Nuclear Inst. and Methods in Physics Research, A 894 (2018) 8–19

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Optimization study on structural analyses for the J-PARC mercury target vessel

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ARTICLE INFO

Keywords:
J-PARC
Mercury target vessel
Thermal stress
Optimization
Structural Analyses
Taguchi method

ABSTRACT

The spallation neutron source at the Japan Proton Accelerator Research Complex (J-PARC) mercury target vessel is used for various materials science studies, work is underway to achieve stable operation at 1 MW. This is very important for enhancing the structural integrity and durability of the target vessel, which is being developed for 1 MW operation. In the present study, to reduce thermal stress and relax stress concentrations more effectively in the existing target vessel in J-PARC, an optimization approach called the Taguchi method (TM) is applied to thermo-mechanical analysis. The ribs and their relative parameters, as well as the thickness of the mercury vessel and shrouds, were selected as important design parameters for this investigation. According to the analytical results of 18 model types designed using the TM, the optimal design was determined. It is characterized by discrete ribs and a thicker vessel wall than the current design. The maximum thermal stresses in the mercury vessel and the outer shroud were reduced by 14% and 15%, respectively. Furthermore, it was indicated that variations in rib width, left/right rib intervals, and shroud thickness could influence the maximum thermal stress performance. It is therefore concluded that the TM was useful for optimizing the structure of the target vessel and to reduce the thermal stress in a small number of calculation cases.

1. Introduction

Liquid mercury target systems have been operated to generate high-intensity pulsed neutrons for various studies on materials science at the Japan Proton Accelerator Research Complex (J-PARC) since 2008 and at the Oak Ridge National Laboratory (ORNL), USA, since 2007 [1–4]. At J-PARC, pulsed high-intensity proton beams with an energy of 3 GeV and a repetition rate of 25 Hz with a pulse duration of 1 μs are injected into the liquid mercury target to produce neutrons via spallation reactions with mercury [1–3]. The beam power is currently at 400 kW. The target vessel comprises a mercury vessel, an inner shroud, and outer shroud, as shown in Fig. 1. It contains liquid mercury and is fabricated of 316L austenitic stainless steel (JIS SUS316L). The dimensions of size of the target vessel are about 2 m in length, 1.1 m in width, and 1.1 m in height. To reduce the internal heat generation due to proton beam injection, the beam entrance portion in the front part of the target vessel, called beam window, is designed to be a thin-walled structure with a wall thickness of 3 mm, whereas the wall thickness in the remainder of the vessel is 8 mm. To prevent the release of mercury outside the vessel in the case of target vessel failure, the mercury vessel is covered with a double-walled water shroud composed of inner and outer shrouds (each 3 mm in thickness), as shown in Fig. 1 [2]. To efficiently remove the heat generated by the spallation reactions, the circular flow of the mercury is maintained perpendicular to the direction of the proton beam. Helium gas fills the interstitial space between the mercury vessel and the inner shroud, whereas the cooling channel is designed to be contained in the water shroud. To completely retain any leaked mercury in the case of mercury vessel failure, the water shroud is coupled with the reinforcement ribs on the mercury vessel, as shown in Fig. 1. In addition, the target vessel was assembled using tungsten inert gas (TIG) welding.

For the Spallation Neutron Source (SNS) target in USA, the targeted proton beam power is 2 MW with an energy of 1 GeV at 60 Hz under a pulse duration of 0.7 μs. In addition, this source has a multi-walled structure composed of a mercury vessel and a double-walled water shroud [4–6]. This structure it is quite different from that of the J-PARC target vessel. The mercury vessel in SNS is not constrained by the water shroud. To endure the higher loads caused by internal pressure and thermal stress under high-power operation of up to 2 MW, the mercury vessel is separated from the water shroud [4]. By contrast, in the design of J-PARC, robust structural reinforcement ribs between the

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https://doi.org/10.1016/j.nima.2018.03.047
Received 6 November 2017; Received in revised form 2 March 2018; Accepted 15 March 2018
Available online 27 March 2018

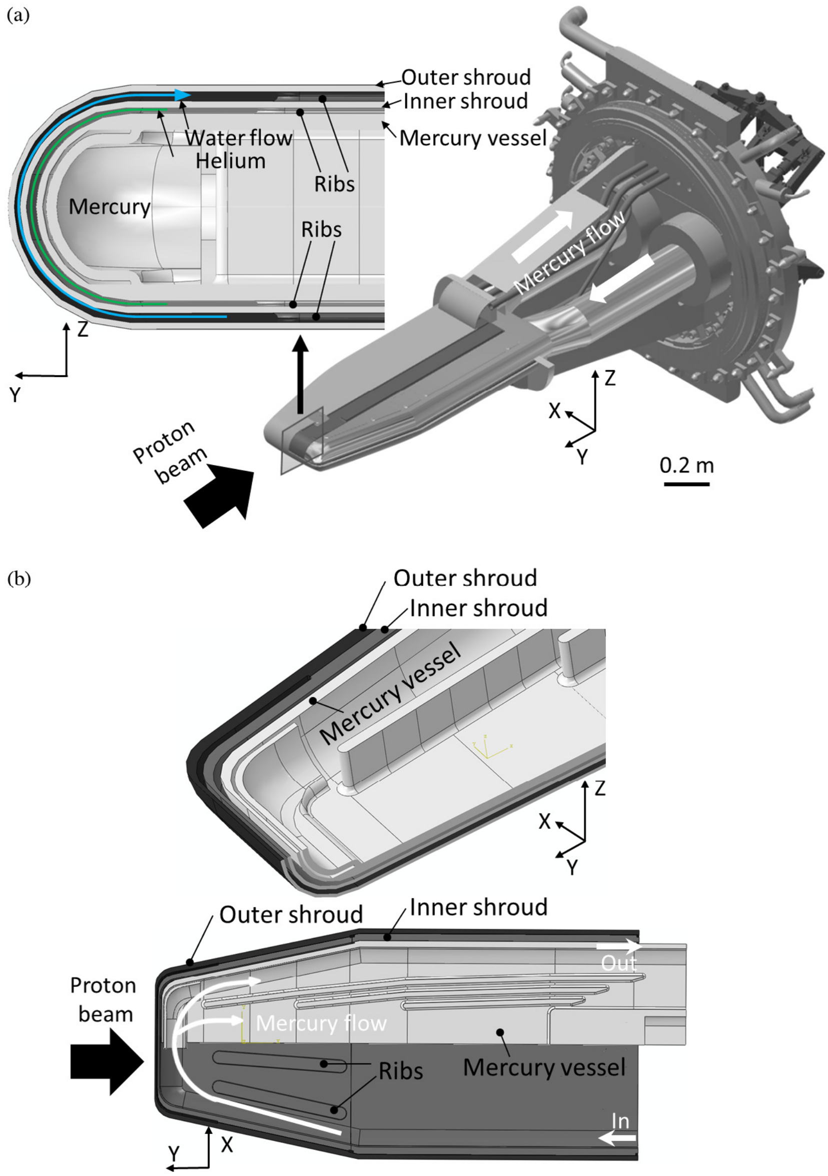

Fig. 1. Mercury target vessel with triple-walled structure: (a) outline of target vessel and vertical cut-away view of target vessel [2] and (b) horizontal cut-away view of target vessel and section drawing.

mercury vessel and the water shroud were included to prevent large plastic deformation of the water shroud due to mercury pressure when the mercury vessel ruptures. Furthermore, the reinforcement ribs can help fulfill the initial safety condition of the target vessel under internal pressure, because the design pressure of the helium layer is equal to the inner pressure of the mercury vessel for preventing the permeation of mercury into the helium layer after failure of the mercury vessel.

According to the design criteria of the target vessel, it should have an available lifetime of 2500 h at 1 MW operation under the limitation of irradiation dose of less than 5 displacement per atom (dpa) in J-PARC [7]. Meanwhile, because of repeated proton beam bombardment and beam tripping, the target vessel undergoes cyclic stresses due to thermal loading and pressure waves [2,8]. Throughout its lifetime, the target vessel is subjected to approximately 10^3–10^4 loading cycles in the region of low cycle fatigue (LCF) owing to beam tripping (two beam trips per hour was assumed) and approximately 10^8–10^9 loading cycles in the gigacycle fatigue region owing to pulsed proton beam injection. Therefore, the fatigue properties of SUS316L definitely influence the structural integrity of the target vessel, and evaluation of fatigue life should be considered. By contrast, thermal stresses occur owing to thermal expansion of the mercury vessel and shrouds, which is caused by different thermal gradients in the target vessel. We have been improving the structural design of the target vessel to achieve stable operation with a beam power of 1 MW. Therefore, to investigate the thermal stress performance, a thermo-mechanical analysis was performed under the condition of 1 MW of beam power based on the current design of the target vessel; note that when the use of the current was commenced, the beam power was 300 kW, and it will be increased to 500 kW [9]. Stress concentration can be observed around the ribs, as shown in Fig. 2, although the current design is qualified to the JIS standard for the construction of pressure vessel [9]. Therefore, there is an urgent need to enhance the structural reliability of the target vessel and further extend its fatigue life at a higher-power state (1 MW), while reducing the thermal stress in the target vessel from the viewpoints of structural integrity and durability.

From a broader perspective, it is necessary to design a more stable and robust structure for improving the structural integrity of the target vessel in J-PARC. Therefore, the objective of this study is to improve and optimize the structure of target vessel through a new approach called the Taguchi method (TM) [10]. The TM is a statistical technique used