1 SLPM. Increasing gas injection rates is performed in accordance with a controlled and monitored process as stipulated in the approved *Procedure to Modify Normal Operating Values of Target Gas Injection Parameters in the Operating Envelope* [10]. Protocols of the procedures ensure accumulation behavior is well characterized and within defined acceptance criteria with actions to be taken should acceptance criteria not be met. Additionally, target designs will limit the achievable gas injection rates in the next two targets to about 1.4 SLPM. Experienced gained with loop performance at 1.4 SLPM will be used in predicting performance characteristics for future targets capable of delivering higher injection rates more closely approaching the 2 SLPM limit. It is not considered credible that injection rates of ~1.4 SLPM for the next target could cause accumulations that approach 100%. Likewise, it is not considered credible that increasing gas injection rates to 2 SLPM after gaining experience with the ~1.4 SLPM target performance could cause accumulations that approach 100% as was conservatively assumed prior to experience with gas injection. Therefore, the analysis based on the original unmitigated accumulation assumptions remains bounding.

Additionally, the mitigated analysis inherently limits the amount of accumulation because the rupture disk opens at a fixed mercury elevation, so the analysis supporting the mitigated case is independent of gas injection rate and accumulation behavior assumptions. This change increases gas injection rate by modifying components while retaining their fundamental design and function, thus no new failure modes are introduced. Therefore, the mercury loop can be safely operated with 2 SLPM of target gas injection flow with the existing set of credited controls and supporting analysis.

III. Does the proposed activity or discovered condition affect information presented in the FSAD-NF or FSAD-PF, e.g. regarding equipment, administrative controls, or safety analyses. If so specify the applicable FSAD and relevant sections.

The Safety Assessment Supplement for Target Gas Injection (SAS) is being incorporated into the FSAD-NF as part of a periodic revision. This information in this USIE impacts information presented in the SAS, so it should be incorporated as appropriate in the same periodic revision of the FSAD-NF.

IV. Does the proposed activity or discovered condition affect and of the requirements of the ASE. If so, list the affected sections.

No, the requirements of the ASE and the Supplemental ASE are unaffected by this change.

V. USI Evaluation Criteria:

1. Could the change significantly increase the probability of occurrence of an accident previously evaluated in the FSADs?
   Yes __ No _X_
   Justification:
   No, the proposed increase in gas injection rate is an incremental increase from a range of known, safe flow rates. Experience with target gas injection up to about 1 SLPM indicates that the evaluated scenario is conservative, and this change is an incremental step to determine if this behavior changes. Procedures are in place to deliberately evaluate each incremental increase in gas injection rate and check for unexpected mercury loop behavior. Therefore, increasing the allowable target gas injection rate does not significantly increase the probability of an evaluated accident.

2. Could the change significantly increase the consequences of an accident previously evaluated in the FSADs?
   Yes __ No _X_
   Justification:
   No, as discussed in Section II, the unmitigated consequences evaluated for helium accumulation are conservative for the proposed target gas injection rate. The assumptions of that analysis remain conservative in light of the experience gained from target gas injection operation. Therefore, the proposed increase in allowable target gas injection rate does not significantly increase the consequences of an evaluated accident.

3. Could the change significantly increase the probability of occurrence of a malfunction of equipment important to safety previously evaluated in the FSADs?
   Yes __ No _X_
   Justification:
   No, increasing the allowable target gas injection rate does not have any impact on the operation or functionality of a credited control. The engineered controls that are credited to mitigate the helium accumulation accident are not influenced by the target gas injection rate as discussed in Section II.B. Therefore, the proposed increase in the allowable target gas injection rate does not significantly increase the probability of malfunction of equipment important to safety.

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:
   No, it is assumed that a malfunction of equipment important to safety provides no mitigation for associated accidents. Therefore, full unmitigated accident consequences are assumed for a CEC malfunction. Since the proposed increase in allowable target gas injection rate does not have an impact on the unmitigated consequences of its associated accidents, the proposed change does not significantly increase the consequences of a malfunction of equipment important to safety.

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 __ No _X_
   Justification:
   No, target gas injection has already been evaluated as a potential accident initiator and credited controls are identified to mitigate the postulated accident. Increasing the allowable target gas injection rate does not introduce any new hazards or accident initiators, so no different type of accident than any previously evaluated is created.

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:
   No, increasing the allowable target gas injection rate does not have any impact on the operation or functionality of a credited control. The engineered controls that are credited to mitigate the helium accumulation accident are not influenced by target gas injection rate as discussed in Section II.B. Therefore, the proposed increase in allowable target gas injection rate does not increase the possibility of a different type of malfunction of equipment important to safety than any previously evaluated.

VI. **USI Determination:** A USI is determined to exist if the answer to any of the 6 questions above (Section V) is "Yes." If the answer to all 6 questions is "No", then no USI exists.

a. Does the proposed activity (or discovered condition) constitute a USI?

__ Yes – DOE approval required prior to implementing.

_X_ No – Proposed activity may be implemented with appropriate internal review.

Drew Winder 6/18/19

Drew Winder, Mercury Target System Engineer, Qualified Preparer — Date

Jacob Platfoot 6/18/19

Jacob Platfoot, Facility Safety Engineer, Qualified Reviewer — Date

Approvals:

6/18/19

Signature of SNS Operations Manager or Designee — Date

References

1. *SNS Operations Envelope*, OPM 2.B-1, Revision 22, August 27, 2018
2. *Safety Analysis Supplement for Target Gas Injection Initial Implementation (GI3)*, 102030102-ES0094-R00, Oak Ridge National Laboratory, September 2017.
3. "Review to Ensure Consistency between the Safety Assessment Supplement for Target Gas Injection Initial Implementation (GI3) and Proposed Operations Envelope Limits on Gas Injection Rate" SNS 102030102-IN0003.
4. *Laser Line Scan Characterization of Cavitation-Induced Erosion to SNS Mercury Target Vessels,* ORNL/TM-2019/1103, McClintock D. et al., January 2019.
5. *Measurements of the Effects of Gas Injection into SNS Target T18,* 106010101-TR0043, Blokland W. et al., January 2018
6. *Target Systems Test Procedure: Mercury Target Gas Injection Initial Implementation (GI3) Helium Supply Panel 9 and Pans 2B / 5 Modifications,* 106060000-TA0020-R00, Thompson, S., Montierth, D., June 2017.
7. *Safety Analysis Supplement for Target Gas Injection Initial Implementation (GI3)*, 102030102-ES0094-R00, Oak Ridge National Laboratory, September 2017.
8. *Break of the He Supply Line Inside the Target,* 106010101-TR0042-R00, Barbier, C., October 2017.
9. *Porous Filter Testing as a Check-Valve Role,* 106010101-TR0034-R00, Barbier, C., January 2017.
10. *Procedure to Modify Normal Operating Values of Target Gas Injection Parameters in the Operating Envelope,* 106010000-PR0009-R02, Barbier, C., et al., November 2018.
11. *TTF Gas Holdup Experiments*, 106010101-TR0019, Barbier, C., et al., January 2016.

Appendix 1: Calculations

Area of Orifice

$$\mathrm{Area} = 60 * \frac{\pi}{4} * \left(9\ \mathrm{micron} * \frac{1\ \mathrm{inch}}{25{,}400\ \mathrm{micron}}\right)^2 = 5.9 \times 10^{-6}\ \mathrm{inch}^2$$

Choked Flow

Gas flow is choked when its flow rate is limited by the speed of sound of the gas. The flow rate in this condition can be calculated using the pressure. The calculations in this section are based on the equations and methods from Section 9.14, Flow in Nozzles and Diffusers of Ideal Gases with Constant Specific Heats, of *Fundamentals of Engineering Thermodynamics*, 4th edition, Moran and Shapiro, 2000.

The critical stagnation pressure, p^*, is downstream pressure below which reductions in pressure can have no effect on the mass flow rate of the orifice. This value is given by the equation below:

$$p^* = \frac{p_{upstream}}{\left(1 + \frac{k-1}{2}\right)^{\frac{k}{k-1}}}$$

In this equation, $p_{upstream}$ is the supply pressure into the orifice, which is 100 psig or 114.7 psia for the target gas injection supply. The ratio of specific heats, k, is 1.66 for helium. Using these values, the critical stagnation pressure for the target is calculated as:

$$p^* = \frac{114.7\ \mathrm{psia}}{\left(1 + \frac{1.66-1}{2}\right)^{\frac{1.66}{1.66-1}}} = 56\ \mathrm{psia}$$

For any downstream pressure at or below this value, the velocity will be the sound speed, or Mach 1. The mass flow can therefore be calculated using the density using the known properties of the gas. The first needed parameter is the temperature downstream. The temperature downstream can be calculated assuming the gas is adiabatic during expansion by the equation below:

$$T_{downstream} = \frac{T_{upstream}}{1 + \frac{k-1}{2} M^2}$$

In this calculation k is the ratio of specific heats as above and M is the Mach number, which is 1 for this calculation. Using the values for helium and an upstream temperature of 293 K, the resulting temperature is calculated as:

$$T_{downstream} = \frac{293\ \mathrm{K}}{1 + \frac{1.66-1}{2} 1^2} = 220.3\ \mathrm{K}$$

The density of the gas downstream of the flow restriction can be calculated by:

$$\rho = \frac{p^*}{R_{He} * T_{downstream}}$$

Where p^* is the critical pressure calculated above of 56 psia or 386,000 Pa, R_{He} is the gas constant for helium of 2077 J/(kg*K), and $T_{downstream}$ is the value calculated above. The resulting density is calculated as:

$$\rho_{choked} = \frac{386{,}000\ \mathrm{Pa}}{2077\ \frac{\mathrm{J}}{\mathrm{kg} * \mathrm{K}} * 220.3\ \mathrm{K}} * \frac{1\ {}^{\mathrm{N}}/_{\mathrm{m}^2}}{1\ \mathrm{Pa}} * \frac{1\ \mathrm{J}}{1\ \mathrm{N} * \mathrm{m}} = 0.844\ {}^{\mathrm{kg}}/_{\mathrm{m}^3}$$

The density at standard conditions of 293 K and 101,300 Pa is used as a standard measurement of gas. The equation above can also be used to calculate the density of helium in these conditions.

$$\rho_{standard} = \frac{101{,}300\ \mathrm{Pa}}{2077\ \frac{\mathrm{J}}{\mathrm{kg} * \mathrm{K}} * 293\ \mathrm{K}} * \frac{1\ {}^{\mathrm{N}}/_{\mathrm{m}^2}}{1\ \mathrm{Pa}} * \frac{1\ \mathrm{J}}{1\ \mathrm{N} * \mathrm{m}} = 0.166\ {}^{\mathrm{kg}}/_{\mathrm{m}^3}$$

The quantity of standard liter per minute (SLPM) is used as a measurement of mass flow. Using the density at standard conditions above, the mass flow rate for a standard liter per minute is calculated below:

$$\dot{m}_{SLPM} = \rho_{standard} * \frac{1\ \mathrm{L}}{1\ \mathrm{minute}}$$

$$\dot{m}_{SLPM} = 0.166\ {}^{\mathrm{kg}}/_{\mathrm{m}^3} * \frac{1\ \mathrm{L}}{1\ \mathrm{min}} * \frac{1\ \mathrm{m}^3}{1000\ \mathrm{L}} * \frac{1\ \mathrm{min}}{60\ \mathrm{s}} = 2.767 \times 10^{-6}\ {}^{\mathrm{kg}}/_{\mathrm{s}}$$

To calculate the mass flow in choked conditions, the downstream velocity is also needed, which is given by the equation below.

$$V_{downstream} = M\sqrt{k * R_{He} * T_{downstream}}$$

In this calculation, M is the Mach number, R_{He} is the gas constant for helium of 2077 J/(kg*K), and $T_{downstream}$ is the value calculated above. The resulting velocity is calculated as:

$$V_{downstream} = 1\sqrt{1.66 * 2077\ \frac{\mathrm{J}}{\mathrm{kg} * \mathrm{K}} * 220.3\ \mathrm{K} * \frac{1\ {}^{\mathrm{m}^2 * \mathrm{kg}}/_{\mathrm{s}^2}}{1\ \mathrm{J}}} = 871.5\ {}^{\mathrm{m}}/_{\mathrm{s}}$$

The mass flow in choked conditions is a function of the available flow area. The mass flow rate in SLPM per inch of flow area is given by the following equation:

$$\frac{\dot{m}}{\mathrm{in}^2} = \rho_{choked} * V_{downstream}$$

$$\frac{\dot{m}}{\mathrm{area}} = 0.844\ {}^{\mathrm{kg}}/_{\mathrm{m}^3} * 871.5\ {}^{\mathrm{m}}/_{\mathrm{s}} * \left(\frac{0.0254\ \mathrm{m}}{1\ \mathrm{inch}}\right)^2 * \frac{1\ \mathrm{SLPM}}{2.767 \times 10^{-6}\ {}^{\mathrm{kg}}/_{\mathrm{s}}} = 171{,}400\ {}^{\mathrm{SLPM}}/_{\mathrm{in}^2}$$

Using this mass rate per area, the maximum flow can be calculated for different areas, and the needed area for a maximum flow can be calculated.

The maximum flow for the current target bubblers with an area of 7.3 x 10^{-6} in² would therefore be 1.25 SLPM.

$$\dot{m} = \frac{\dot{m}}{\mathrm{area}} * \mathrm{area} = 171{,}400\ {}^{\mathrm{SLPM}}/_{\mathrm{in}^2} * 5.9 \times 10^{-6}\ \mathrm{inch}^2 = 1.01\ \mathrm{SLPM}$$

The maximum flow for an orifice with a diameter of 0.0051 inch would be:

$$\dot{m} = \frac{\dot{m}}{\text{area}} * \text{area} = 171{,}400\ {}^{\text{SLPM}}\!/_{\text{in}^2} * \frac{\pi}{4} * (0.0051\ \text{inch})^2 = 3.5\ \text{SLPM}$$

The maximum flow for an orifice with a diameter of 0.0102 inch would be:

$$\dot{m} = \frac{\dot{m}}{\text{area}} * \text{area} = 171{,}400\ {}^{\text{SLPM}}\!/_{\text{in}^2} * \frac{\pi}{4} * (0.0102\ \text{inch})^2 = 14\ \text{SLPM}$$

The area for 10 SLPM of flow would be:

$$\text{area} = {}^{\dot{m}}\!\Big/_{\left(\frac{\dot{m}}{\text{area}}\right)} = {}^{10\ \text{SLPM}}\!\Big/_{171{,}400\ {}^{\text{SLPM}}\!/_{\text{in}^2}} = 5.8 \times 10^{-5}\ \text{inch}^2$$