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OAK RIDGE
NATIONAL LABORATORY
MANAGED BY UT-BATTELLE
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Target Management Plan

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Prepared by
Neutron Technologies Division
Neutron Science Directorate

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Neutron Technologies Division
Research Accelerator Division

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TABLE OF CONTENTS

Objectives 1
Schematic Baseline Plan 1
Current Knowledge Base 2
  Terminology 3
  State of the Art 4
  Development Efforts Currently Under Way 6
Initial Conditions 8
Detailed Baseline Plan 8
Target T19 8
  Target T19 Contingencies 9
Target T20 9
  Target T20 Contingencies 9
Target T21 9
  Target T21 Contingencies 10
Target T22 10
  Target T22 Contingencies 10
Target T23 10
  Target T23 Contingencies 10
Target T24 through T26 11
  Target T24 through T26 Contingencies 11
Discussion 11
  Avoiding Unexpected Target-Related Outages 12
  Maintaining Sufficient Target Inventory While Controlling Costs 12
  Ensuring Consistency with the Planned Operating Schedule 13
  Developing the Knowledge Base for Target Design and Operations 13
  Balancing Performance, Risk, And Attainment of the Key Objective 14
Summary 15

OBJECTIVES

This plan describes the strategy to interleave First Target Station (FTS) target design and engineering analysis, transient response measurements, manufacturing, capability enhancements, and post-irradiation examination (PIE) with the planned Spallation Neutron Source (SNS) operating schedule to best use the existing and anticipated inventory of target module hardware for neutron production at SNS. The key objective is to develop a robust target module that can operate predictably and reliably at a beam power of 1.4 MW and an accumulated energy of no less than 3,500 MW-hr and up to 5,000 MW-hr. Constraints in achieving this key objective are:

- Avoid unexpected target-related outages,
- Maintain sufficient target inventory while controlling costs,
- Develop the knowledge base for target design and operation,
- Achieve the key objective within the constraints imposed by risk and performance, and
- Ensure consistency with the planned operating schedule.

This plan also provides information and experience that is key to the development of a future target capable of operating at 2.0 MW, which is a necessary part of the Proton Power Upgrade (PPU) project.

SCHEMATIC BASELINE PLAN

Figure 1 shows the baseline, success-oriented plan for target operation and fabrication through mid CY 2020. Additional details are provided through the end of CY 2020 in Table 1 at the end of the text. This plan strives to balance operational and schedule risks to achieve goals as soon as possible. Suggested milestones for tracking the progress are offered in Table 2 at the end of the text.

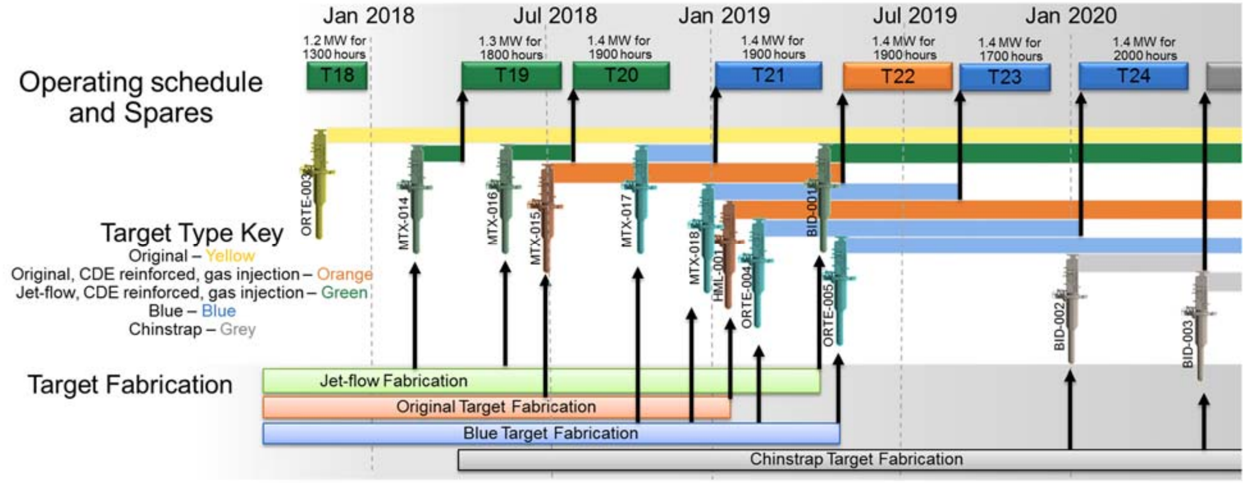

Figure 1. Schematic target operations and management plan to mid CY 2020

The current knowledge base for the SNS mercury target is summarized, terminology is introduced, and a synopsis of the current state of the art is presented. The initial conditions at the start of the plan are then stated, followed by a summary of target improvement efforts currently under way. Each planned successive target operation is then described, along with the rationale for the proposed target sequence and an account of what each target should contribute to the knowledge base. Each target operation also includes a list of contingencies and associated responses. The flow chart in Figure 2 illustrates the plan organization.

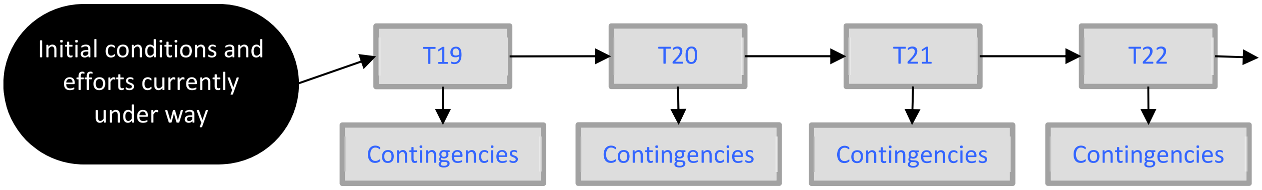

Figure 2. Example of flow of the target management plan

CURRENT KNOWLEDGE BASE

The current SNS mercury target knowledge base is derived from the following sources.

- The 18 target modules expended at the SNS FTS over approximately 11 years of operation, with a total delivered energy of more than 40 GW-hr,
- Instrumentation of recent target modules leading to direct measurement of mercury vessel dynamic response at several locations under varying beam pulse power and temporal delivery conditions,[1] as well as with and without small bubble gas injection,[2]
- Post-irradiation examination (PIE) of targets augmented by new techniques which provide quantitative measurements of cavitation erosion from selected areas of recent target modules,
- Cooperative development of improved manufacturing and quality assurance techniques with support from the Research Reactor Division (RRD) quality assurance personnel and in partnership with an engaged target module vendor,
- Research studies focused on cavitation damage erosion, strain prediction, and strain mitigation at the Los Alamos Neutron Science Center (LANSCE),[3]
- Operational experience with the mercury target vessels at the Japan Proton Accelerator Research Complex (J-PARC)—including initial experience in strain mitigation with gas bubble injection[4]—along with a close, ongoing collaboration with J-PARC in all aspects of target design and operation, and
- Information gained from the Target Test Facility (TTF) at Oak Ridge National Laboratory (ORNL),[5] particularly regarding development of gas bubble injection techniques for SNS targets.

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[1] Blokland, W. SNS-RAD-BI-TR-0001, *Target Instrumentation, Development, Installation, and Initial Results*. ORNL, 2016.

[2] Blokland, W. et al., 106010101-TR0043, *Measurements of Effects of Gas Injection into SNS Target T18*. ORNL, 2017.

[3] Riemer, B. et al. 'Cavitation damage experiments for mercury spallation targets at the LANSCE – WNR in 2005' *Journal of Nuclear Materials* 377 (2008) 162-173.

[4] Wan, T. et al. 'In-situ structural integrity evaluation for high-power pulsed spallation neutron source – Effects of cavitation damage on structural vibration' *Journal of Nuclear Materials* 468 (2016) 321-330.

[5] Wendel, M. et al. 'Choked-Flow Inlet Orifice Bubbler for Creating Small Bubbles in Mercury' FEDSM2013-16017, *Proc. of FEDSM2013*: ASME 2013 Fluids Engineering Division Summer Meeting, July 2013.

This knowledge base is the foundation of the current state of the art for SNS FTS mercury target vessel design.

TERMINOLOGY

Two types of target designs have been built and used for SNS operation: original and jet-flow styles. These designs are classified by the bulk mercury flow arrangement within the target module. Some modules of each type were improved based on operational experience, leading to variations between modules of the same type. Table 3 at the end of the text provides historical information on targets.

Original: These targets use the original standard mercury flow design,[6] of which 15 have been received from three different vendors, and all but one has been expended. Of these 15, 12 included a welded trapezoidal plate on the underside of the mercury vessel transition body, which was the location of a leak which ended the life of three such targets. The one remaining target of this type (ORTE-003) includes the trapezoidal plate, but it was reinforced in 2017.[7] The remaining 3 of 15 original-style targets delivered were fabricated without the trapezoidal plate feature and with other improvements based on operational experience. Targets T12 and T13 both developed leaks from cavitation damage at the front, outside of the beam area. Two more original-style targets have been ordered from two different vendors that have a thicker wall where the T12/T13 targets leaked and these targets are also being retrofit to include the capability for small bubble gas injection.

Jet-flow: This designation refers to targets with a mercury flow pattern that includes a wall jet that sweeps across the inside of the front of the target vessel from bottom to top.[8] Four of these targets have been used, T10, T16, T17, and T18. The first such target (T10) had a partial-penetration weld which developed a leak that led to early end of life. Comparison of erosion between T10 and an original target with a similar early end of life showed that the cavitation damage at the jet location was reduced by the presence of the jet.[9] The weld design was improved in the subsequently delivered jet-flow targets. As with the original-style targets, small incremental improvements to the target module have been made based on PIE observations, operational experience, and engineering analysis. This includes the capability for small bubble gas injection. Recent PIE observations on T16 and T17, which were operated at higher flow rates and for longer exposures, did not confirm the reduced cavitation damage that was observed in T10. Two more jet-flow targets are on order and a third is planned.

Two future designs are also discussed:

Blue: The blue target design is based on the jet-flow design, but has additional baffle structures to modify the mercury flow pattern away from the beam entrance region to address the cavitation

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[6] ORNL Drawing 106010101-M8E-8700-A001, *Target Module Assembly*.

[7] ORNL Statement of Work 106010101-SW0001, *ORTE-003 Reinforcement*.

[8] ORNL Drawing 106010101-M8U-8700-A221, *Jet-Flow Target Module Assembly*.

[9] McClintock, D. 106010101-TR0001, *Observations of Cavitation-Induced Erosion of AISI 316L Target Vessels at the Spallation Neutron Source*. ORNL, 2016.

damage issues observed with T12 and T13. Four blue targets are being fabricated, two each at two separate vendors.

Chinstrap: This designation refers to a future design generation that will represent additional improvements to the target module based on additional engineering analysis and new operational information. The intent is to have this updated design available for target purchases needed in FY2018 to maintain sufficient inventory.

STATE OF THE ART

Conventional engineering design cannot definitively ensure in-service reliability using only analysis and/or experimental data. Analysis of the mercury-filled target module is dependent upon material models and evaluation techniques that have considerable uncertainties for the dynamic conditions present during SNS operation. Synergies between fatigue and cavitation damage also compound the analysis challenges. The SNS target modules remain first-of-a-kind technology and are subject to loadings and operating conditions that are not experimentally achievable. Therefore, the performance limits of target module hardware cannot be ensured apart from actual operating experience. The state of the art for target design represents a combination of engineering analysis, experimental data, and actual operating experience that can be used to direct the target design effort.

- Operational experience for targets 1–18 (T1-T18) indicates that the main challenges to target reliability are fatigue failures and cavitation damage.
  - The target is subject to cyclic stress from beam-induced pressure pulses and thermal transients. SNS has developed methodologies to predict these stresses and predict fitness-for-service,[10] but additional performance data and measurements of in-service targets are required to improve these predictive capabilities. The number of pulse stress cycles a target module experiences is on the order of 10^9, a regime of probabilistic life prediction.
  - The proton beam pulse introduces a compressive pressure wave that leads to induced tensile forces in the mercury, causing cavitation. The collapse of the cavitation bubbles causes erosion of the inner surfaces of the mercury target vessel structure. SNS has developed rudimentary methods of predicting cavitation damage potential, but the models need refinement.[11]
  - The administrative material damage limit arising from exposure to high-intensity radiation is not currently a constraint on target life. This limit protects the water shroud that surrounds the mercury vessel and serves to contain mercury leaks.[12] The shroud must remain strong and ductile enough to contain the mercury from a leaking inner mercury vessel. Tests on specimens extracted from spent targets have extended the limit sufficiently to run a single target for up to an operational year at 1.4 MW beam power without exceeding the radiation damage limit.[13]

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[10] Riemer, B. ‘Benchmarking dynamic strain predictions of pulsed mercury spallation targets’ *Journal of Nuclear Materials* 343 (2005) 81-91.

[11] Riemer, B. et al. ‘Correlation between simulations and cavitation-induced erosion damage in Spallation Neutron Source target modules after operation’ *Journal of Nuclear Materials* 450 (2014) 183-191.

[12] McClintock, D. 106010000-TR00130, *Recommendation to Change the Region of Consideration for the SNS Target Administrative Dose Limit*. ORNL, 2015.

[13] McClintock, D. 106010000-TR00131, *Displacement Dose Calculations for SNS Target 12 and Recommendation for Fall 2015 Target Operation*. ORNL, 2015.

- The jet-flow target mercury vessel is predicted by validated engineering analysis to be as mechanically robust as the original flow target.[14]
    - T10 lasted for only 5 weeks of beam time before registering a mercury leak, and the location and cause of the leak were determined. The leak was due to stress concentration and manufacturing associated with a weld design. Target construction was suspended until engineering efforts, bolstered by the PIE information, led to design modifications to remove the identified vulnerability. Target construction was then resumed.
    - PIE of T10, T16, and T17 shows that the jet-flow design has a different cavitation erosion pattern that may be more robust than the original design targets. Further measurements of samples are pending.
    - Current engineering analysis and the operational experience of targets T16, T17, and T18 indicate that the current jet-flow design variant is as robust as the original design. The analytical methodology used to draw this conclusion is strongly supported by strain measurements of in-service target vessels.[1,2]

- Gas injection will be beneficial to prolong target lifetimes.[15] The level of beneficial effects of gas injection in full-scale operating SNS targets remain to be determined.
    - Gas injection is known from experiments to reduce cyclic loading amplitudes,[16] and this effect has been measured on T18 and targets operated at J-PARC. It is expected that optimization of gas injection designs, target geometries, and flow patterns will lead to even greater reduction of cyclic loads.
    - Gas injection has been shown in experiments to reduce cavitation damage,[17] but specific results for gas injector designs, target geometries, and flow patterns will come only through operating experience and PIE of T18 and following targets.

- Some level of risk must be assumed to reach unproven power levels.
    - SNS has operated three targets reliability and predictably at 1.2 MW; T15 (original) and T17/T18 (jet-flow with and without gas injection).
    - Until the ultimate operational goal is achieved, targets must be tested in a more challenging operating environment than has been demonstrated in the past. Measures must and will be taken to anticipate potential failure modes, but there is always a chance of an unforeseen negative-impact on neutron production.
    - The long cycle time of target design, fabrication, and operation of approximately 30 months limits the opportunities to learn and assimilate knowledge into future target module hardware. It may therefore become necessary at times to implement multiple changes at once. The management plan must balance the need for methodical learning and understanding against the potential to reach operational goals as soon as possible.

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[14] Barbier, C. et al. 106010101-TR0013, *Modifications for Jet-Flow Targets*. ORNL, 2016.

[15] Riemer, B. 106010000-TR0132, *Conceptual Design Report: Mercury Target Gas Injection*. ORNL 2016.

[16] Okita, K. et al., 'Propagation of Pressure Waves, Caused by a Thermal Shock, in Liquid Metals Containing Gas Bubbles' *Journal of Fluid Science and Technology* Vol. 3 (2018) 116-128.

[17] Riemer, B. 'Small gas bubble experiment for mitigation of cavitation damage and pressure waves in short-pulse mercury spallation targets' *Journal of Nuclear Materials* 450 (2014) 192-203.

DEVELOPMENT EFFORTS CURRENTLY UNDER WAY

- Cavitation Damage Erosion Measurements and Analysis
    - SNS has removed samples from the nose of original-style targets and jet-flow targets. Several of these samples from the area of the T12 and T13 leak have been laser scanned to provide a map of the erosion area and depth.[18] This sampling effort will continue for every target removed from service. In addition, efforts are underway to develop the tooling required for measuring erosion in the highly activated beam entrance area.
    - Analytical predictions of areas of potential damage have correlated well to actual observed damage; however, these estimates are based on the underlying simulation model that shows some disagreement with in-beam measurements.
    - Work continues to develop empirical relationships that can be used to predict target erosion for existing target designs operated at increasingly higher power and for longer numbers of hours. In addition, work continues to improve simulation models to provide better predictive ability for new target designs.

- Survey of Cavitation Damage
    - In addition to photographing samples cut from spent targets, photographs and videos are taken of all accessible internal surfaces that were exposed to mercury. The images are regularly reviewed and correlated with analytical predictions to improve cavitation damage modeling.

- Target Strain Measurements
    - Targets since T13 have included strain gauges and other instruments to measure the in-situ response of the target to individual beam pulses and beam pulse trains. The current material models used for target engineering analysis are based on measurements from testing of simpler and smaller targets at the LANSCE facility at Los Alamos National Laboratory. Initial comparisons of strain data from these targets indicate that the modeled response is generally conservative.[1] Strain data measurement systems are now a regular part of the target fabrication and post-installation commissioning procedure. The instrumentation systems are continually expanded and improved, and as more data are collected from each target the strain response is revealed with increasing detail and certainty.

- Gas Injection Hardware
    - Jet-flow targets have been retrofitted with gas injection hardware. Original targets are now being retrofitted with similar hardware. The blue target design and all future target designs will also include gas injection hardware. Efforts to develop, install, and safely operate a gas injection system culminated in the first operation with T18 in late CY 2017. Development of gas injection methods and bubbler hardware such as swirl bubblers continues, with tests of these methods under way at the TTF. Swirl bubblers may be included in the chinstrap design.

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[18] McClintock, D. et al., 106010100-TR0002-R01, *Laser Line Scan Characterization of Cavitation-Induced Erosion to SNS Mercury Target Vessels*, ORNL 2017.

- Improved Target Design and Analysis
    - *After the T10 and T11 leaks in 2014*, a comprehensive review of target design, analysis, and fabrication was performed. Plans were developed to address known issues and revitalize target development efforts. This process culminated in a review by DOE in February 2015.[19]
    - *After the February 2015 review,* changes to targets under fabrication were issued to improve fatigue resistance based on lessons learned from T10 PIE. In addition, jet-flow targets were modified to include gas injection hardware. A new target design was developed in FY 2016 that included changes intended to improve target fatigue life. However, detailed analysis showed that some of the changes had introduced a new area of high stress in the pulse response. At this time, the unanticipated leaks in T12 and T13 were found to originate from cavitation damage erosion. Further efforts on this new target design were suspended to develop a response to this new information.
    - *In March 2017*, this Target Management Plan document was initially issued. After issuance, the blue target design was developed to improve resistance to the T12 and T13 failure mechanism and released to fabrication. Also in 2017, targets T16 and T17 were operated in accordance with the plan. These targets provided the first demonstration that the improvements to the jet-flow targets had resolved the weld issue seen in T10. In addition, PIE of these targets has provided more information on the cavitation patterns associated with this target design. Most recently, T18 was the first target to operate with gas injection. While PIE of T18 has not been completed, the efficacy of gas injection to reduce proton-pulse-induced strain was successfully quantified using the vessel strain measurements.
    - *Currently*, the recent results from PIE of jet-flow targets and the measurements of strains on T18 informed the erosion pattern and rates for the jet-flow target and the efficacy of gas injection. An improved chinstrap target design is in final analysis; like the blue target, it is based on the jet-flow design. The chinstrap target design includes swirl bubblers and other changes to improve fatigue resistance. When the detailed analysis is successfully completed, this target will be released for fabrication. The first blue target should be delivered in mid-CY 2018.
    - *In the future*, additional targets need to be purchased each year to keep up with operational demand. After reliable operation is achieved at 1.4 MW, efforts will continue to increase margins and improve the longevity of target modules. Target modules are expensive to build, install, and dispose of. Work will continue to maximize the value obtained from each target by operating it for as long as possible without failure. Future target designs will incorporate further improvements based on lessons learned from operation, fabrication, analysis, in-situ strain measurements, and post-irradiation examination efforts. The goal is to provide target designs for fabrication based on the current state of the art, and to operate targets for as long as is practical up to 5,000 MW-hr.

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[19] *Office of Project Assessment Review Report on the Spallation Neutron Source Target Design and Operations at Oak Ridge National Laboratory*. US DOE Office of Science, 2015.

INITIAL CONDITIONS

- One spare target at SNS
    - ORTE-003 is the only spare target available at the current time. It is an original-style target similar to some which have had fatigue-related failures near to the trapezoidal cover plate feature. ORTE-003 was reinforced against this failure mode in 2017.

- Eight targets in fabrication
    - Targets MTX-014 and MTX-016 are jet-flow targets currently being fabricated. They include gas injection and have an additional change to increase the vessel wall thickness by 66% at the location of the T12 and T13 cavitation erosion leaks.
    - MTX-015 and HML-001 are two additional original-style target which will be delivered in CY 2018. These two targets also will have the 66% wall thickness increase outside of the beam entrance area where leaks developed in T12 and T13, and they are being retrofit with gas injection capability. These targets are being fabricated at two different vendors to diversify the target supply chain.
    - MTX-017, MTX-018, ORTE-004, and ORTE-005 are four blue targets currently being fabricated. The blue target design is based on the jet-flow design but adds features to direct the mercury flow across the area of cavitation damage outside of the beam impingement area. These targets will also have gas injection capability. These targets are also fabricated by two different vendors.

DETAILED BASELINE PLAN

This discussion informs the schematic plan in Figure 1 and conforms to the flow illustrated in Figure 2. Starting in 2017, the operating tempo shifted from two major planned outages and target changes per year to three. This tempo is expected to continue until the start of Proton Power Upgrade construction currently projected to start in mid-2021. In 2018, SNS will have an extended shutdown, and only two targets will be consumed.

TARGET T19

- MTX-014 will be installed as T19. This jet-flow target module is similar to MTX-008 which was operated as T18. It includes additional thickness at the T12 and T13 location and gas injection capability. Based on operating experience gained from T15–T18, it will be operated at 1.3 MW until its planned removal, currently assumed to be August 2018. T19 will be the first target to operate after the long outage associated with replacement of the inner reflector plug and the radio frequency quadrupole accelerating structure.
- It is expected that the gas flow rate of T19 will be higher than that of T18 due to improved bubbler fabrication.
- Strain sensor and PIE erosion measurements will provide additional information about target response and cavitation damage erosion in the jet-flow targets with gas injection.

TARGET T19 CONTINGENCIES

- If T18 cavitation erosion measurements indicate that gas injection has led to a dramatic decrease in cavitation erosion, the power level may be increased to 1.4 MW.
- If MTX-014 does not arrive in time, then ORTE-003 will be installed as T19. The operating power would be reduced from the planned 1.3 MW to a lower value for which the target could be expected to operate until its replacement, likely 1.0 MW.
- If T19 fails early in its lifetime because of an unknown issue, then ORTE-003 may be installed. The power level used for this target will be chosen based on operational needs for target life until the next target change and the latest available information about target life prediction. It is expected that this power level would be less than the planned 1.3 MW power level for T19.
- If the target fails late in life, then MTX-016 or a new original type target may be installed.

TARGET T20

- MTX-016 will be installed as T20. This jet-flow target module is similar to the jet-flow targets T18 and planned for T19. Based on operating experience gained from T15–T19, T20 will be operated at a power level that is conducive to reliable operation until its planned removal, currently assumed to be 1.4 MW. It is projected that T20 will be operated through the end of CY 2018.
- It is expected that the gas flow rate of T20 will be higher than that of T19 due to improved bubbler design.
- Strain measurements and PIE measurement will provide additional information about target response and cavitation damage erosion in the jet-flow targets with gas injection.

TARGET T20 CONTINGENCIES

- If measurements of cavitation damage in T18 and T19 indicate that gas injection dramatically decreases cavitation damage, the operational life of T20 could be extended by not replacing the target as shown in the plan but rather extending it to two run cycles (assuming three cycles per year).
- If T20 fails early in its lifetime because of an unknown issue, then ORTE-003 or one of the new original-type targets may be installed. The power level used for a substituted target will be chosen based on operational needs for target life until the next target change and the latest available information about target life prediction.
- If T20 fails late in life, then the first blue target, MTX-017, may be installed.

TARGET T21

- MTX-017 will be installed as T21. This would be the first operational experience with a blue target module. Based on operational experience gained from jet-flow targets T16 through T20, it will be operated at a power level that is conducive to reliable operation until its planned removal period, currently assumed to be 1.4 MW.
- Strain and PIE measurements will provide additional information about target response of a new design type, including the efficacy of features intended to be improvements over the jet-flow targets, especially the additional baffles added to redirect the mercury flow.

TARGET T21 CONTINGENCIES

- If measurements of cavitation damage in T18, T19, and T20 indicate that gas injection dramatically decreases cavitation damage, the operational life of T21 could be extended by not replacing the target as shown in the plan but rather extending it to two run cycles (assuming three cycles per year).
- If T21 fails, then one of the new original type targets will be installed. The power level used for this target will be chosen based on operational needs for target life until the next target change and the latest available information about target life prediction.

TARGET T22

- MTX-015 will be installed as T22. MTX-015 is an original type target which will include gas injection capability. Based on operational experience gained from target T16 through T21, it will be operated at a power level that is conducive to reliable operation until its planned removal period, currently assumed to be 1.4 MW. Since original style targets have previously been limited by cavitation erosion, operating T22 at 1.4 MW is contingent on evidence of reduction in cavitation erosion due to gas injection.
- After operation of T22, the original design will become the second design which was operated both with and without gas injection. Comparison of T22 strain and PIE measurements with those of original targets without gas injection will aid the general understanding of the impact of gas injection on target performance.

TARGET T22 CONTINGENCIES

- If measurements of cavitation damage in T18 through 21 indicate that gas injection dramatically decreases cavitation damage, the operational life of T22 could be extended by not replacing the target as shown in the plan but rather extending it to two run cycles (assuming three cycles per year).
- If T22 fails, then a blue target may be installed. The power level used for this target will be chosen based on operational needs for target life until the next target change and the latest available information about target life prediction.

TARGET T23

- MTX-018, a blue target, will be installed as T23. Based on operational experience gained from target T16 through T22, it will be operated at a power level that is conducive to reliable operation until its planned removal period, currently assumed to be 1.4 MW.
- Strain and PIE measurements will provide additional information about target response of the blue design, which can be compared to results from T21 and used to improve predictive capability.

TARGET T23 CONTINGENCIES

- If strain and PIE measurements up to this point indicate that the blue target design can be expected to operate for longer than shown on the baseline plan, T23 could be extended by not replacing the target as shown in the plan but rather extending it to two run cycles (assuming three cycles per year).

- If T23 fails because of an unknown issue, then an original type target or a jet-flow target may be installed. The power level used for this target will be chosen based on operational needs for target life until the next target change and the latest available information about target life prediction.

TARGET T24 THROUGH T26

- Targets T24 through T26 are expected to operate in calendar year 2020. These targets are expected to operate at 1.4 MW, and will be blue and chinstrap targets which incorporate improvements over the jet-flow design.
- Strain measurements and PIE information on newer target designs will provide additional information which will be a significant help in tuning predictive models for target response and lifetime.

TARGET T24 THROUGH T26 CONTINGENCIES

- If results from operations and PIE measurements indicate that improvements such as gas injection and flow mitigation have reduced the rate of cavitation damage where longer target lifetimes are projected, the pace of target consumption may be decreased from the planned 3 targets per year pace.
- Any unexpected failures will be managed with the adequate spare target inventory.

DISCUSSION

Although unexpected target failures have significantly reduced SNS availability in earlier years, SNS has learned a great deal from the end-of-life target events that have occurred beginning in 2012 and from the operational experience of targets which have lasted through their planned operational periods.

- Lifetime limits for early target designs are well explored:
    - Extended-duration operation (~3,000 hours) at 850 kW (T2, T3, T9, and T12),
    - Moderate-duration operation (~2,500 hours) at 1 MW (T9 and T14), and
    - Shorter-duration operation (>1,000 hours) at 1.2 MW (T9, T12, T13, T15, and T17) and (>700 hours) at 1.3 MW (T9, T12, and T13).
- Vulnerable design features are identified and improved:
    - The trapezoidal plate on the underside of the target that was responsible for three of the four end-of-life events in 2012 and 2014 was eliminated from the mercury vessel transition body and improved manufacturing techniques were developed,
    - The weld that joins the transition body to the front body was redesigned to eliminate the partial penetration vulnerability identified on the first jet-flow target module in the fourth of these four end-of-life events in 2014.
- Oversight of the manufacturing process has been enhanced, including improved quality assurance requirements and new evaluation techniques.
- In-situ measurements of target response to the proton beam are routinely collected, beginning with T13:
    - Provided valuable information to compare with engineering models,
    - Substantially increased confidence in the understanding of the margins of safety for vulnerable areas in the mercury target vessel.

- The limiting locations for cavitation damage erosion have been identified:
    - The unexpected result that the first cavitation erosion failures occurred *away from the direct area of beam impingement* in T12 and T13 has led to increased emphasis on design and development of gas bubble injection techniques, which can be demonstrated at the TTF at ORNL,
    - PIE has confirmed that engineering models of cavitation erosion potential generally predict the location of cavitation damage erosion,
    - Operation of T10 demonstrated that enhanced mercury flow adjacent to the inner surface in the region of beam impingement can significantly reduce such erosion, although photos taken from T16 and T17 indicate that this reduction may not hold for higher flow rates and longer exposures,
- Observations of T16 and T17 also show a significantly different pattern and amount of erosion outside of the direct area of beam impingement, demonstrating that the structural configuration of the target is a key driver of the cavitation pattern. Gas bubble injection, increased wall thickness, modifications to structure, and modification of mercury flow patterns are all being implemented as part of an effort to address this challenge.

AVOIDING UNEXPECTED TARGET-RELATED OUTAGES

There are two key parameters that must be managed to minimize the likelihood of an unexpected target-related outage for a given target design: beam power and duration of exposure. For a specific target, proven operating experience with similar targets provides the best basis for recommended power and exposure. The dynamic, evolutionary nature of target design and manufacturing limits available information. Until the operation of T14 through T18 at fixed power (1 MW and 1.2 MW), the only other target to operate at fixed power for most its life was T8 (850 kW). All other targets have seen highly nonuniform distributions of power as part of the efforts to improve and sustain facility performance and neutron flux, making it difficult to interpret and predict target lifetime limits.

Precautions that are taken to avoid unexpected target-related outages include:

- Initial strain measurements,
- Initial conditioning of the target module for about 3×10^6 cycles at 850 kW,
- Gradual ramp-up of power consistent with SNS foil conditioning protocols (about 24 hours to reach target powers after initial operation at 850 kW), and
- Planned exposure durations based on prior demonstrated performance for the class of target (or its near relatives) in operation.

However, even this conservative approach cannot fully eliminate the risk of an in-service failure.

MAINTAINING SUFFICIENT TARGET INVENTORY WHILE CONTROLLING COSTS

Target modules are expensive; with lifecycle costs for each target approaching $2M. It is therefore important to maximize the benefit derived from each target module.

Currently, the target supply chain is as follows:

- Only one original target (with a reinforced trapezoidal plate) is available as a spare.

- Two jet-flow targets, both of which are equipped with gas injection capability, will arrive in the next 6 months. The plan is to use these targets shortly after delivery.
- Two original type targets, with gas injection added, are in fabrication. The first delivery is projected for June 2018.
- Four blue targets are in fabrication, with the first scheduled to be delivered in September 2018.

Thus, the projected inventory through May 2018 will consist of jet-flow targets, three original targets, and the relatively unproven blue targets.

The following procurements are planned to add to the supply chain:

- An order for an additional jet-flow target is being placed as soon as possible.
- Two chinstrap targets will be procured in FY18. If the chinstrap design does not meet requirements or is not available in time, additional blue targets may be procured instead.

This strategy should result in a minimum inventory of one spare target, and a maximum inventory of three spare targets until CY 2019. This relatively low number of spares is due to the increased operational pace of three target per year, which reduces the burden on each target but consumes targets at a faster rate than was expected in previous years. After February 2019, the number of spares is projected to rise to 5 or more targets. If experience shows that target life can be extended for more than one operational cycle, this would represent a significant savings. In a three cycle per year operational schedule, this would mean that a target would need to operate for 2/3 of a year.

In the event of a target failure, this plan provides for flexibility through diversity of spare targets. The intent is to use the proven targets sustain neutron production while allowing time for investigation of an unplanned outcome associated with a particular target design, and for corrective actions to completed.

To control costs and obtain the maximum value from each target module, targets will be operated for longer periods as operational experience is gained which shows that this will not lead to unacceptable operational risk.

ENSURING CONSISTENCY WITH THE PLANNED OPERATING SCHEDULE

The planned exposure times for future targets are based on the latest available operational schedule. Constraints on understanding target performance through planned runs at steady beam powers are just one of several considerations in finalizing the planned operating schedules for future years. This management plan document will be revised as needed to reflect changes in operating schedules.

The upcoming change in the operating schedule to shift from three to two major outages per year is expected to occur around July 2021, around the time of target T29. To support this operational tempo, targets which can sustain 1.4 MW operation for 3,500 MW·hr are needed.

DEVELOPING THE KNOWLEDGE BASE FOR TARGET DESIGN AND OPERATIONS

Structural aspects of target engineering and fabrication are increasingly well-understood, with associated increasing confidence in the modeling approach based on accumulating operational experience. However, actual margins to failure remain uncertain for the high cycle fatigue. The most limiting issue toward reliable 1.4 MW operation at present is the insufficient knowledge base to effectively address cavitation damage erosion.

Experimental studies with beam at LANSCE, mechanical impact testing performed at J-PARC, and limited operating experience with T18 and at J-PARC indicate that injection of gas represents the most promising path to limiting cavitation damage erosion and high cycle fatigue. Continued collaboration with J-PARC is vital in advancing the state of the art in mercury target technologies, especially with continued implementation of gas injection.

The SNS TTF supports the development of gas injection techniques and permits the characterization of prototypical mercury/gas hydraulic performance. Understanding how injected gas affects the normal and off-normal operation of the mercury system is crucial to implementing higher gas flows at SNS. Therefore, use of the TTF is very important to the design basis of future gas injection systems.

Difficulties in fabricating gas injection hardware expose the need for advanced manufacturing techniques that permit the development of novel gas injection systems with reliable performance that can be included in future target designs.

Future targets will combine changes in mercury flow, structure, and bubble gas rates and generation locations, and other improvements that will be necessarily compounded as new information is obtained from measurements and analysis. Unfortunately, operating new targets with more than one significant change from previous target operation limits opportunities to understand and de-convolute positive and negative attributes associated with each change. The challenge is to balance our need for understanding with the desire to move quickly toward the most reliable target design.

BALANCING PERFORMANCE, RISK, AND ATTAINMENT OF THE KEY OBJECTIVE

Balancing performance, risk, and attainment of the key objective is the most challenging aspect of this plan, together with the important element of ensuring that product delivery schedules are met with appropriate attention to quality.

Every target placed into operation presents some risk for an unplanned end-of-life event, especially with increasingly higher beam powers. These risks include the following:

- Undetected manufacturing or material defects can lead to premature end-of-life triggered fatigue,
- New design modifications to targets may carry flaws that are not revealed by engineering analysis models,
- Uncertainties in interpretation of prior target performance can lead to overly optimistic estimates of anticipated target performance, and
- Inadequate understanding of the power dependence of cavitation damage or structural fatigue may lead to overly optimistic expectations.

The plan presented above recognizes these risks, and the contingencies presented for each target address how elements of this risk profile can be managed.

SUMMARY

This plan outlines a roadmap of target operation to satisfy the high-level goals of reliability, performance, and stewardship. Steady operation at higher power can be reached with managed risks of user program interruption by operating targets with progressively increasing power levels, maximizing learning opportunities, and taking advantage of new information as soon as possible. The plan includes some contingencies and extends in detail to the end of FY 2020. The plan includes the expectations for new information that is critical to the development of 2.0 MW capable targets needed as part of the Proton Power Upgrade project.

Projecting target operations past the end of FY 2020 is much more speculative owing to the accumulation of likely new discoveries. The intent of moving past FY 2020 in the planning process is to converge to a sustainable operating pattern that provides a steady supply of reliable targets with increasing lifetimes as the facility provides steady operation at a beam power of 1.4 MW. Improved-capability targets, such as the blue and chinstrap designs, will be developed, fabricated, and operated. Lessons learned from in-beam strain measurements, PIE, and operational experience will inform these improved designs and their operational use. Updating this document annually and when an unexpected result occurs can ensure that coordination between design, development, and operational activities is improved and maintained.

Table 1. Planned target operation through CY 2020

Target	Planned Start	Planned End	Approximate Hours of Operation	Type of Target	Serial Number/Type	Expected Stable Power Level[1]
T19	April 2018	July 2018	1800	Jet-Flow with gas injection and reinforcement of nose	MTX-014/Jet-flow	1.3 MW
T20	August 2018	November 2018	1900	Jet-Flow with gas injection and reinforcement of nose	MTX-016/Jet-flow	1.4 MW
T21	January 2019	April 2019	1900	Gas injection, flow mitigation	Blue	1.4 MW
T22	April 2019	July 2019	1900	Gas injection	Original	1.4 MW
T23	August 2019	November 2019	1700	Gas injection, flow mitigation	Blue	1.4 MW
T24	January 2020	April 2020	2000	Gas injection, flow mitigation	Blue	1.4 MW
T25	April 2020	July 2020	1900	To be determined	Chinstrap	1.4 MW
T26	August 2020	November 2020	1900	To be determined	Chinstrap	1.4 MW

[1] All targets are expected to be operated at 850 kW for one week, after which power would be ramped to the stable power level and operated there as much as practical for the remainder of their life.

Table 2. FY18 – 19 milestones for target management plan

Milestone	Projected Date
Final design review for chinstrap target	March, 2018
Receive original target with CDE reinforcement and gas injection	July, 2018
Initial PIE assessment of T18, the first gas injection target	June, 2018
Receive first blue target	October, 2018
Strain measurements of blue target	January, 2019
Strain measurements of original target with gas injection	April, 2019
Initial PIE assessment of blue target	June, 2019
Initial PIE assessment of original target with gas injection	October, 2019

Table 3. Target historical information

Target	Serial Number	Date Installed	Date Removed	Accumulated Energy (MW-hrs)	Ave. Power (kW)	Peak Power (kW)	Mercury Flow Pattern	Transition cover plate removed	Robust front body to transition	Sensors	Gas injection capable	Thickened to resist erosion outside beam	Comments
T1	MTX-001	4/2006	7/2009	3055	379	850	Original						
T2	MTX-002	8/2009	7/2010	3145	771	1000	Original						
T3	MTX-005	7/2010	4/2011	2791	845	1050	Original						Leak location not determined.
T4	MTX-006	4/2011	1/2012	3252	782	1020	Original						
T5	MTM-001	1/2012	7/2012	2362	938	1020	Original						
T6	MTX-004	8/2012	9/2012	617	916	1010	Original						Leak at transition cover plate. Traced to manufacturing error.
T7	MTX-003	10/2012	10/2012	98	943	1000	Original						Leak at transition cover plate. Traced to manufacturing error.
T8	MTM-003	11/2012	10/2013	3750	851	1400	Original						
T9	ORTE-001	10/2013	7/3/2014	4195	1033	1415	Original						
T10	MTX-007	7/2014	9/2014	601	1052	1160	Jet-Flow	Yes					Leak at front body to transition weld.
T11	ORTE-002	9/2014	11/2014	167	1116	1230	Original						Leak at transition cover plate. No evidence of manufacturing error.
T12	MTM-002	11/2014	9/2015	4445	964	1357	Original						Leak due to cavitation erosion outside of beam spot.
T13	MTX-009	10/2015	3/2016	2588	1075	1441	Original	Yes		Yes			Leak due to cavitation erosion outside of beam spot.
T14	MTX-010	3/2016	10/2016	2732	968	1000	Original	Yes	Yes	Yes			
T15	MTX-013	10/2016	12/2016	1290	1104	1250	Original	Yes	Yes	Yes			
T16	MTX-011	1/2017	6/2017	1783	1110	1059	Jet-flow	Yes	Yes	Yes	Yes		Gas injection disabled.
T17	MTX-012	6/2017	10/2017	1936	1127	1250	Jet-flow	Yes	Yes	Yes	Yes		Gas injection disabled.
T18	MTX-008	10/2017	1/2018	1261	1120	1261	Jet-flow	Yes	Yes	Yes	Yes	Yes	First target with gas injection operable.
Reserve Targets													
	ORTE-003						Original						Reinforced transition cover plate.
Targets in Fabrication													
	MTX-014						Jet-Flow	Yes	Yes	Yes	Yes	Yes	
	MTX-015						Original	Yes	Yes	Yes	Yes	Yes	
	HML-001						Original	Yes	Yes	Yes	Yes	Yes	
	MTX-016						Jet-Flow	Yes	Yes	Yes	Yes	Yes	
	MTX-017						Blue	Yes	Yes	Yes	Yes	Yes	Jet-flow, gas injection, and changed flow pattern outside of beam.
	MTX-018						Blue	Yes	Yes	Yes	Yes	Yes	
	ORTE-004						Blue	Yes	Yes	Yes	Yes	Yes	
	ORTE-005						Blue	Yes	Yes	Yes	Yes	Yes	