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

# Target Management Plan

March 2017

**Prepared by**
Instrument and Source Division
Neutron Science Directorate

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Instrument and Source Division

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March 2017

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
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**Approvals:**

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## 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 up to 3,500 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 which 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 project.

## SCHEMATIC BASELINE PLAN

Figure 1 shows the baseline, success-oriented plan for target operation and fabrication through the FY 2019. 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.

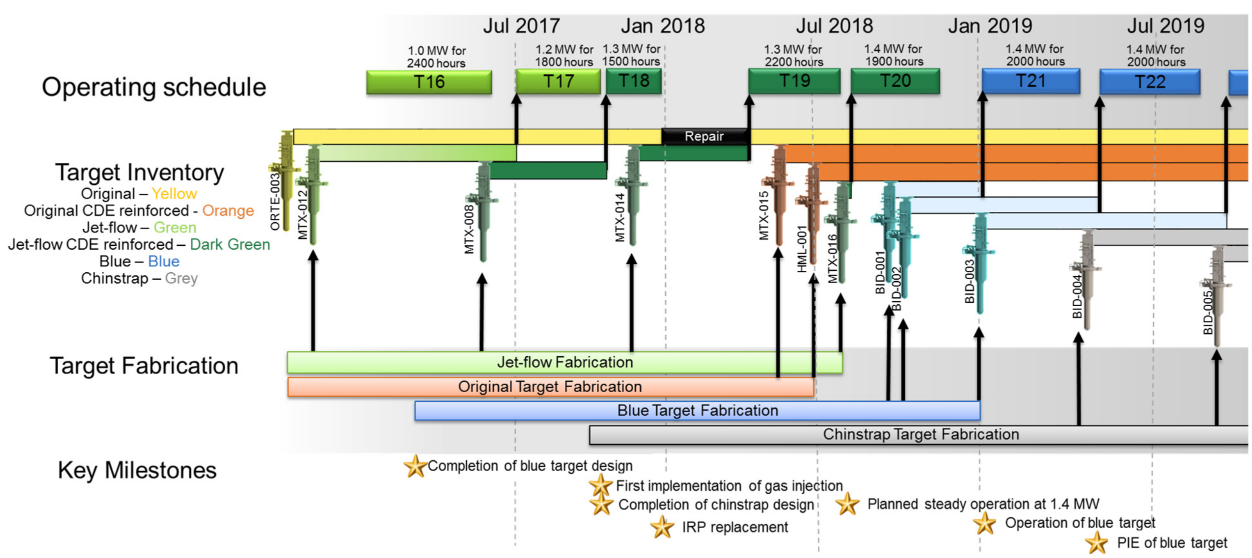


Figure 1. Schematic target operations and management plan through FY 2019.

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 will 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.

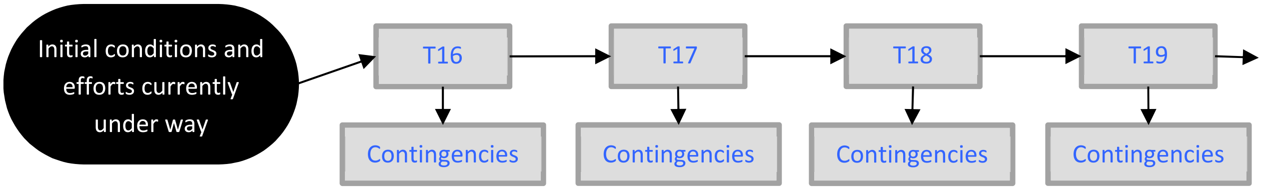


Figure 2. Example of flow of the target management plan.

# CURRENT KNOWLEDGE BASE

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

- The 15 target modules expended at the SNS FTS over approximately 10.5 years of operation, with a total delivered energy more than 35 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]
- Cooperative development of improved manufacturing and quality assurance techniques with support from High Flux Isotope Reactor 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),[2]
- 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[3]—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),[4] particularly regarding development of gas bubble injection techniques.

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

[1] Blokland, W. SNS-RAD-BI-TR-0001, *Target Instrumentation, Development, Installation, and Initial Results*. ORNL, 2016.
[2] 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.
[3] 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.
[4] 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.

## 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 during fabrication, 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, [5] 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 has been associated with early structural problems. The one remaining target of this type (ORTE-003) includes the trapezoidal plate. A second round of three additional original-style targets were fabricated without the trapezoidal plate feature and with other improvements based on operational experience. Two more original-style targets have been ordered from two different vendors that have the additional improvement of a thicker wall at the front location outside the beam entrance region, where the T12/T13 targets leaked.

Jet-flow: This designation refers to targets with a mercury flow pattern that includes a wall jet to sweep across the inside of the target vessel from bottom to top.[6] Only one of these targets has been operated (T10), and a partial-penetration weld issue led to an early end of life. The jet-flow idea proved successful in mitigating cavitation damage,[7] so 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. One spare jet-flow target is currently installed, one is on site, and three more are on order.

Two future designs are also discussed:

Blue: The blue target design has additional baffle structure to modify the mercury flow pattern away from the beam entrance region to address the cavitation damage issues observed with T12 and T13. The design is almost complete, and construction will soon begin.

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 by the use of 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.

[5] ORNL Drawing 106010101-M8E-8700-A001, *Target Module Assembly.*
[6] ORNL Drawing 106010101-M8U-8700-A221, *Jet-Flow Target Module Assembly.*
[7] McClintock, D. 106010101-TR0001, *Observations of Cavitation-Induced Erosion of AISI 316L Target Vessels at the Spallation Neutron Source*. ORNL, 2016.

The SNS target modules are first-of-a-kind technology and are subject to loadings and operating conditions that are not experimentally achievable. Because of this, 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 1–15 (T1-T15) 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,[8] but additional performance data and measurements of in-service targets are required to improve these predictive capabilities. The number of pulse stress cycles 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.[9]
  - 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.[10] The shroud must remain strong enough to contain the mercury from a leaking inner mercury vessel. Recent 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.[11]

- The jet-flow target mercury vessel is predicted by validated engineering analysis to be as mechanically robust as the original flow target.[12]
  - PIE of T10, the only jet-flow target operated to date, shows that the jet-flow design demonstrably reduces cavitation damage on the inner window surface in the area of direct beam impingement.
  - Although T10 lasted for only 5 weeks of beam time before registering a mercury leak, the location and cause of the leak have been determined; the leak was due to stress concentration and manufacturing associated with a particular weld design.
  - Three other jet-flow targets were being constructed at the time that the cause of the T10 leak was diagnosed. Construction was suspended until engineering efforts, bolstered by the PIE information, led to design modifications to remove the identified vulnerability. Construction was then resumed.

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[8] Riemer, B. 'Benchmarking dynamic strain predictions of pulsed mercury spallation targets' *Journal of Nuclear Materials* 343 (2005) 81-91.
[9] 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.
[10] McClintock, D. 106010000-TR00130, *Recommendation to Change the Region of Consideration for the SNS Target Administrative Dose Limit*. ORNL, 2015.
[11] McClintock, D. 106010000-TR00131, *Displacement Dose Calculations for SNS Target 12 and Recommendation for Fall 2015 Target Operation*. ORNL, 2015.
[12] Barbier, C. et al. 106010101-TR0013, *Modifications for Jet-Flow Targets*. ORNL, 2016.

  - Current engineering analysis indicates 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 original-style in-service target vessels.[1]

- Gas injection will be beneficial to prolong target lifetimes.[13] 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,[14] an effect that is expected to extend throughout most of the target.
  - Gas injection has been shown in experiments to reduce cavitation damage,[15] but specific results for gas injector designs, target geometries, and flow patterns will come only through operating experience.

- Some level of risk must be assumed to reach unproven power levels.
  - 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 discovering something that was unforeseen.
  - 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.

## Development Efforts Currently Under Way

- T10 (Jet-flow) Leak Location Investigation
  - Jet-flow target T10 developed a leak early in its operation. Core samples taken from the leak location for this target are currently at a facility off-site where the leak location is being analyzed. Early results confirm that the leak is indeed related to a partial penetration weld that has been removed as a vulnerability in subsequent targets.[16]

- Cavitation Damage Erosion Measurements and Analysis
  - SNS has removed or will soon remove samples from the leak areas of original-style targets T12, T13, T14 and T15. The first set of these samples have been laser scanned to provide a map of the erosion area and depth.[17] This effort will continue for other samples are available. Using these data, predictive methods will be improved for making estimates of the time required for cavitation damage erosion to cause a target leak.

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

[14] 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.

[15] 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.

[16] Ruminski, A. DRAFT MCOE-TR-16-8, *Materials Characterization of ORNL Spallation Neutron Source Target 10,* Westinghouse Electric Company, 2017.

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

  - Analytical predictions of areas of 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.

- Survey of Cavitation Damage
  - In addition to photographing samples cut from spent targets, many photographs and videos have also been taken of internal surfaces that were exposed to mercury. The images are being reviewed and will be 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 response of the target to individual beam pulses and beam pulse trains in situ. 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 being expanded and improved; and as more data are collected with every target, the strain response is revealed with increasing detail and certainty.

- Gas Injection Hardware
  - Jet-flow targets have been retrofitted with gas injection hardware. The blue target design also will include gas injection hardware. Efforts to develop, install, and safely operate a gas injection system are under way with a success-oriented goal of first operation with T18 in late CY 2017. In addition, development of gas injection methods and bubbler hardware such as swirl bubblers continues, with tests of these methods under way at the TTF.

- Original Target Repair
  - Target ORTE-003 requires repair to reinforce the target at the trapezoidal plate area where leaks occurred on T6, T7, and T11. In addition, instrumentation will be added to the mercury target vessel to enable measurement of strain, particularly in the trapezoidal plate area, to validate engineering models. This work requires removal of the water-cooled shroud, and the target will not be available as a spare during the repair. Owing to limited target inventory, this work is planned to coincide with the extended shutdown now planned for early CY 2018.

- Target Fabrication
  - Three of five targets currently under fabrication are jet-flow type targets. Only one jet-flow target, T10, has been used in production: it developed a leak early in its operation. All new jet-flow targets have been reinforced against the T10-type failure. The newest jet-flow targets (see Table 3) will also have a thicker wall at the T12/T13 leak location.
  - Owing to the limited operational experience with this jet-flow design, additional units of the proven original-type design are in fabrication to provide spares in case an unexpected problem develops. These targets will be reinforced to mitigate cavitation damage erosion at the T12/T13 failure location but because of schedule demands and resource constraints they will not include

gas injection hardware. These targets are therefore not expected to provide the same lifetime at higher powers as would be expected for targets with gas injection. The first of these units will be delivered in the first half of CY 2018.

- 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.[18]
  - *After the February 2015 review,* changes to targets under fabrication were issued to improve fatigue resistance based on lessons learned from T10. 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 unforeseen 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. Resulting design changes to future targets should improve their resistance to the T12 and T13 failure mechanism.
  - *Currently*, an improved blue target design is in final analysis; it includes new mercury flow features, in addition to those of the jet-flow design, to combat cavitation damage at the location seen in T12 and T13. It will also include integrated gas injection hardware and other changes to improve fatigue resistance. When the detailed analysis is successfully completed, this target will be released for fabrication. Its design is based on lessons learned from operational experience of past target leaks, expanded fatigue analysis methods, and better modeling practices. 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 with the goal of increasing margins and improving longevity of target modules. The goal is to develop a further improved target design, referred to as chinstrap, to support needed target fabrications in FY 2018. The chinstrap will incorporate further improvements based on lessons learned from operation, fabrication, analysis, and post-irradiation examination efforts. It will include feedback from strain sensors and PIE of original-type targets, as well as strain sensors from the jet-flow T16. The details of the chinstrap design are therefore unknown, but it is expected to include improved gas injection hardware and further improvements to fatigue resistance. Analysis is always ongoing and contributing to improved target design; for the foreseeable future, the goal is to provide designs based on the then current state of the art for fabrication.

[18] *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

- Two spare targets at SNS
    - MTX-012 has recently been delivered to ORNL. This module is an improved jet-flow target with a modification for a full-penetration weld at the T10 leak location, and it includes additional hardware to provide for gas bubble injection into the mercury. It is of the same design as MTX-011 which is currently installed as T16.
    - ORTE-003 is the other spare target available at the current time. It is also an original-style target. Similar targets of this type and vintage have had fatigue-related failures associated with the trapezoidal cover plate design and fabrication.

- Five targets in fabrication
    - Targets MTX-008, MTX-014, and MTX-016 are also jet-flow targets being fabricated. They have an additional change to increase the thickness of their wall by 66% at the location of the T12 and T13 cavitation erosion leaks.
    - MTX-015 and HML-001 are two additional original-style target orders that have just been placed and 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. These targets are being fabricated at two different vendors, which helps to diversity our target supply chain.

## Detailed Baseline Plan

This discussion builds on the schematic plan outlined in Figure 1 and conforms to the flow illustrated in Figure 2. Starting immediately with calendar year 2017 and continuing through 2020 when Proton Power Upgrade construction begins, it is expected that the operating tempo will shift from the previous two major planned outages per year to three outages per year. This will be interrupted by the extended shutdown in 2018, and that year will only consume two targets.

### Target T16

- MTX-011 is currently installed as T16. This module would be the first jet-flow target to be used since T10 was operated in 2014. MTX-011 includes modifications to the weld joint that failed in T10.
    - MTX-011 is also the first target to be fitted with gas bubblers that facilitate gas injection at low gas flow rates into the mercury to extend the mercury target vessel lifetime by reducing overall cyclic strain. While this target module has the needed hardware to supply gas, neither the required hardware outside of the target module to supply the gas nor the necessary approvals were in place for the installation of T16. Therefore, the gas injection hardware has been disabled.
- After the initial 1 week conditioning at 850 kW beam power, the plan is to operate T16 at a steady 1.0 MW.
    - Operation at 1.0 MW will provide a good baseline of performance of the jet-flow design and allow comparison with the T14 which operated steadily at 1.0 MW.

- MTX-011 is also equipped with strain sensors.
  - Strain measurements will allow for the first comparison of the original and jet-flow target designs.
  - Strain measurements will allow for comparison of predicted and actual strains for the jet-flow target.
  - The information gained from in-beam measurements will be used in the development of the chinstrap target design. This information supports not just future improvements for 1.4 MW targets, but also is critical for future higher power targets associated with the Proton Power Upgrade project.
- PIE sampling of T16 will provide the first measurements of cavitation damage erosion at the T12 and T13 erosion leak location in a jet-flow target. This information also supports not just future improvements for 1.4 MW targets, but also is critical for future higher power targets associated with the Proton Power Upgrade project.

### T16 Contingencies

- If T16 fails early in its planned lifetime as the result of an unknown issue, then ORTE-003 module will be installed and operated at lower power (likely ≤1 MW) after the initial burn-in period at 850 kW. This will provide time to diagnose the problem with T16 to ensure that the failure mode is not common to other jet-flow targets or, if it is, to make appropriate modifications to future targets. If the T16 target fails late in its run, then MTX-012 will be installed.
- If initial strain measurements were not favorable on MTX-011—e.g., if they revealed higher stresses than expected—the power level could be decreased. The magnitude of the decrease would be related to the measured stresses.

### Target T17

- MTX-012 will be installed as T17. It is a twin of the jet-flow target MTX-011 installed as T16. It is expected that the gas injection will be disabled on MTX-012 in the same manner as it was for MTX-011 due to the unavailability of hardware and approvals necessary to operate with gas injection.
- T17 will be operated at 1.2 MW, preferably at a stable power level.
  - If a correlation for cavitation damage as a function of power is established from previous targets, then cavitation damage measurements on T15/T16 could be extrapolated to provide operational guidance to T17. This could result in a modification of this planned power level.
- Strain measurements and PIE will provide additional information about target response and cavitation damage erosion in the jet-flow type targets.

### Target T17 Contingencies

- If T16 fails late in life as a result of cavitation erosion damage, the operating power level of T17 may be reduced to help ensure that the target will last until its scheduled removal time.
- If T17 fails late in life as a result of cavitation erosion damage, the operating power level of T18 may be adjusted to help ensure that the target will last until its scheduled removal time.

- If T17 fails early in its planned lifetime owing to an unknown issue, then ORTE-003 module will be installed while engineers diagnose the problem. If T17 fails late, then MTX-008 will be installed.

## TARGET T18

- MTX-008 will be installed as T18. This jet-flow target module is similar to MTX-011 and MTX-012 but also includes additional thickness at the T12 and T13 leak location. Based on operating experience gained from T15–T17, it will be operated at a power level that is conducive to reliable operation until its planned removal, currently assumed to be 1.3 MW. Currently, T18 is expected to be the last target operated before the long outage associated with replacement of the inner reflector plug and the radio frequency quadrupole accelerating structure.
- MTX-008 is projected to be the first target planned to operate with gas injection.
  - The use of gas injection on any target is contingent on successful completion of design and installation activities, together with safety basis modifications and attendant readiness reviews and approvals required for the gas supply and removal systems.
  - The initial use of gas injection is expected to require an additional system commissioning time before beam on target.
- Strain measurements and PIE measurements will provide additional information about target response and cavitation damage erosion in the jet-flow type targets.
  - Strain measurements on T18 may provide the first measurements of the effect of gas injection on the target strain response in the SNS beam. This supports not just future improvements for 1.4 MW targets, but also is critical for future higher power targets associated with the Proton Power Upgrade project.
  - Cavitation measurements on T18 may provide the first measurements of the effect of gas injection on cavitation erosion in a production target. This supports not just future improvements for 1.4 MW targets, but also is critical for future higher power targets associated with the Proton Power Upgrade project.
- By varying the amount of gas injected, the effects of gas injection on the target strain response can be isolated to allow us to compare operation with simulations with no gas injection. Cavitation damage measurements on the thicker wall section (where T12/T13 leaked) will provide information about the cavitation damage rate.

## TARGET T18 CONTINGENCIES

- If T18 fails early in its lifetime as a result of an unknown issue, then ORTE-003 may be installed.
- If the target fails late in life, then MTX-014, a twin of MTX-008, may be installed. One item or note is that it is expected that a target change must occur during the long outage to support inner reflector plug replacement. In the event of a late failure of T18, this could mean that a target must be used and disposed of after only a very short operating cycle. If this were to occur, consideration may be given to operating ORTE-003 at a low power level for this short period.
- If gas injection hardware or approvals are not in place in time to support its use in T18, the gas injection hardware would be disabled and first implementation of gas injection would be postponed to T19.

## Target T19

- MTX-014 will be installed as T19. This jet-flow target module is similar to MTX-008 planned for T18. Based on operating experience gained from T15–T18, it will be operated at a power level that is conducive to reliable operation until its planned removal, currently assumed to be 1.3 MW. It is expected that T19 will be the first target to operate after the long outage.
- Strain measurements and PIE measurement will provide additional information about target response and cavitation damage erosion in the jet-flow targets with gas injection.
- Cavitation damage measurements on the thicker wall section (where T12/T13 leaked) will provide additional information about how the local wall affects cavitation damage rate.

## Target T19 Contingencies

- If T19 fails early in its lifetime as a result of an unknown issue, then a repaired ORTE-003 or one of the new original-type targets 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 may be installed.

## Target T20

- MTX-016 will be installed as T20. This jet-flow target module is similar to the jet-flow targets planned for T18 and T19. Based on operating experience gained from T15–T19, it 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's operational period will last through the end of calendar year 2018.
- Strain measurements and PIE measurement will provide additional information about target response and cavitation damage erosion in the jet-flow targets with gas injection.
- Cavitation damage measurements on the thicker wall section (where T12/T13 leaked) will provide additional information about how the local wall affects cavitation damage rate.

## Target T20 Contingencies

- If T20 fails early it its lifetime as a result of an unknown issue, then a repaired ORTE-003 or one of the new original-type targets 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 1.4 MW power level for T20.
- If the target fails late in life, then a blue target may be installed.

## Target T21 through T26

- Targets T21 through T26 are expected to operate in calendar years 2019 and 2020. These targets are expected to operate at 1.4 MW, and will be of designs 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. In particular, the modifications of mercury flow in the blue targets which will provide additional information on the efficacy of mercury flow velocity at prevention or slowing of cavitation damage erosion. This information supports not just future improvements for 1.4 MW targets, but also is critical for future higher power targets associated with the Proton Power Upgrade project.

### TARGET T21 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 operating pace of targets may be modified from the planned 3 target a year pace.
- Any unexpected failures will be dealt with using the stable of available targets.

## DISCUSSION

SNS has learned a great deal from six of the seven in-service end-of-life target events that have occurred beginning in 2012.

- Extended-duration operation (~4,500 hours) at 850 kW (T8), moderate-duration operation (~2,900 hours) at 1 MW (T14), and shorter-duration operation (~800 hours) at 1.2 MW (T15) and (~500 hours) at 1.3 MW (T9 and T12) have been demonstrated.
- Improved designs and fabrication have addressed known structural vulnerabilities susceptible to high cycle fatigue. Specifically, the mercury vessel transition body was redesigned and improved manufacturing techniques were developed to eliminate the trapezoidal plate on the underside of the portion of the target that was responsible for three of the four end-of-life events in 2012 and 2014. Also, 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.
- The addition of strain and other instrumentation on mercury vessels, beginning with T13, has provided valuable information to compare with engineering models and has substantially increased confidence in the understanding of the margins of safety for vulnerable areas in the mercury target vessel.
- The identification of failures relating to cavitation damage erosion *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 cavitation potential modeling generally predicts the location of cavitation damage erosion, and operation of T10 demonstrated that enhanced mercury flow adjacent to the inner surface in the region of beam impingement can significantly reduce such erosion. These observations inform efforts to mitigate cavitation damage erosion at locations away from the beam impingement area. Gas bubble injection, increased wall thickness, 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. The relatively limited prior operating experience with similar targets must inform how these parameters are chosen; the present dynamic, evolutionary nature of target design and manufacturing necessarily limits available information. Until the operation of T14 and T15 at fixed power (1 MW and 1.2 MW), the only other target to operate at fixed power for most its life was T8 at a beam power of 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 understand and predict target operation based on prior experience.

Concrete steps taken to avoid unexpected target-related outages now include initial strain measurements, initial conditioning of the target module for about 3E+06 cycles at 850 kW, careful 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 associated with an in-service failure.

## Maintaining Sufficient Target Inventory While Controlling Costs

Target modules are expensive; the unit cost exceeds $1M. It is therefore important to maximize the benefit derived from each target module for both neutron production and contribution to the target operation knowledge base. The approach to maximizing neutron production has been discussed. Fourteen of the 15 target modules operated to date have been of the standard flow design, for which vulnerabilities are reasonably well understood but not necessarily fully controlled. Only one was of the jet-flow design, which was designed and fabricated based on post-irradiation inspection of earlier targets, and was intended to mitigate cavitation damage erosion in the region of direct beam impingement. This target reached end-of-life prematurely owing to fatigue at a partial penetration weld. This weld vulnerability has now been eliminated for future targets.

The timing of the two 2014 end-of-life conditions had a significant impact on the fabrication of new targets. It was necessary to stop production of certain models until the root cause of the T10 failure could be determined and a solution developed. New original-style targets were advanced to ensure a ready supply of known target modules while the jet-flow models were moved to a later delivery. These decisions have led to the following condition:

- One original target is available as a spare, but it requires rework to provide mitigation against early failure at the trapezoidal plate location seen in other original-style targets. This is the only current original-type spare target.
- One additional jet-flow target is on-site as a spare.
- The current supply chain includes three jet-flow targets, all of which will be equipped with gas injection capability.
- Two original type targets are in fabrication, with the first delivery projected to be May 2018.

Thus, the available inventory through May 2018 will consist of the relatively unproven jet-flow targets and one original target with a known vulnerability.

Planned target procurements are as follows:

- An order has been placed now for the long-lead water-cooled shroud for a single blue target. After the completion of final design and analysis, the remaining portions will be ordered for delivery of the completed unit in July/August 2018. At the same time, an order for a second complete blue target will be made. A third blue target will be ordered not after July 2017.
- The chinstrap target design should be ready to support needed future fabrications in FY 2018.

This strategy will, barring unplanned end-of-life conditions, result in a minimum inventory of one and a maximum inventory of two spare units from February 2017 to June 2018. 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 planned for in previous years. After June 2018, the number of spares is projected to rise to 3 or more targets.

## Developing the Knowledge Base for Target Design and Operations

Structural aspects of target engineering and fabrication are much better understood, with greater confidence in the modeling approach and operational experience for 15 targets, although 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, particularly in areas away from direct beam impingement.

Experimental studies with beam at LANSCE, mechanical impact testing performed at J-PARC, and limited operating experience at J-PARC indicate that injection of gas bubbles and/or development of a "gas wall" represent the most promising path to limiting cavitation damage erosion as well as high cycle fatigue. The SNS TTF supports the development of gas injection techniques and permits the initial assessment of possible fluid dynamic performance related to gas injection. Advanced manufacturing techniques permit the development of novel gas injection systems that can be included in future target designs.

Most of the existing knowledge base for cavitation damage erosion is derived from original-style targets. It is not known how the jet-flow target will experience cavitation damage erosion away from the region of beam impingement, but this design clearly is dramatically resistant to damage in the region where the beam strikes.

Future targets will combine mercury flow changes, varying wall thicknesses, baffle changes, and other improvements that will be necessarily compounded as new information is obtained from measurements and analysis: We will not learn the effects of each individual change. 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 a 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 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.

### Ensuring Consistency with the Planned Operating Schedule

The planned exposure times for the targets listed above are based on the latest available operational planning. Of course, the operational plan is influenced by more than just target related issues. Constraints on understanding target performance through planned runs at steady beam powers are one consideration in finalizing the planned operating schedules for future years. This management plan document will be revised as needed to reflect changes in operating schedules.

## 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 through the end of FY 2018. Also noted is where information gained is expected to be 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 2018 is much more speculative owing to the accumulation of likely new discoveries. The intent moving past FY 2018 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 | Stable Power Level[1] |
|---|---|---|---|---|---|---|
| T16 | February 2017 | May 2017 | 2400 | Jet-Flow | MTX-011 | 1.0 MW |
| T17 | July 2017 | September 2017 | 1800 | Jet-Flow | MTX-012 | 1.2 MW |
| T18 | October 2017 | December 2017 | 1500 | Jet-Flow with Gas Injection and reinforcement of nose | MTX-008 | 1.3 MW |
| T19 | April 2018 | July 2018 | 2200 | Jet-Flow with Gas Injection and reinforcement of nose | MTX-014 | 1.3 MW |
| T20 | August 2018 | November 2018 | 1900 | Jet-Flow with Gas Injection and reinforcement of nose | MTX-016 | 1.4 MW |
| T21 | January 2019 | April 2019 | 2000 | Gas injection, flow mitigation | Blue | 1.4 MW |
| T22 | April 2019 | July 2019 | 2000 | Gas injection, flow mitigation | Blue | 1.4 MW |
| T23 | August 2019 | November 2019 | 2000 | Gas injection, flow mitigation | Blue | 1.4 MW |
| T24 | January 2020 | April 2020 | 2000 | To be determined | Chinstrap | 1.4 MW |
| T25 | April 2020 | July 2020 | 2000 | To be determined | Chinstrap | 1.4 MW |
| T26 | August 2020 | November 2020 | 2000 | 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. FY17 – 18 milestones for target management plan.**

| Milestone | Projected Date |
|---|---|
| First strain measurements on jet-flow target | February, 2017 |
| Final design review for blue target | March, 2017 |
| PIE assessment of T15 | April, 2017 |
| Receive jet-flow target with CDE reinforcement | June, 2017 |
| PIE assessment of T16 | September, 2017 |
| First strain measurements with gas injection | October, 2017 |
| Final design review for chinstrap target | October, 2017 |
| PIE Assessment of T17 | November, 2017 |
| Complete repair of ORTE-003 | April, 2018 |
| Receive original target with CDE reinforcement | May, 2018 |
| $2^{nd}$ gas injection target removed for PIE | July, 2018 |
| Receive first blue target | September, 2018 |

**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 weld | 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 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 | 1200 | Original | Yes | Yes | Yes | | | |
| T16 | MTX-011 | 1/2017 | | | | | Jet-flow | Yes | Yes | Yes | Yes | | Gas injection disabled. |
| | | | | | | | Reserve Targets | | | | | | |
| | ORTE-003 | | | | | | Original | | | | | | Repair planned to reinforce transition cover plate and add sensors. |
| | MTX-012 | | | | | | Jet-Flow | Yes | Yes | Yes | Yes | | |
| | | | | | | | Targets in Fabrication | | | | | | |
| | MTX-008 | | | | | | Jet-Flow | Yes | Yes | Yes | Yes | Yes | |
| | MTX-014 | | | | | | Jet-Flow | Yes | Yes | Yes | Yes | Yes | |
| | MTX-015 | | | | | | Original | Yes | Yes | Yes | | Yes | |
| | HML-001 | | | | | | Original | Yes | Yes | Yes | | Yes | |
| | MTX-016 | | | | | | Jet-Flow | Yes | Yes | Yes | Yes | Yes | |