Recent Status of The Pulsed Spallation Neutron Source at J-PARC

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At the Japan Proton Accelerator Research Complex (J-PARC), the pulsed spallation neutron source has been in operation with a redesigned mercury target vessel from October 2017 to July 2018, during which the operational beam power was restored to 500 kW and the operation with a 1-MW equivalent beam was demonstrated for one hour. The target vessel includes a gas-micro-bubbles injector and a 2-mm-wide narrow mercury flow channel at the front end as measures to suppress the cavitation damage. After the operating period, it was observed that the cavitation damage at the 3-mm-thick front end of the target vessel could be suppressed less than 17.5 μm. Further improved target vessel with eliminating coupling between the water shroud and the mercury vessel is under fabrication.

KEYWORDS: spallation neutron source, mercury target, 1-MW, cavitation damage, micro-bubbles injection, narrow channel

1. Introduction

At the Japan Proton Accelerator Research Complex (J-PARC), a pulsed spallation neutron source has been in operation with injecting a 3-GeV proton beam with a repetition rate of 25 Hz since 2008 [1, 2]. This source includes a mercury target, three types of liquid hydrogen moderators and a reflector with inner-beryllium and outer iron, providing high intensity and/or narrow-width neutron pulses ranging from cold to thermal energies to a suite of state-of-the-art neutron instruments [3] for promoting cutting edge researches in various fields of materials science. The goal of the facility operation is to achieve stable target operation for 5000 h annually at the rated power of 1 MW. In the Japanese fiscal year 2018 (from April 2018 to March 2019), operating period for 176 days was completed with a high operation efficiency of 93% during which the beam power was mostly 500 kW.

For the mercury target used for short pulsed neutron source, cavitation damage induced by pressure waves on the front end of the target vessel made of stainless steel limits the life-time [4]. In order to mitigate the cavitation damage, we have developed a technology to inject gas-micro-bubbles into flowing mercury in the target vessel [5-7]. We have also improved structure of the front end of the target vessel, the beam injection portion, from single wall to double wall with a gap of 2 mm [2, 8] to suppress cavitation growth by making high-speed mercury flow in the narrow gap. Note that the mercury target of the Spallation Neutron Source at Oak Ridge National Laboratory [9]...
had included a double-walled narrow channel structure, but it is replaced three times during annual operation with the rated power of 1.4 MW at 60 Hz.

Furthermore, in 2015, the water shroud surrounding the mercury vessel of the target vessel failed twice during operation at 500 kW [2,10]. The initial structure that outer water shroud is coupled with inner mercury vessel with bolts had weakness of making welding defect during the manufacturing process which caused the failure due to the thermal stress loaded repetitively by the beam trips [10]. Therefore, we have changed the forward part of the target vessel to a monolithic structure to eliminate bolts connecting although the jointing rib structure remains. This type of target vessel, #8 in fabrication order, has been in use since October in 2017. Further improved target vessel eliminating the coupling between the mercury vessel and the water shroud is designed and under fabrication.

In this paper, we provide an overview of recent operational history in Section 2, result of the damage measured in the target vessel #8 in Section 3 and design of a coupling-free type target vessel in Section 4.

2. Operational history of spallation neutron source at J-PARC

Beam power history of the spallation neutron source at J-PARC since 2008 is shown in Fig.1. In 2015, two times unplanned interruptions due to the target vessel failures deteriorated the operation efficiency of the facility down to 46%. We used a spare target vessel (#2) with more reliable water shroud structure from February in 2016 to June in 2017 at low power of 150 kW to 200 kW because it was not equipped with any gas micro-bubbles injection device, during the period a re-designed target vessel #8 had been fabricated.

![Fig. 1. Beam power history delivered to the spallation neutron source at J-PARC. The numbers in white in the solid circles and solid diamonds stands for the target vessel in and the proton beam window in fabrication order which are started to use, respectively.](image)

The target vessel #8 was started to use from October 2017 at 300 kW. The beam power was increased stepwise and restored to 500 kW in April 2018. In July 3, we have demonstrated the target operation with a 1-MW equivalent proton beam for one hour.
Since certain proton pulses are shared to the Main Ring (30 GeV synchrotron) of J-PARC, the beam power delivered to the mercury target was estimated 945 kW. In the summer outage, the target vessel was replaced with the one (#9) with the same structure as #8. The target operation resumed at 500 kW. Resultant operation efficiencies since Japanese fiscal year 2016 are remarkably high as 93.8%, 92% and 92.7%, respectively.

The proton beam window (PBW) made of double walled aluminum alloy of Al5083 was also replaced in the summer outage in 2017. At that time, the accumulated beam power on the PBW was 2510 MWh which was much less than the design lifetime of 10,000 MWh. However, we considered that the PBW might be corroded because it was exposed under high humidity environment for some period at the location just 1.8 m upstream from the mercury target vessel after the target vessel failure in 2015. Figure 2 shows photographs of the removed PBW. As seen in Fig.2 (b), color of the surface of the vacuum (proton beam line) side was changed in coincidence with the profile of injecting proton beam, but there was no damage. In front of the PBW, a multi-wire profile monitor with stretching a tungsten wire of 0.01 mm in diameter covered with 0.15-mm-thick SiC on an aluminum frame with a spacing pitch of 6 mm in horizontal and vertical direction, respectively, was assembled [11]. It was observed that some of wires were slackened. Since this was caused by thermal expansion of the wire during the proton beam irradiation, any mechanism should be equipped for preventing the wire slack in the course of further proton beam window fabrication. As for the opposite side (mercury target side) of the PBW, its surface was quite clear (see. Fig.2 (c)).

![Fig. 2. Photographs of proton beam window: (a) appearance of proton beam window with a shield plug, (b) view from the vacuum (proton beam line) side and (c) view from the mercury target side.](image-url)
In Fig. 3, two results of the target operations including 1-MW equivalent beam operation are given. The left-hand-side figure shows relation between the displacement velocity of the target vessel at the time of proton beam injection and the beam power $P$ (kW) and the peak current density $Q$ (J/cc). For the beam power less than 500 kW, we had observed that the displacement velocity became higher as the peak current density in the proton beam profile increased at the same beam power, concluding that it could be fitted with a linear approximation (dotted line) as a function of $P^\alpha$ and $Q^\beta$ with appropriate parameters of $\alpha$ and $\beta$, where $\alpha=0.4375$ and $\beta=0.5625$ [12]. The present data taken in the higher beam power than 500 kW are also described with the linear relation. It is noted that the current pressure wave mitigation rate by the gas micro-bubbles injection is estimated about 1/3 in comparison with the case without bubbles [7]. The right-hand-side figure shows the temperature rise of mercury flowing out of the target vessel after the irradiation. It is also in proportion to the incident proton beam power. This indicates that the design of the target vessel is reasonable.

![Fig. 3. Velocity amplitude of the target vessel measured with a laser doppler vibrometer (left) and temperature rise between outlet and inlet of mercury flow (right) as a function of incident proton beam power. The marks are measured data and the dotted lines are for eye-guide.](image)

3. Damage inspection of the front end of the target vessel

After the operation with the target vessel #8 ended in July 2018, we cut out specimens from the double-walled front end of the target vessel and inspected cavitation damages created on them. Photographs of the specimens cut out from the outmost and the inner wall of the mercury vessel are shown in Fig. 4 with a schematic of the horizontal cross section of the mercury vessel. The thicknesses of those walls are 3 mm and 5 mm, respectively. The accumulated beam power on the target vessel #8 was 1812 MWh with an average power of 434 kW. The inner surface of the outmost wall is quite clear while that of the inner wall is much rough.

Detailed inspection of the damage with a replica method using a silicon rubber concluded that maximum depth of cavitation damage on the inner surface of the outmost wall was 17.5 $\mu$m while that of the inner wall was 268 $\mu$m. It is noted that mercury flows in the 2-mm-wide narrow channel between the outmost and the inner
wall without gas micro-bubbles. Effectiveness of the narrow channel on the cavitation damage mitigation had been demonstrated through the target operations of SNS at ORNL although the flow pattern is different from J-PARC’s mercury target [13]. High-speed mercury-flow in narrow channel is likely to be more effective than the current performance of gas-micro-bubbles injection technique.

On the other hand, in 2015, we measured the cavitation damage of the target vessel #5 with a double-walled front end after the operating condition that the accumulated beam power was 670 MWh with an average of 402 kW. At that time, an obvious band-like surface roughness was formed along the mercury flow direction on the inner surface of the outmost wall where the maximum depth of the cavitation damage was estimated 25 μm [2, 14]. Present damage depth of 17.5 μm is less than the value predicted from the result of target vessel #5.

Details of damage inspection procedure and more discussions of the measured results are described elsewhere in this proceedings [15].

![Fig. 4](image)

**Fig. 4.** (a) Photo of inner surface of a specimen cut out from the outer wall of the mercury vessel. (b) Photo of inner surface of a specimen cut out from the inner wall of the mercury vessel. (c) Schematic of horizontal cross section of the mercury vessel. Arrow in (a) and (b) shows the place where erosion depth is maximum, respectively.

### 4. Design improvement of target vessel

As shown in Fig 5(a), in the original design of the target vessel, the water shroud was coupled with the mercury vessel with bolts where upper and lower plates of the water shroud were joined with a diffusion bonding. In the current target vessel #8 (see Fig. 5(b)), the trapezoidal-shaped forward part of the target vessel where heat load is high during the beam operation was fabricated from a steel block with a wire-electron-discharge-machining (wire-EDM) as an integrated body without welding line. The rear part of the water shroud was fabricated with the wire-EDM and then joined with the mercury vessel with bolts. This change reduced the welding line to 55% in comparison with the initial design. Details of fabrication and inspection technologies applied to the target #8 are described elsewhere in this proceedings [16].

For the coupling-free target vessel shown in Fig. 5(c), the following two geometrical conditions are critical in the design: 1) ensuring an interstitial helium layer
with a 3-mm gap, 2) suppressing deformation of the water shroud to the outside within 1.6 mm to ensure the space surrounding moderators and reflectors. Note that the design pressures of mercury, helium, and coolant (light water) are 0.5 MPa, 0.2 MPa and 0.5 MPa, respectively. To meet the conditions, geometry of the cooling channel was changed to a cylinder with a diameter of 5 mm. The thickness of the water shroud was changed to 8 mm for the rear part while it was 3.5 mm for the forward part. We also have optimized an end plate region where a steel-made beam dump is installed to stop incident protons slowed down in mercury. As the beam dump is cooled from one side, high stress is induced in the end plate due to the steep temperature distribution. As enlarged in Fig. 5(c), a space was introduced in the end plate as a thermal shield to suppress the stress. It is also noted that we employed an electron beam welding in view of reducing welding deformation.

![Diagram](image)

**Fig. 5.** Schematics of vertical cross sections and typical structural characteristics of the target vessels Step-wise design changes from (a) original design to (b) with monolithic structure and (c) joint-free between mercury vessel and water shroud.

5. Conclusion

The mercury target vessel #8 introducing a monolithic structure to the coupling between outer water shroud and inner mercury vessel has been used for the operation from October 2017 to June 2018 during which stable operation at 500 kW was successfully achieved. It has a 2-mm-wide narrow mercury-flow channel at the front end, resulting that cavitation damage induced on the 3-mm-thick outmost wall was effectively suppressed as the maximum depth of the damage was only 17.5 µm after the operation with an accumulated beam power of 1812 MWh. The measured depth is less than the result of the target vessel #5 with the same flow channel structure. Further studies are required to discuss the effect of the narrow channel flow on the cavitation damage mitigation through operations with higher proton beam power.

In view of enhancing reliability of the structural integrity of the target vessel, the
target vessel with eliminating coupling between the mercury vessel and the water shroud is under fabrication with introducing an electron beam welding technique. The coupling-free type target will be used for operation from autumn in 2019.

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