Department of Energy
Office of Science
Washington, DC 20585

APR 20 2015

MEMORANDUM FOR HARRIET KUNG
ASSOCIATE DIRECTOR
OF THE OFFICE OF SCIENCE
FOR BASIC ENERGY SCIENCES

FROM: STEPHEN W. MEADOR
DIRECTOR
OFFICE OF PROJECT ASSESSMENT

SUBJECT: Final Report on the DOE/SC Review of the SNS Target Design and Operations, February 2015

Attached for your consideration and use is the final report on the Department of Energy/Office of Science review of the Spallation Neutron Source (SNS) Target Design and Operations. The SNS Target review was conducted on February 24-25, 2015, at the Oak Ridge National Laboratory in Oak Ridge, Tennessee.

If you have any questions or would like to discuss the report further, please contact me.

Attachment

cc:
E. Merrill, SC-28
J. Murphy, SC-22
J. Rhyne, SC-22
D. Arakawa, DOE/ORSO
D. Paul, DOE/ORSO
J. Moore, DOE/ORSO

Office of Project Assessment
Review Report on the

Spallation Neutron Source Target Design and Operations

at Oak Ridge National Laboratory

February 2015

EXECUTIVE SUMMARY

A Department of Energy Office of Science (DOE/SC) review of the Spallation Neutron Source (SNS) Target Design and Operation was conducted at Oak Ridge National Laboratory (ORNL) on February 24-25, 2015. The review was conducted by the Office of Project Assessment and chaired by Stephen W. Meador at the request of Dr. Harriet Kung, Associate Director of Science for the Office of Basic Energy Sciences (BES). The purpose of this review was to determine whether changes in the design, manufacturing, and/or operational parameters for the SNS mercury target assembly are warranted in view of the recent premature failures of two targets.

The Committee noted that the SNS project team did an excellent job preparing materials for the review and were very open and candid during the on-site discussions. The SNS project team has and is continuing to allocate significant effort to determine the cause(s) of the premature target failure and has already made significant progress in understanding the root cause. In addition, the SNS project team's efforts thus far give confidence that they possess the capabilities and dedication required to meet these formidable challenges.

It was reported that since the beginning of operation in 2006, five of eleven spallation targets have failed during operation. In particular, four of the five targets that have failed operated less than 617 MW·hrs. Targets 6, 7, 10, and 11 failed at 617, 98, 601, and 167 MW·hrs, respectively. Post irradiation examinations of the failed targets revealed that all of them failed at welds in the transition region located behind the window and front body. These premature failures have led to the situation that only a small number of spare targets are currently available. In order not to jeopardize the neutron production by yet another target failure, it has been decided to initially run Target 12 with an average power of 850 kW instead of the possible 1.4 MW target design power level, until a second spare target is received on or about April 15, 2015.

In response to the Charge Memorandum, the Committee evaluated numerous aspects including target dynamic response, target welds, gas injection, post irradiation examination, instrumentation, jet flow implementation and results, the current resource-loaded schedule, project priorities for continuing evaluation of target design and modification, and operational plans.

Key Recommendations

A complete set of recommendations is provided within the body of the report. Below is a summary of key recommendations provided by the Committee.

- Consider removing the center baffle or re-designing to allow more flexing of the front body during the pressure pulse.

- Consider re-design of inner window to allow more flexibility to damp the pressure pulse.

- Investigate running at higher Hg pump speeds to evaluate the cost/benefit case for target survival versus pump/seal survival, considering lifetime of pump seals, increased erosion, and higher pressures.

- Consider re-designing the transition-body to front-body weld area (EBW3) (including more realistic modeling) beyond just the modification of targets in queue (FY 2016 targets). The re-design should effectively move the weld-line away from discontinuities, ensure complete penetration, and allow access for thorough non-destructive examination.

- In the near term, modify the weld designs for the targets that are currently being fabricated to minimize partial penetration welds.

- Perform R&D to develop effective bubble populations in the required regions of the target to mitigate high-cycle pulse stresses, while avoiding negative gas layer conditions.

- Implement, in the near term, a helium bubble injection system with gas injection ratio $>10^{-4}$ and mean bubble radius $<100\ \mu m$, but not at the expense of weld area re-design and reduction of thermal stress efforts.

- Incorporate helium bubblers in the FY 2016 target design.

- Proceed with plan to install fiber optic strain gauges in the near term, and develop an Laser Doppler Velocimetry system, like at J-PARC, in the longer term.

- Pursue jet flow as planned, but not at the expense of bubble injection or weld/baffle re-design efforts.

- Assign, as high priority, the investigation on the Hg-pump, as increased flow rates will decrease stresses in the transition region.

- Present and defend a resource loaded and leveled schedule to support the listed completion dates, taking into consideration relative priorities, as soon as possible. The split into only two priority categories should be revised and be more detailed; introduce a priority scheme 1 - 10.

CONTENTS

1. INTRODUCTION

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) began operation in 2006 and has become a world-leading center for neutron scattering. A suite of 19 state-of-the-art instruments is providing unique research opportunities for users in disciplines ranging from condensed matter physics, biology, materials sciences, to polymer chemistry. The facility is powered by a 1 GeV proton linear accelerator operating at 60 Hz with a design power of 1.4 MW. The facility has generally been operated at a lower power level of around 1 MW with excellent accelerator reliability and currently serves approximately 900 unique users per year.

Against this backdrop of high research achievements there have been issues with premature failures of the flowing liquid Hg target. Two such failures occurred in 2012 and an additional two back-to-back failures occurred in 2014. One of the 2014 failures was of a newly designed “jet flow” target configuration and the other was of the original conventional flow design. Post Irradiation Examination (PIE) of the failed targets was able to pinpoint welds as the failure points; however, there was no obvious consistency in the failure modes. Several identical targets have exhibited no evidence of failure and were removed because they exceeded their atom displacement limit or because of schedule.

In order to gain insight from external experts who are familiar with high power targets and other disciplines critical to target design, this review of the SNS target history, remediation plans, and possible future design changes was recommended. The review was held at ORNL on February 24-25, 2015.

2. TECHNICAL SYSTEMS EVALUATIONS

The Committee noted that the SNS project team did an excellent job preparing materials for the review and were very open and candid during the on-site discussions. The Project Team has and is continuing to allocate significant effort exploring the premature target failure and has already gone a long way to understanding the root cause. In addition, the Project Team's efforts thus far inspire confidence that they possess the capabilities and dedication required to meet these formidable challenges.

It was reported that since the beginning of operation in 2006, five of eleven spallation targets have failed during operation. In particular, four of the five targets that have failed operated less than 617 MW·hrs. Targets 6, 7, 10 and 11 failed at 617, 98, 601 and 167 MW·hrs, respectively. These premature failures have led to the situation that only a small number of spare targets are currently available. In order not to jeopardize the neutron production by yet another target failure it has been decided to run Target 12 with an average power of 850 kW instead of the possible 1.4 MW until a second spare target is received.

Post Irradiation Examinations (PIE) of the failed targets revealed that all of them failed at welds located in the transition region located behind the window and front body. The cross section of the target is conically increased in this region and then connects via the core vessel seal flange to the manifold block. The welding techniques used to join the different parts are either electron beam welding (EBW) or tungsten inert gas welding (TIG). The PIE of the Targets 6 and 7 also showed an offset of the cover plate and transition body; it was also found that the weld(s) of the transition cover plate had failed in both targets. A review was held after the target failures in 2012 checking the stresses and Computational Fluid Dynamics (CFD) calculations. As a consequence, quality assurance (QA) efforts were increased by a closer cooperation with the target vendors, increasing the control of the target fabrication itself and the welds in particular. Moreover, the design of the target was changed to allow for easier PIE inspections. Instead of welding the outer water-cooled shroud to the target, it was decided to join the parts by bolting the water cooled shroud to the Hg vessel. Hence it is possible to remove the water cooled shroud after operation remotely and inspect the Hg-vessel visually.

In 2014, two targets, 10 and 11, failed in quick succession. The bolt on water cooled shroud allowed for inspection of the jet flow Hg vessel and the failure location was subsequently found the EBW 3 joining the front and transition body. The failure location for Target 11 was identified using a video bore scope and was again found at the transition cover plate weld similar to earlier failures. These failures triggered a series of internal panels to identify methods to mitigate the target failures. In addition the power level was reduced from 1.4 to 0.85 MW.

2.1 Target Dynamic Response

2.1.1 Findings

From visual inspection, the center baffle appears to be cracked in all targets that have survived some sustained operation at high power (approximately 1 MW).

Previous analysis indicated that the presence of the center baffle increases stress (due to both pressure pulse and thermal stress response) in other locations in the target assembly. The center baffle was originally added to the target design to avoid "dilatational" resonance at close to 60 Hz, the frequency of beam pulsing.

2.1.2 Comments

It appears that higher stress was considered as an acceptable trade-off for the confidence to avoid resonance. However, the dilatational modal analysis is heavily dependent upon acoustic properties of the mercury, which are likely unstable and hard to calculate due to the cavitation phenomenon. In addition, modal analysis done with a center baffle indicates that cantilever modes at 57 Hz and 121 Hz are now evident. Since the cantilever mode has little acoustic participation (primarily dependent upon mass), confidence in the results of the cantilever modes are much higher than dilatational modes. It is therefore not clear if the original reason for adding a central baffle has much merit and may actually be detrimental.

Running at the originally planned, higher Hg flows reduces thermal stresses and seems a logical candidate to help resolve the premature failures experienced recently.

2.1.3 Recommendations

1. Consider removing the center baffle or re-designing to allow more flexing of the front body during the pressure pulse.

2. The same argument (aside from modal analysis) holds for the inner window. Consider re-design of inner window to allow more flexibility to damp the pressure pulse.

3. Investigate running at higher Hg pump speeds to evaluate the cost/benefit case for target survival versus pump/seal survival, considering lifetime of pump seals, increased erosion, and higher pressures.

2.2 Welds

2.2.1 Findings

Details describing the evaluation and combination of stresses, induced by the pressure pulse and thermal loads was presented. These evaluations followed the methodology given in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME BPVC). The simulations indicate high stresses, both due to the Hg pressure and thermally induced stresses due to the pulsed beam and beam outages in the region of the welds of the front body and the transition region. However, these unrealistically high stresses were partially assigned to meshing problems; nevertheless the stresses at the welds in the transition region are high.

Five of eleven targets were replaced due to the leak of mercury before reaching the administratively imposed design lifetime of 10 Displacements per Atom (DPA). The original designs were made based on the detailed numerical simulations according to the design criteria put in place at the beginning of the SNS project. Since that time, the basis of the design criteria—the ASME BPVC—was significantly changed, with more stringent requirements for fatigue put in place.

It was noted that all leaks, except for one or two, occurred around the transition plate. The Target 10 leak occurred on or close to the weld joining the front body to the transition. This welded region contained features that precluded complete penetration and was not modeled realistically (predicting extremely high stress (500 MPa) due to thermal (static) stress).

The design is being modified in the Target 10 leak location to avoid incomplete penetration welds and reduce the discontinuity in wall thickness at the weld-line. However, another incomplete penetration area, in a lower stress region, was discovered (race-track weld cover location) without a design solution identified.

SNS also recognized that prior stress analyses did not properly de-rate materials properties in weld regions through the application of knock-down factors, consistent with revised ASME BPVC. Also, earlier analyses did not properly model weld penetration depths. Partial penetration welds, and difficult weld inspection conditions cause significant fatigue strength degradation.

Prior to welding, the surfaces of the target exposed to Hg are treated by Kolsterization in order to increase the surface hardness. This process increases the carbon content to about 5w% within several microns of the surface. When welded, this added carbon is likely distributed throughout the heat-affected zone. Further, retention of the beneficial attributes derived from Kolsterization prevent post heat treatment of welds above 300°C.

2.2.2 Comments

The forward body is relatively stiff, especially with the center baffle. The transition section is likewise relatively stiff. The connection between the two is a 3 mm thick weld with locations where incomplete penetration is likely. It makes sense to re-design this area to have a smoother transition between wall thicknesses, away from the weld line. This will reduce concentration of stress (hinge-point) at the weld.

The SNS design criteria should be updated to the most recent version of ASME BPVC accordingly. Furthermore, while detail and sophistication of numerical simulations have improved over the years, more effort needs to be put into accurately modeling areas of the target, in particular weld joints. Weld joints should be redesigned to avoid partial penetration, and to allow more thorough inspection, i.e., design of welded parts with simple geometry resulting in continuous wall thickness.

There has been substantial recent progress in implementing appropriate QA procedures in specifying weld procedures and inspecting welds at the manufacturers. Although some weld preparation modifications addressing these shortcomings can be made to targets in queue, they can only be fully addressed by adequate weld design in the Mark III target design, which should place a high priority on designing and fabricating the Mark III target design in order to achieve reliable high-power operation.

It has been shown that an increase of the Hg-pump speed will reduce thermal stresses, in particular in the region were the welds failed. However, the increased pump speed also results in higher loads in the target vessel due to a higher Hg pressure. Currently, the risk of seal and bearing failure/problems in the Hg-pump, known since 2006, outweighed the benefit of increase of the heat transfer coefficient with increased Hg flow rates. However, increasing Hg flow rate will improve the thermal stress margin. It is also important to consider the negative effects of a higher flowrate (Hg pump seals, flowing erosion (jet-flow), increase in pressure, etc.).

The bearing and seal problems of the pump should be investigated as soon as possible, as it will allow running at higher flow rates thus decreasing the thermal loads in the Hg-vessel. J-PARC uses an electromagnetic pump (EMP), which has not shown the same problems as the pump used at SNS. It might be advantageous for both projects to use the same (or at least similar) pumps. This would allow both facilities to collaborate on issues like bearing lifetimes and seal problems. In addition an EMP for Hg has been successfully designed, fabricated, and tested in the EURISOL project by IPUL (Latvia).

The 300°C limit imposed by Kolsterization for post heat treatment of welds may leave high residual stresses in the heat affected zones and the added carbon may also influence its microstructure.

2.2.3 Recommendation

4. Improve the design to reduce thermal stresses on welds.

5. Consider re-design the transition-body to front-body weld area (EBW3) (including more realistic modeling) beyond just the modification of targets in queue (FY 2016 targets). The re-design should effectively move the weld-line away from discontinuities, ensure complete penetration, and allow access for thorough non-destructive examination.

6. Clearly understand the implications of not post heat treating (stress relieving) during the fabrication process.

7. Consider limiting the portions of the target treated by Kolsterization in order to stress relieve as many welds as possible.

8. Evaluate the effectiveness of stress relieving at temperatures less than 300°C for long durations.

9. Continue program of weld sample evaluation to develop effective weld parameters and explore the effect of welding on treated (Kolsterization) surfaces.

10. In the near term, modify the weld designs for the targets that are currently being fabricated to minimize partial penetration welds.

2.3 Gas Injection

2.3.1 Findings

SNS implemented the jet flow design to mitigate the damage of the vessel in the window region in order to reduce cavitation damage of the inner window. In order to introduce the jet-flow across the window region an additional wall had to be introduced to the target vessel. This stiffens the whole region, especially also in the transition region. As a consequence, the thermal and pulse stresses in the weld region between front body and transition region increase. However, visual inspections of the inner window surface (facing the Hg) show a significant reduction of erosion and cavitation damage in the window region, confirming the efficacy of the jet flow design to address this issue.

On the other hand, J-PARC successfully introduced the injection of Helium bubbles into the Hg flow. It has been demonstrated by J-PARC that the bubbles significantly decrease the dynamic response of the target vessel to the proton pulse, i.e., they have a dampening effect on the pressure pulse. SNS has been working on a helium gas bubble injection system together with J-PARC for several years; however, a similar system has not yet been installed in the SNS target.

Evidence that bubble injection works to reduce the magnitude of the pressure pulse was presented, and has been experimentally verified at the J-PARC target. The work by J-PARC staff in implementing a helium bubble injection system in their mercury target, and the measurement of reduced pressure wave clearly indicate the efficacy of this approach. SNS presented a plan to implement, in the short-term, a once-through helium injection system, with the goal of implementing a closed loop system over the longer term.

2.3.2 Comments

Reduction of the pressure pulses that fatigue the target and induce cavitation damage is paramount to prolonging target lifetime and reducing the chance of premature target failure at 1.4 MW and beyond. Implementation of a helium injection system should be given high priority. However, it should be noted that it is not clear that bubble injection alleviates the thermal stress case at all. Since the alternating stress due to the pressure pulse is relatively low at the areas where leaks were identified and the thermal stresses are relatively high, bubble injection alone may not help solve the current leak predicament. So, although bubble injection should be a high priority, methods of reducing thermal stress and strengthening the weld design should be at least the same priority as bubble injection for the short term.

Surface flaws deeper than about 10 microns affect the fatigue strength. This trend will be enhanced if ductility is degraded due to neutron and proton irradiation and/or Liquid Metal Embrittlement (LME). Sufficient margin should be taken into account in high stress regions. Unfortunately, it is difficult to quantitatively evaluate the effects in the design due to a lack of measured data. The He micro-bubble injection definitely has the effect to reduce the cyclic pressure pulse induced by proton beam bombardment. It is essential, however, to consider the effective bubble condition; bubble size, population, and distribution throughout the target. One must also consider the negative effect, i.e. bubble coalescence, etc. That is, the degradation of heat transfer due to the bubbles coalescence creating an insulating gas layer and the increase in flow resistance.

Efforts should be made to reduce the pressure wave and imposed stresses as low as possible because of the uncertainty in the unique environment presented by mercury targets. It is difficult to quantitatively evaluate the effects in the design due to lack of data in the literature.

Investigations by Futukawa, et.al, indicate that pressure wave mitigation requires gas bubbles in the range of 50 μm radius and void fraction of at least 10^{-4}. The swirl bubbler successfully implemented in the JSNS target can deliver the proper bubble conditions, and should be evaluated by SNS to see if it can be retrofitted into the targets currently being fabricated, as an alternative to the SNS-designed bubblers.

2.3.3 Recommendations

11. Perform R&D to develop effective bubble populations in the required regions of the target to mitigate high-cycle pulse stresses, while avoiding negative gas layer conditions.

12. Implement, in the near term, a helium bubble injection system with gas injection ratio $>10^{-4}$ and mean bubble radius <100 μm, but not at the expense of weld area re-design and reduction of thermal stress efforts.

13. Incorporate helium bubblers in the FY 2016 target design.

2.4 Post Irradiation Examination (PIE)

2.4.1 Findings

The status and outlook of the Post Irradiation Examination (PIE) at SNS was presented. Previous PIE sample taking has focused on the target window region. A plan for examining Targets 10 and 11 was presented. Efforts are underway to sample the leak locations, analyze the fracture surfaces, and gain insight into possible failure mechanisms. Tools to allow sample taking from the front body and transition region were presented.

2.4.2 Comments

Getting direct evidence of failure and data on ductility beyond 10 DPA is very important to understand uncertainties in target longevity and to enable informed design of the next generation of high power targets.

The Committee also suggested the project examine the center baffle fracture in more detail to ascertain its possible connection to the target failures.

2.4.3 Recommendation

14. Continue PIE efforts with high priority on all three targets.

2.5 Instrumentation

2.5.1 Findings

Sensors will be installed in Target 13 to measure strains due to pressure pulses and therefore help understand the dynamic responses in mercury targets.

2.5.2 Comments

Diagnostic systems are very valuable to understand the present status of the target and to consider the next strategy for target lifetime extension.

The lifetime of the sensors might not be enough to obtain meaningful data. Furthermore, without a robust calibration procedure, strain signals may be hard to discriminate from noise sources.

The stress components' dependence on vibrational models should be carefully considered to decide the best measuring locations and directions.

2.5.3 Recommendation

15. Proceed with plan to install strain sensors in the near term, and develop a Laser Doppler Velocimetry (LDV) system, like at J-PARC, in the longer term.

2.6 Jet Flow

2.6.1 Findings

Following the identification of the causes of target failures, a re-evaluation of the stress calculations for the original and Jet Flow Design (JFD) targets identified some shortcomings in the analyses. The analysis of the JFD target identified unacceptably high thermal stresses in the weld zone where Target 10 failed, a portion of which was attributed to limitations in the thermo-mechanical analysis (interfacing coarse and fine meshes).

2.6.2 Comments

The JFD appears to have successfully addressed the problem of cavitation damage erosion (CDE) of the front flow baffle, but CDE is not the source of the in-service target failures. Interestingly, the JFD target has likely exacerbated thermal and dynamic stresses, relative to the original target design, that are the likely source of the target failures. In this respect, the original target design may be more robust than the JFD.

Jet Flow does not address pressure pulse issues (as bubble injection does) and therefore is not likely to do much to resolve the leaks experienced recently. Running at higher Hg flows reduces thermal stresses and seems a logical candidate to help resolve the leaks experienced recently.

The Committee agreed with Ludtka, et. al., that appropriate knock-down factors should be applied to the mechanical properties in weld zones, and for mechanical property changes due to radiation damage and liquid metal embrittlement.

Ludtka, et. al., comprehensively assessed the stress analyses of the original and JFD targets, and the Committee agreed with their recommendations. In particular, the Committee agreed with their observation that "the extreme conditions experienced by SNS mercury targets during operation are very difficult to model and simulate accurately." While stress analyses are clearly valuable in developing a robust design, the unique environment and conditions under which the SNS target operates, and the specific properties of the targets (e.g., partial weld penetrations and non-bonded contacting surfaces) introduce significant uncertainty into the calculations.

2.6.3 Recommendation

16. Pursue jet flow as planned, but not at the expense of bubble injection or weld/baffle re-design efforts.

2.7 Resource Loaded Schedule, Priorities, and Operations

2.7.1 Findings

The Committee requested an additional presentation including a detailed schedule with the available resources, prioritization and assigned manpower to overcome the current target operations issues. It was reported that in total approximately 9,000 hours of nine full-time personnel (and one student), i.e., equal to five full-time equivalent man-years, will be spent to study seven major tasks to overcome the premature target failures. Besides the SNS staff already assigned to these tasks, additional ORNL and SNS personnel have been listed as persons involved in the above mentioned tasks. A total of 4,220 hours of additional workforce is planned to be used for high priority tasks in the current year (2015).

These tasks have been separated in two priority categories: high and medium—assigned working hours and the priority ranking are shown below:

1. Target Design (5,200 hours, high)
2. Instrumentation of the Target (1,600 hours, high)
3. PIE of Target 9 (600 hours, high)
4. PIE of Target 10 and 11 (2,700 hours, high)
5. He-Injection into Hg to Reduce Pressure Pulse Loads on the Target Vessel (3,800 hours, high)
6. Investigations of the Welding Techniques and Procedures (400 hours, high)
7. Elaboration of New/Adapted Fabrication Specification of the Targets (450 hours, high)

8. Investigations on the Hg-pump, i.e., Pump Speed, Bearings and Seals (300 hours, medium)
9. Revision of the target design criteria (1,500 hours, medium)
10. Analysis of the different fatigue scenarios in the target (1,700 hours, medium)

The annual operations schedule has only two maintenance periods that are sufficiently long enough to allow target replacement. This means some targets have been removed before they reached their 10 DPA administrative limit.

2.7.2 Comments

The 10 activities were prioritized into just two levels: high and medium. Seven of the ten activities were ranked as high. It is not clear that this prioritization scheme will allow easy resolution of resource conflicts or availability. Although the Committee was told that consideration of resource (people) availability resulted in the listed plan, without a resource-loaded/leveled schedule and a description of the "team-players" it is very difficult for the Committee to judge whether the plan will be successful with the currently identified staff while still maintaining support of other core mission elements.

The necessary labor resources should be re-checked in detail to identify possible shortages. In particular, the workload of key personnel should be reviewed and, if necessary, additional personnel should be hired or made available to relieve key personnel from too high workloads. Attention should also be focused on the preservation and expansion of expertise—i.e., hand-over processes and proper documentation of key-findings by possible part-time/external personnel.

In general, the Committee agreed with the priorities. Consideration should be given to raising the priority of the pump speed issue from medium to high.

Given the premature target failure experience, it may be worthwhile to run long-lived targets to their full 10 DPA life or even slightly longer, e.g., another three months. The introduction of an approximate 12-day outage within each five-month run cycle could offer greater flexibility to continue using well-running targets to their full lifetimes. If a target were to fail in service, the time dedicated to the mid-cycle outage could be re-scheduled and dedicated to replace the failed target. Of course, the two long outages in the current schedule would each need to be reduced accordingly in order to preserve the total number of annual operating hours. Such reductions in the long outage periods may not be consistent with certain maintenance activities that require four or five weeks to complete.

2.7.3 Recommendations

17. Consider assigning priorities, with greater resolution to distinguish between all those tasks currently rated high.

18. Consider introducing mid-term outages that offer the flexibility to change out targets more frequently.

19. Present and defend a resource loaded and leveled schedule to support the listed completion dates, taking into consideration relative priorities, as soon as possible. The split into only two priority categories should be revised and be more detailed; e.g., introduce a priority scheme 1-10.

20. Assign a high priority to the investigation of the Hg-pump, as increased flow rates will decrease stresses in the transition region.

Appendix A Charge Memo

DOE F 1325.8
(08-93)

United States Government **Department of Energy**

memorandum

DATE: January 4, 2015

REPLY TO
ATTN OF: Office of Basic Energy Sciences, SC-22

SUBJECT: DEPARTMENT OF ENERGY REVIEW OF THE SPALLATION NEUTRON SOURCE (SNS) TARGET DESIGN AND OPERATION

TO: Stephen Meador, Director, Office of Project Assessment, SC-28

I request that you organize and lead an Office of Science Independent review of the Spallation Neutron Source (SNS) Target Design and Operation at Oak Ridge National Laboratory on February 24-25, 2015. The purpose of this review is to determine whether changes in the design, manufacturing, and/or operational parameters for the SNS mercury target assembly are warranted in view of the recent premature failures of two targets.

In carrying out its charge, the review committee is requested to consider and respond to the following items:

- Assess the original designs for both the conventional and jet flow design targets and the adequacy of the stress analysis calculations performed on these designs.
- Consider the value of introducing He bubble injection into the Hg flow as done at J-Parc to mitigate cyclic stresses.
- Consider if adequately conservative assumptions were made in the design of internal welds and other components of the target assembly.
- Examine the quality assurance procedures and manufacturing oversight involved in constructing the targets and especially of the welding procedures.
- Evaluate possible power level dependent stress sources on the target in light of the operating history of the 11 targets installed at SNS since 2009.
- Make recommendations for design or manufacturing changes in future targets or in the proton beam power ramp to mitigate future failures.
- Evaluate possible changes in Hg flow rate to provide increased overhead heating margin.
- Provide guidance on the relative merits of the conventional design targets vs the jet-flow design or other alternate configurations.
- Suggest additional diagnostic evaluations that should be made on the targets recently removed from operation.

- In the future, we are looking forward to the opportunities that would be enabled by a second target station at SNS, which will likely include an increase in proton beam power for the target. Any suggestions or recommendations for changes in the target should be considered in light of this possible future upgrade.

James J. Rhyne, Program Manager for neutron scattering facilities, will serve as the Office of Basic Energy Sciences point of contact for this review. I would appreciate receiving your committee's report within 60 days of the review's conclusion.

Harriet Kung
Associate Director of Science
for Basic Energy Sciences

cc: T. Mason, ORNL
P. Langan, ORNL
K. Jones, ORNL
J.B. Murphy, SC-22.3
J. Rhyne, SC-22.3
L. Cerrone, SC-22.3
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Appendix B Review Committee

Department of Energy/Office of Science Review of the
Spallation Neutron Source (SNS) Target
February 24-25, 2015

REVIEW COMMITTEE PARTICIPANTS

Department of Energy

Stephen W. Meador, DOE/SC, Chair
Ethan Merrill, DOE/SC

Committee Members

Toshi Futakawa, JAEA
Patrick Hurh, FNAL
Eric Pitcher, ESS
Michael Wohlmuther, PSI

Observers

Jim Murphy, DOE/SC
Jim Rhyne, DOE/SC
David Arakawa, DOE/ORO
Doug Paul, DOE/ORO
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Appendix C Review Agenda

Department of Energy/Office of Science Review of the
Spallation Neutron Source (SNS) Target Project
February 24-25, 2015

AGENDA

Tuesday, February 24, 2015—Building 8600, Conference Room C-156

8:00 am	DOE Full-Committee Executive Session	S. Meador
9:00 am	Target Overview	Galambos
9:30 am	Target Design Basis: Original and Jet Flow	Riemer
10:30 am	Break	
10:45 am	Fabrication and Quality Assurance Experience	Abercrombie
11:15 am	Fabrication Plans	Winder
12:00 pm	Lunch	
1:00 pm	Plans for Target Examination	McClintock
1:30 pm	Power Level Dependence	Peters
2:00 pm	Proposed Target Instrumentation	Wendel
2:15 pm	Break	
2:45 pm	Gas Injection Options	Wendel
3:15 pm	Summary of Proposed Target Actions	Abercrombie
4:00 pm	DOE Full Committee Executive Session	Review Committee
5:00 pm	Adjourn	

Wednesday, February 25, 2015

8:00 am	Subcommittee Working Sessions	All
12:00 pm	Lunch	
1:00 pm	Closeout Dry Run	Review Committee
2:30 pm	Closeout Presentation	All
3:00 pm	Adjourn	

Appendix D Response to Charge Questions

1. Assess the original designs for both the conventional and jet flow design targets and the adequacy of the stress analysis calculations performed on these design.

The original designs were made based on the detailed numerical simulations according to the design criteria put in place at the beginning of the SNS project. Since that time, the basis of the design criteria—the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME BPVC)—was significantly changed, with more stringent requirements for fatigue put in place. The SNS design criteria should be updated accordingly. Furthermore, while detail and sophistication of numerical simulations have improved over the years, more effort needs to be put into accurately modeling areas of the target, in particular weld joints.

Imposed stress on the center baffle plate seems to be high enough to initiate failure regardless of whether the target is of the jet flow or conventional design. With pitting damage on the surface, fracture of the center baffle is likely. Surface flaws deeper than approximately 10 microns will affect fatigue strength. This effect will be accelerated if ductility is degraded due to neutron and proton irradiation and/or Liquid Metal Embrittlement (LME). So, sufficient margin should be taken into account in locations of high stress. However, unfortunately it is difficult to quantitatively evaluate these effects in the design due to limited experimental data.

The center baffle was added to mitigate a perceived vulnerability to modal excitation from the beam pulse. Otherwise, this baffle actually makes the thermal and pulse stress cases worse. A design without a center baffle would be better if this mode of excitation can be avoided. In order to increase the stiffness to avoid the resonance mode of vessel, alternative techniques might be considered; e.g., structural ribs between the mercury vessel and the shroud. Alternatively, reducing the mass of the front part of the target could help, perhaps by shortening the target or making it less wide.

2. Consider the value of introducing He bubble injection into the Hg flow as done at J-Parc to mitigate cyclic stress.

The He bubble injection may be effective to mitigate both the damages—cavitation erosion and fatigue cracking, because micro-bubbles suppress cavitation bubble inception and reduce pressure waves.

In the case of low beam power, the damage due to cavitation erosion may be dominant on the beam window area. On the other hand, with increasing the power, the damage due to fatigue cracks initiating at pits may become dominant because the stress imposed on the pitted area may become large enough to initiate cracks at the pits.

The He micro-bubble injection definitely has the effect to reduce the cyclic pressure pulse induced by proton beam bombardment. It is essential, therefore, to consider the effective bubble condition; bubble size, population, and distribution throughout the target. One also must consider any negative effects, i.e., bubble coalescence, etc. That is, the degradation of heat transfer due to the bubbles coalescence creating a gas layer which increases flowing resistance.

R&D to develop effective bubble populations in the required regions of the target, while avoiding negative gas layer conditions, is recommended.

3. Consider if adequately conservative assumptions were made in the design of internal welds and other components of the target assembly.

The design of the welds is no longer conservative with respect to the current version of the ASME BPVC design by analysis method. Partial penetration welds, and difficult weld inspection conditions, impose significant fatigue strength knock-down factors, as well as not being good practice. However, it is recognized that even after design changes and improved analysis, there are still many unknown factors to be considered. These factors must be known to assess the resulting margin on structural integrity within the context of fatigue degradation due to irradiation and the liquid mercury environment. With increasing power, these unique conditions will be become even more harsh. It is still difficult to quantitatively estimate these unknown factors in the design criteria. R&D on the fatigue degradation taking account of the environments should be performed to maintain steady operation and increase the power in the future. In the meantime, measures to reduce fatigue stresses, either pressure pulse or thermal fatigue, are highly recommended to gain margin on structural integrity.

4. Examine the quality assurance procedures and manufacturing oversight involved in constructing the targets and especially of the welding procedures.

The present procedures are much improved over previous practice. In the area of weld inspection, measures to allow more thorough examination of the weld conditions are recommended. The engineering team identified several vendor processes that were occurring without explicit direction, documentation, or approval by the design team. These processes are currently being evaluated and vetted so that future production documentation will capture the relevant criteria. A study of welding parameters and procedures is ongoing, resulting in several weld samples being produced. The samples are being metalurgically analyzed to assess the capability of the weld design and welding procedure to produce an acceptable joint.

5. Evaluate possible power level dependent stress sources on the target in light of the operating history of the 11 targets installed at SNS since 2009.

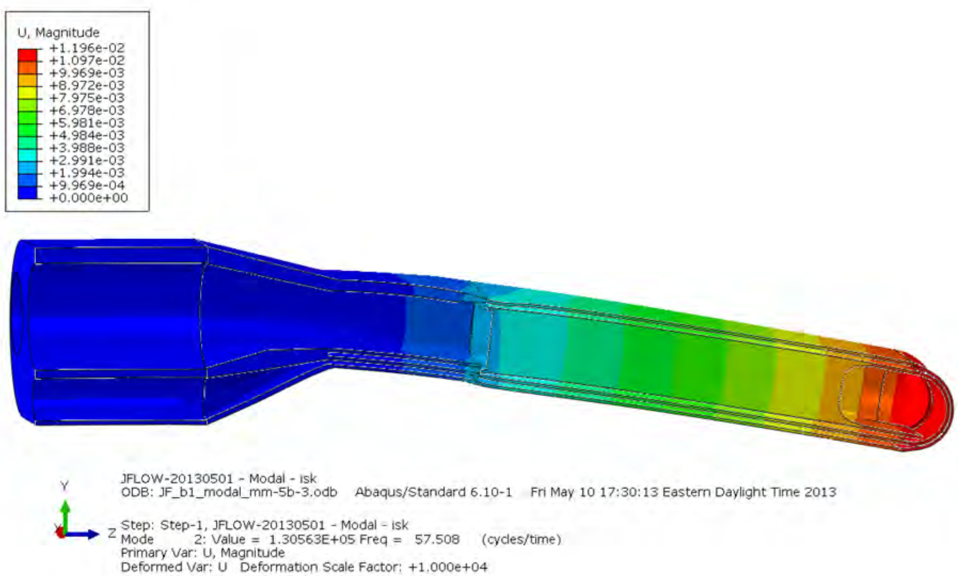
The proposed correlation of successful high power target life after extended initial operation at limited power is based on low statistics and lacks credible causation. The transition stress reduction associated with fracture of the inner beam window is based on overly simple modeling of crack behavior and should not be relied upon. Running at initial low power for several weeks is not justified as a means to assure long life at higher power.

Higher power clearly results in higher pressure pulse and thermal stress for a given design and mercury flow. Investigating design changes that reduce stresses due to the pressure pulse (e.g., helium bubble injection) and thermal gradients (e.g., thinning or removing the center baffle) should be pursued over attempts to “break-in” targets at low power before operating at high power.

6. Make recommendations for design or manufacturing changes in future targets or in the proton beam power ramp to mitigate future failures.

Weld joints should be redesigned to avoid partial penetration, and to allow more thorough inspection including the root side surface. Simpler weld geometry will help make checking the robustness of welds easier. Improve welds by matching thickness across the joint to avoid sudden discontinuities. Explore design options to remove the center baffle and otherwise keep structural members out of high beam heating regions. In-situ monitoring systems, a helium bubble injection system to suppress the pressure pulse, welding procedure studies, and increasing mercury flow all should help mitigate future failures.

Design should be reconsidered to shift the modal frequency in Mode 2 over 60 Hz. Modal analysis found this mode to be 57.5 Hz in a cantilever configuration. This mode would be induced by 60 Hz beam injection, especially if the beam center were shifted higher or lower on the target. If excited, large stresses will be generated by this mode at the joints between the transition plate and the front-body.



7. Evaluate possible changes in Hg flow rate to provide increase overhead heating margin.

Increasing Hg flow rate will improve thermal stress margin. However it is important to consider the negative effects of a higher flow rate (e.g., Hg pump seals, flowing erosion (jet-flow), increased pressure due to higher flow resistance, etc.) Also, the impact of flow rate on the bubbling technology and the effect of the accumulated gas due to bubbles coalescence and strong buoyancy should be taken into account.

8. Provide guidance on the relative merits of the conventional design target vs the jet-flow design or other alternate configurations.

The jet flow appears to reduce the pitting erosion because the strong shear pressure or strong gradient pressure distribution by jet flow distorts cavitation bubbles to mitigate the aggressiveness or reduce the negative pressure for cavitation bubbles inception and growth, but there may be flowing erosion damage due to turbulent flow. Consider the balance. The effect of jet flow might be localized. The jet speed perhaps could be reduced. It is more effective to mitigate the original factor to generate the cavitation phenomenon (i.e., negative pressure caused by pressure wave). The jet-flow vessel seems to have higher pulse and thermal stress compared to original design, perhaps due to its greater stiffness. These demerits appear solvable, while keeping the benefit of reduced erosion and delayed fracture of the inner window. Also, jet-flow offers a good option for small gas bubble injection at the point of jet exit. It should be noted that the jet flow design does not address pressure pulse issues (as bubble injection does) and therefore is not likely to do much to resolve the leaks experienced recently.

9. Suggest additional diagnostic evaluations that should be made on the targets recently removed from operation.

Efforts are underway to sample the Target 10 and 11 leak locations, analyze the fracture surfaces, and gain insight into possible failure mechanisms. Getting this kind of direct evidence is highly valuable. The Committee also suggested examining the center baffle fracture to evaluate the likely fracture mechanism. If possible, micro-structural evaluation of the weld material near the leak locations should be done to determine if microstructure, as a result of the welding and heat treatment processes, shows an increased susceptibility to failure.

10. In the future, we are looking forward to the opportunities that would be enabled by a second target station at SNS, which will likely include an increase in proton beam power for the target. Any suggestion or recommendations for changes in the target should be considered in light of this possible future upgrade.

The present concept for the Second Target Station (STS) at the SNS includes accelerator upgrades that provide increased power to the first target station (FTS) mercury target. With this upgrade, the accelerator will be capable of delivering 2 MW at 50 Hz to the first target station, corresponding to a 70% increase in the energy per pulse (from 23 to 40 kJ) over current conditions. Therefore more stress and fatigue margin of the mercury target will be needed compared to 1.4 MW operation to have a target that survives to the radiation damage limit. A sustained effort to continually improve the design, create more effective bubble populations to mitigate high-cycle pulse stresses, and reduce thermal stress (more mercury flow, improved weld design) is recommended. Reducing uncertainty in fatigue strength with consideration of the radiation and mercury environment can be achieved by Post Irradiation Examination (PIE) and R&D. Pursue better understanding of modal vulnerabilities and accuracy of modal simulations through experiments with mercury-filled targets. Continue and strengthen collaboration with JSNS, which has the same challenges for the target.

Because JSNS operates at 25 Hz, the energy per pulse that is a critical issue to keep the structural integrity is 2.4 times higher in the JSNS target than that in the SNS target, at the same beam power. JSNS considers very deeply about this condition in the design, and struggles to solve this problem with some ideas as it plans to ramp up the 1 MW power equivalent to 2.4 MW in SNS with 60 Hz rep. These ideas include: JSNS installed the bubbling pressure mitigation technique; an in-situ diagnostic system to monitor target vibration originated by the high intense impulsive proton bombardment; and flattening the beam profile to reduce peak current and avoid localized irradiation damage. Any information and sources of data including PIE relating to target operation is very important to enable the design and operation of MW class target facilities in the future. Thus it is important to maintain the strong collaboration between SNS and JSNS in all the relevant fields and disciplines.