Journal of Nuclear Materials 377 (2008) 268–274

Contents lists available at ScienceDirect

Journal of Nuclear Materials

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

Moderator poison design and burn-up calculations at the SNS

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ABSTRACT

The spallation neutron source (SNS) at Oak Ridge National Laboratory was commissioned in April 2006. At the nominal operating power (1.4 MW), it will have thermal neutron fluxes approximately an order of magnitude greater than any existing pulsed spallation source. It thus brings a serious challenge to the lifetime of the moderator poison sheets. The SNS moderators are integrated with the inner reflector plug (IRP) at a cost of ~$2 million a piece. A replacement of the inner reflector plug presents a significant drawback to the facility due to the activation and the operation cost. Although there are a lot of factors limiting the lifetime of the inner reflector plug, like radiation damage to the structural material and helium production of beryllium, the bottle-neck is the lifetime of the moderator poison sheets. Increasing the thickness of the poison sheet extends the lifetime but would sacrifice the neutronic performance of the moderators. A compromise is accepted at the current SNS target system which uses thick Gd poison sheets at a projected lifetime of 6 MW-years of operation. The calculations in this paper reveal that Cd may be a better poison material from the perspective of lifetime and neutronic performance. In replacing Gd, the inner reflector plug could reach a lifetime of 8 MW-years with ~5% higher peak neutron fluxes at almost no loss of energy resolution.

1. Introduction

The spallation neutron source (SNS) [1] completed facility commissioning in April 2006. The current operating target system of the SNS is equipped with four moderators, with the two upstream moderators decoupled and poisoned to achieve desirable pulse-shape characteristics. As it is to be operated at a full power of 1.4 MW, the SNS is capable of generating thermal neutron fluxes approximately an order of magnitude greater than any existing pulsed spallation source. Irradiated at this flux rate, a conventional poison sheet of 40 μm Gd or equivalent (as used in some existing pulsed spallation source facilities) would be depleted within 1000 h of operation [2]. Thus, the lifetime of the moderator poison sheets is an important issue at the SNS.

Frequent replacement of poison sheets is inapplicable at the SNS since the moderators are integrated with the inner reflector plug. A replacement of the inner reflector plug presents a significant drawback to the SNS facility in the economical and radiological aspects. The procurement cost alone for the inner reflector plug is about $2 million. The high activation of the used inner reflector plug presents a serious radiological hazard, which demands extra radiation protection and hence significantly increases the cost of the removal and replacement operations. Although there are other concerns on the lifetime of the inner reflector plug, e.g. radiation damage to the aluminum alloy vessel and helium production of the beryllium reflector, the short lifetime of the poison sheets has proven to be the limiting factor. Ferguson and Gallmeier [3] thoroughly examined the radiation damage in the SNS target system. It was found that the maximum radiation damage to the aluminum alloy vessel is ~7 dpa/SNS year (1 SNS year is 5000 operation hours) and the maximum helium production of the beryllium reflector is less than 40 appm/SNS year. The operating experience at HFIR (High flux isotope reactor), Oak Ridge National Laboratory shows that aluminum alloy 6061 is able to withstand up to 40 dpa of irradiation [4].

Iverson and Murphy [2] calculated and proposed to use thick Gd sheets as a measure to balance the lifetime of the poison sheets, hence the lifetime of the inner reflector plug, and the moderator neutronic performance. Based on their estimation, the current operating target system at SNS adopts a Gd poison sheet of 0.81 mm for the top upstream hydrogen moderator and 0.99 mm for the bottom upstream water moderator. Those poison sheets are expected to last three years at 2 MW (6 MW-years), but the moderators may suffer approximately 20% loss of the neutron intensity at the beginning of the service life compared to the use of conventional 40-μm Gd sheets.

The estimation of the lifetime made for the thick poison sheets by Iverson and Murphy is conservative since it was concluded on the extrapolation of initial burn-up rate. The burn-up rate for a thick poison sheet is determined by two factors: the depressed neutron flux and the atomic density of the poison sheet. As it is gradually depleted, the poison sheet may undergo a slower burn-up rate due to a combined effect of the two factors. On the other

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0022-3115/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jnucmat.2008.02.087

hand, the assessment of Iverson and Murphy may be an over-estimate of the lifetime since it reports the average lifetime of the poison sheet instead of the lifetime at the worst spot. Furthermore, the work of Iverson and Murphy is based on a physics design model, the details of which were gradually changed over the construction of the SNS target system.

All the above factors cloud the accuracy of the lifetime estimation made for the poison sheets at the SNS. Recently an as-built model based on the engineering drawings for the SNS target system was developed [5]. It is so far the most accurate representation of the SNS target system. Taking advantage of the as-built model, this paper is intended to rigorously re-examine the lifetime estimation of the poison sheets and to propose an improved moderator poison design which will extended the poison sheet lifetime and enhanced neutronic performance.

2. Moderator system at the SNS

The SNS moderator system consists of two pairs of moderators above and below the mercury target module. Each pair of moderators is located about 19 cm apart from each other and the centers of the moderators are about 18–19 cm from the center plane of the target module. The moderator system is housed in the inner reflector plug, which includes an inner beryllium layer with a radius of 32 cm and an outer stainless steel reflector and shield with an outer radius of 47 cm. The inner reflector plug is placed inside the outer reflector plug made of stainless steel alloy 304 (SS 304) with an outer radius of 95 cm. Both of the inner and the outer reflector plugs are cooled by heavy water.

There are three cryogenic moderators and one ambient moderator. The two downstream moderators are coupled and filled with hydrogen at a temperature of 20 K. The top upstream moderator is also cryogenic but is decoupled and poisoned. The bottom upstream moderator is decoupled and poisoned but is filled with water at room temperature. The two upstream moderators are of interest to this paper since they contain poison sheets whose lifetime estimation is to be investigated.

The details of the two upstream moderators are described in Figs. 1 and 2 as they were modeled in the as-built model. Fig. 1 shows vertical cross sections at the center of the top upstream moderator. The top upstream moderator is a double-vessel structure made of aluminum alloy 6061 (Al 6061). The hydrogen vessel is filled with super critical hydrogen and is contained within the vacuum vessel. In between the two vessels, a high level of vacuum is maintained for insulation. A Gd poison sheet of 813 μm is placed in the middle of the hydrogen vessel along the long axis of the vessel. The poison sheet is held within an Al 6061 plate with a thickness of 1.8 mm. The poison depth is 27 mm from either moderator viewed surface. Except for the viewed surfaces, the outer surface of the moderator is covered with Cd decoupler. The thickness of the decoupler is 1.4 mm to ensure a lifetime of 6 MW-years [6].

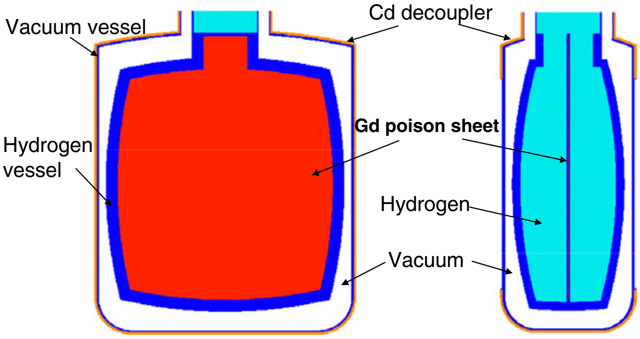

Fig. 1. Vertical views of the top upstream moderator (for reference, the depth of the moderator is 8.2 cm at the center and the thickness of the poison sheet is 813 μm).

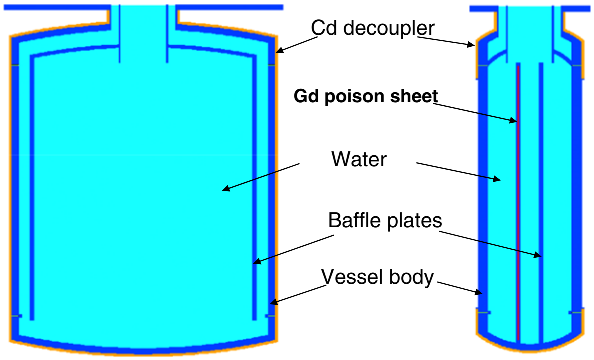

Fig. 2. Vertical views of the bottom upstream moderator (for reference, the depth of the moderator at the center is 5.4 cm and the thickness of the poison sheet is 991 μm).

Unlike the top upstream moderator, the bottom upstream moderator, as shown in Fig. 2, is a single-vessel structure. It is made of Al 6061 and is filled with water. A baffle assembly is built inside the bottom moderator to create flow passages for the circulating water. The Gd poison sheet in the bottom upstream moderator is 991 μm in thickness contained within a 2 mm Al 6061 plate. It is, however, not placed at the center of the moderator. The poison depth is 25 mm from the upstream surface and 15 mm from the downstream surface. The position of the Gd poison sheet was designed in such a way to provide as many neutrons as possible with acceptable time resolution for various instruments at the upstream and downstream surfaces of the moderator.

3. Burn-up calculations for the SNS Gd poison sheets

The burn-up calculations in this study were performed for the top and bottom upstream moderators using MCNPX [7] (version 2.5.0) and CINDER90 [8] alternately. The as-built model of the SNS target system was adopted in the MCNPX simulation for tallying the neutron fluxes in the moderator poison sheets. Those neutron fluxes served as the input to the CINDER90 code for calculating the inventory of radionuclides in the poison sheets over a certain amount of irradiation time, or one time step. The Gd abundances of the depleted poison sheets were thus updated in the MCNPX input file for beginning the calculation in the next time step. The length of one time step in this study is 200 h, which is sufficiently short for an expected burn-up time of 3 SNS years (1 SNS year = 5000 h). Because potential upgrades may increase the beam power incident on the target system, all analyses were performed assuming 2 MW of beam power on target.

Since the poison sheets are positioned in a region approximately 2–19 cm above or below the mercury target top, they are exposed to significantly different neutron fluxes from the bottom to the top. The burn-up rate of the poison sheet is therefore not uniformly distributed. To detect the location of the most significant depletion, the poison sheet was divided into 1–2 cm segments vertically.

Compared to the mean free path of thermal neutrons in the Gd (6.7 μm), both poison sheets are so thick that the thermal neutron flux depression must be considered. One ideal way of mapping thermal neutron fluxes inside the poison sheet is to slice it into layers with a thickness close to the mean free path. However, this direct slicing method together with the height segments would cost over 5 GB of memory for each computing node. It is hence not practical for our computer system. An improved slicing scheme was

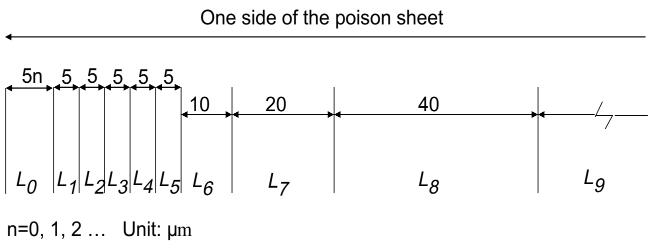

Fig. 3. Slicing scheme of the poison sheet for burn-up calculations.

suggested and is presented in Fig. 3, which shows the application of the scheme at one side of the poison sheet. The poison sheet is sliced into 10 layers (L_0–L_9) on each side. The first layer, L_0, is a depleted layer with a thickness of multiples of 5 μm (the nominal perpendicular thermal neutron transmission is 0.5 through 5 μm Gd), followed by 5-μm layers, L_1–L_5. Moving inwards, the thickness of layers L_6–L_8 is doubled at each slicing until L_9 which consists of the rest of the poison sheet on one side. The thickness of L_9 is the half distance between the inner boundaries of L_8 and L_8' (the corresponding 9th layer at the other side). The majority of the thermal neutron flux impinges on the outer boundary of L_1 since L_0 is considered depleted. The thermal flux depression occurs greatly in the region of L_1–L_5, out of which the nominal perpendicular thermal neutron transmission, f, is less than 5%. L_6–L_8 serves as a buffer area to catch neutron fluxes at energies above but close to the peak energy of the Maxwellian distribution. The thickness of L_9 is not a concern as neutrons reaching L_9 are nearly all fast ones whose resonant absorption is uniformly distributed in the poison sheet. The initial thickness of L_0 is 0. When L_1 is depleted it is merged with L_0 and the complete slicing structure is moved inwards 5 μm, the thickness of L_1. The depletion of L_1 is determined by the nominal perpendicular thermal neutron transmission of L_0–L_5 (f_{0-5}). If f_{0-5} is approximately greater than 0.125 (f'), L_1 is considered depleted. The value of f' is corresponding to f through 3 layers of 5 μm Gd. It is carefully picked to ensure the expanding rate of the depleted layer, L_0, is proper.

The main neutron absorbing isotopes in the Gd poison sheets are ^{155}Gd and ^{157}Gd. There is no significant decay or build-up of any neutron absorbing nuclide during the burn-up process. This study is hence focused on the depletion of ^{155}Gd and ^{157}Gd in three years of full power (2 MW) operation at the SNS. Fig. 4 shows that after an irradiation of 3.2 SNS years (16 000 h) there are only 37% ^{155}Gd and 30% ^{157}Gd left in the top upstream moderator and 29% ^{155}Gd and 14% ^{157}Gd in the bottom upstream moderator. ^{157}Gd burns faster than ^{155}Gd because its neutron absorption cross section is much higher. Since water is a better moderating material than the liquid hydrogen due to its higher hydrogen density, the bottom upstream moderator produces more thermal neutrons and burns the poison sheet faster than does the top upstream moderator. In both moderators the depletion rate of ^{155}Gd or ^{157}Gd is nearly constant though it slows slightly as the irradiation progresses. This indicates that the poison sheet is likely depleted one layer at a time. As the outer layer is depleted, the inner layers receive higher thermal neutron fluxes, which compensate, to a great extent, the decrease of atomic density of ^{155}Gd or ^{157}Gd. However, this compensation is limited and gradually outweighed by the decreasing atomic density of the absorbing isotope, because in addition to the thermal neutron absorption, the resonant neutron absorption is another factor contributing to the atomic density decrease of the absorbing isotope. The depletion rate is slowed down when the decrease of the absorbing isotope atomic density becomes dominant.

To ensure the functionality of the poisoned moderators, the Gd poison sheets are required to be thicker than 50.4 μm (2 mil) at the SNS. Therefore the lifetime of the poison sheet is defined as when the nominal perpendicular thermal neutron transmission, f, of the worst segment reaches the same value as that of a fresh 50.4 μm Gd poison sheet (f_0, 5.49×10^{-4}). Fig. 5 shows the nominal thermal neutron transmissions over 3.2 SNS years for the worst segments of the poison sheets in the top and bottom upstream moderator. The worst poison segment in the bottom upstream moderator, as observed in Fig. 5, reaches the targeted nominal thermal transmission (f_0) at the end of 3.2 SNS years of irradiation (16 000 h). At the same time the nominal thermal neutron transmission of the worst poison segment in the top upstream moderator is still well under f_0. The nominal thermal neutron transmission in the top upstream moderator can be confidently fitted by a two order polynomial curve for the log-linear scales in Fig. 5. The extrapolation of the curve reveals that the worst poison segment in the top upstream moderator reaches f_0 after an irradiation time of 4.2 SNS years (21 200 h). Fig. 5 confirms that the poison sheet lifetime is 3.2 SNS years for the bottom upstream moderator and 4.2 SNS years for the top upstream moderator. Fig. 6 shows the lifetime estimation for each segment of the poison sheets for both moderators. As already discussed above, the poison sheet in the top upstream moderator burns slower and hence has a longer lifetime. In the case of the top upstream moderator, as the segment is positioned away from the mercury target, the poison sheet lifetime first

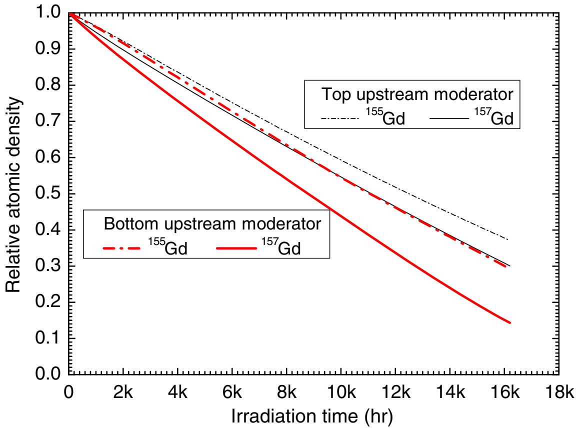

Fig. 4. Relative abundances of ^{155}Gd and ^{157}Gd in the depleted poison sheets of the top and bottom upstream moderators.

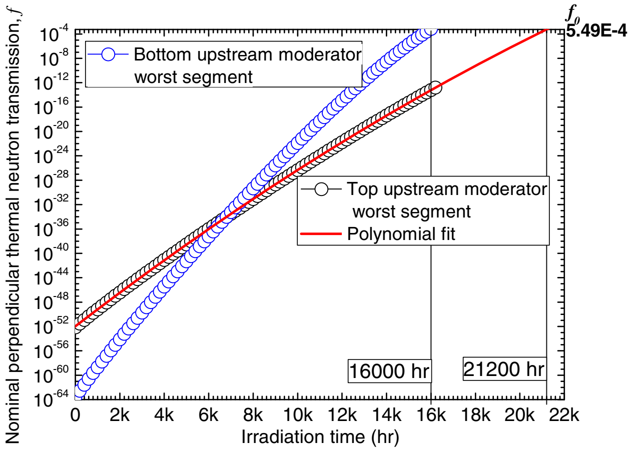

Fig. 5. Nominal perpendicular thermal neutron transmission rates in the worst segments of the depleted poison sheets in the top and bottom upstream moderators.

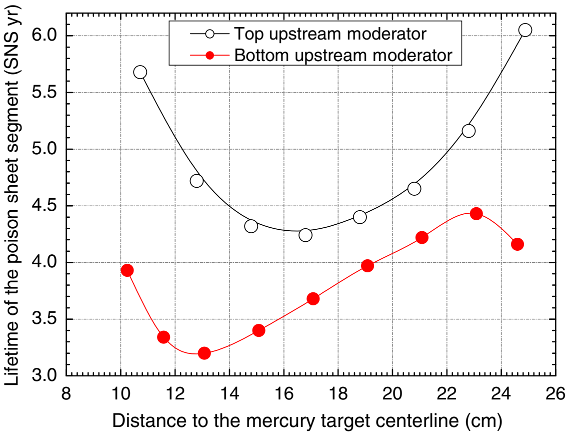

Fig. 6. Lifetime estimation of the poison sheets in the top and bottom upstream moderators.

decreases, reaches the minimum value of 4.2 SNS years at ~17 cm from the mercury target centerline and then increases. The lifetime of the poison sheet is greatly dependent on how much thermal neutron flux it receives. Although it is closest to the target and is supposed to receive the highest neutron fluxes, the bottom of the poison sheet is not necessarily the worst location for the lifetime because the moderation process is not well developed there. The lifetime distribution shown in Fig. 6 is a reflection of the combined effect of the neutron flux and the moderation process. In the case of the bottom upstream moderator, the shortest lifetime of the poison sheet (3.2 SNS years) occurs ~13 cm from the mercury target centerline. The lifetime distribution of the poison sheet is similar to that in the top upstream moderator except that at the top of the poison sheet in the bottom moderator the lifetime drops. This is partly due to the large amount of water placed on the top of the poison sheet in the bottom upstream moderator.

As a thick poison sheet is gradually depleted, there are fewer resonant absorptions and more thermal neutrons are emitted from the moderator. The moderator performance is expected to improve. Figs. 7 and 8 show neutron intensity spectra at the top and bottom upstream moderators at different stages (every service year) of the depleted poison sheets. The peaks of the spectra are plotted in the enlarged scales on the right top corners of Figs. 7 and 8. The calculations were performed using MCNPX2.5.0 with point detectors 10 and 5.3 m, respectively, from the view surfaces of the top and bottom upstream moderators. The details of the calculation technique are described in [9]. For the bottom upstream moderator, the neutron intensity was tallied at the downstream side with a thinner poison depth of 15 mm. As indicated in the enlarged scales of Figs. 7 and 8, the average gain in the neutron intensity in each service year (1 SNS years or 5000 h) is ~4% for the top upstream moderator and ~6% for the bottom upstream moderator during the three years of irradiation. Since the poison sheet lifetime, as already discussed above, is 4.2 SNS years for the top upstream moderator and 3.2 SNS years for the bottom upstream moderator, the total gain in the neutron intensity at the end of the poison sheet lifetime is expected to be ~16% for the top upstream moderator and ~19% for the bottom upstream moderator. In other words, the performance loss of the SNS poisoned moderator is greater than ~13% for the top upstream moderator and greater than ~16% for the bottom upstream moderator when a conventional 40–50 μm Gd poison sheet is thickened to 800–1000 μm.

4. Optimization of moderator poison design

Using the results from the discussion of the burn-up calculations in the previous section, one immediate optimization can be introduced to the poison sheet in the top upstream moderator at the SNS. That is to reduce the poison sheet thickness from an expected lifetime of 4.2–3.2 SNS years since the inner reflector plug has to be replaced after 3.2 SNS years. The top upstream moderator would hence gain 4% in the neutron intensity at the beginning of the service.

The decrease in the moderator performance due to the use of a thick poison sheet is mainly caused by resonant absorption. One way to optimize the moderator poison design is to find a material that has a lower resonant absorption cross section and a comparable or higher thermal absorption cross section than Gd. Thus, the moderator performance can be improved even with a thicker poison sheet, i.e., a longer poison sheet lifetime. Cd may be one such material suitable to this purpose. Fig. 9 shows the neutron

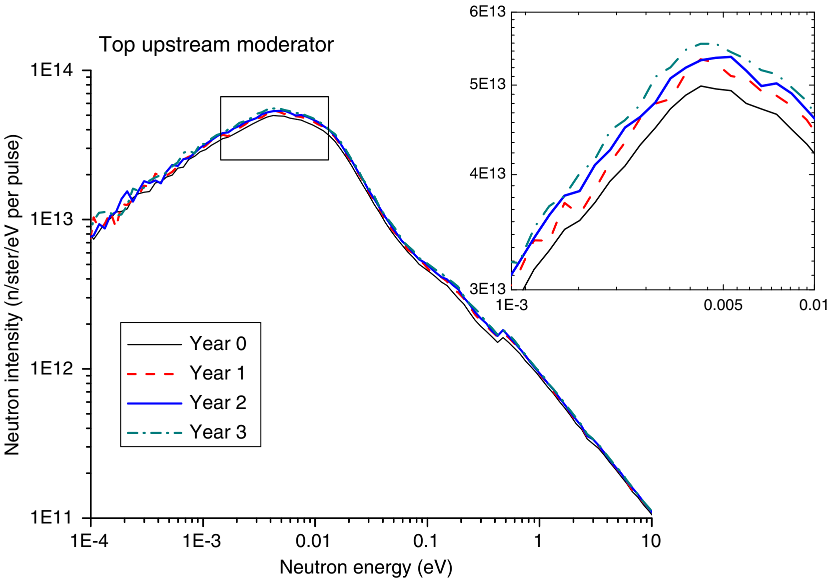

Fig. 7. Neutron intensity spectra at the different burn-up stages of the poison sheet in the top upstream moderator.

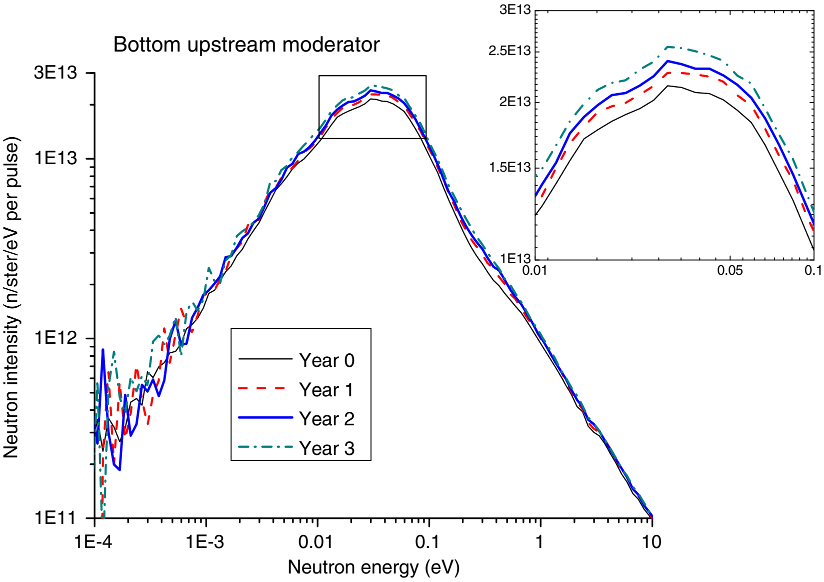

Fig. 8. Neutron intensity spectra at the different burn-up stages of the poison sheet in the bottom upstream moderator.

absorption cross section as a function of energy for Gd and Cd. Although the thermal absorption cross section of Cd is one order of magnitude lower than Gd, its resonant absorption cross section is also one order of magnitude lower.

The initial Cd burn-up rates were scaled to estimate the thicknesses necessary to make a four-year lifetime for the poison sheets in the top and bottom upstream moderators. ^{113}Cd is the only Cd isotope with significant neutron absorption, and its atomic density is lower than the summed atomic density of ^{155}Gd and ^{157}Gd. Therefore, the calculation found that the poison sheet must be 1.5 times thicker for the top upstream moderator and 1.8 times thicker for the bottom upstream moderator if Gd is replaced by Cd to make a lifetime of four years.

The moderator performances due to Gd and Cd poison sheets at the beginning of the service life are compared and summarized in Figs. 10–15 for the top and bottom upstream moderators. The investigation of the bottom upstream moderator was performed for the downstream viewed surface with a poison depth of 15 mm. As indicated in the time averaged intensity spectra and ratio plots in Figs. 10 and 12, the Cd poison sheet generally yields higher neutron intensity than the Gd poison sheet in both moderators. The ratio plots show that the time averaged intensity increase due to the Cd poison sheet is ~5% for neutron energies

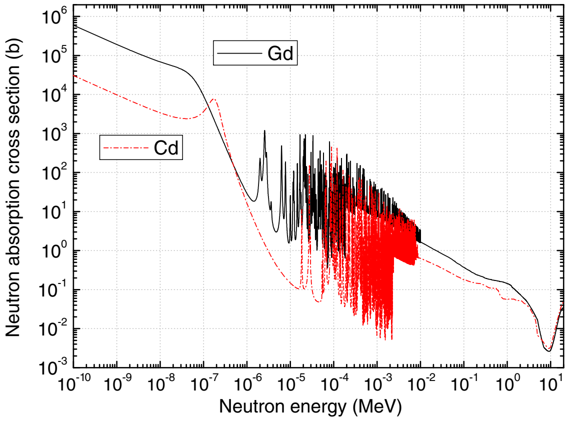

Fig. 9. Neutron absorption cross sections for Gd and Cd.

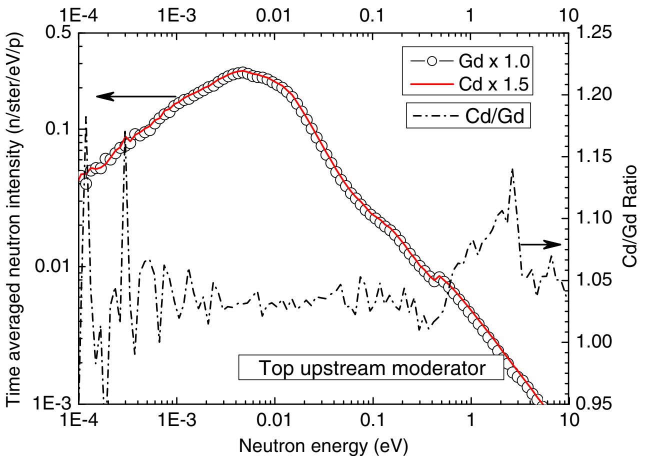

Fig. 10. Comparison of neutron intensity between Gd and Cd (1.5 times thickness of Gd) poison sheets in the top upstream moderator.

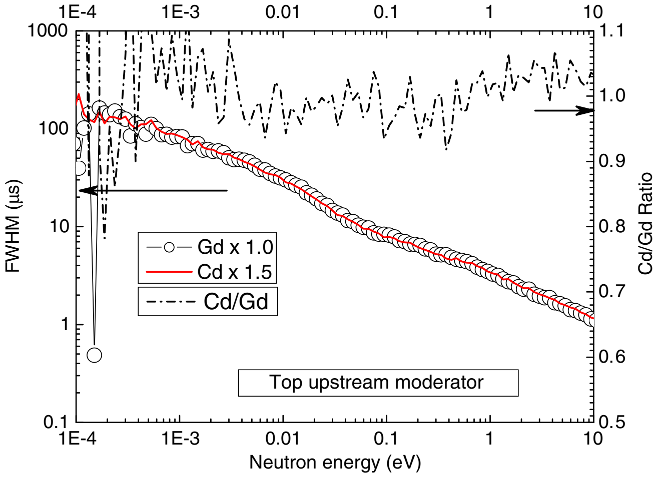

Fig. 11. Comparison of energy resolution (FWHM) between Gd and Cd (1.5 times thickness of Gd) poison sheets in the top upstream moderator.

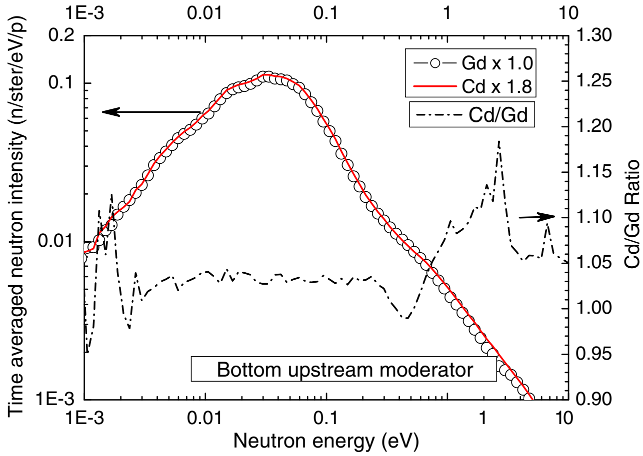

Fig. 12. Comparison of neutron intensity between Gd and Cd (1.8 times thickness of Gd) poison sheets in the bottom upstream moderator.

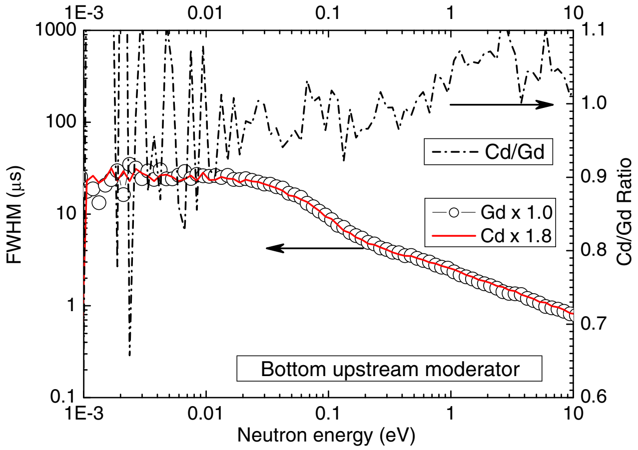

Fig. 13. Comparison of energy resolution (FWHM) between Gd and Cd (1.8 times thickness of Gd) poison sheets in the bottom upstream moderator.

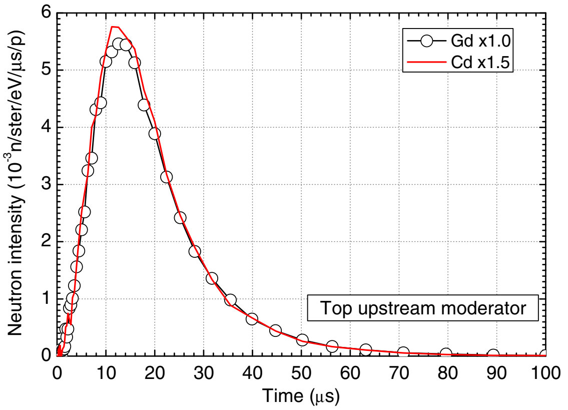

Fig. 14. Comparison of time distribution at 20 meV between Gd and Cd (1.5 times thickness of Gd) poison sheets in the top upstream moderator.

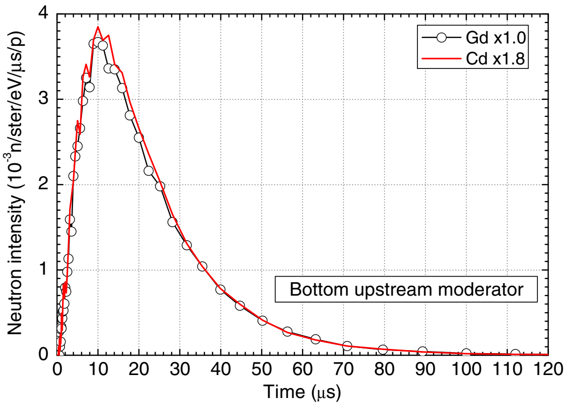

Fig. 15. Comparison of time distribution at 20 meV between Gd and Cd (1.8 times thickness of Gd) poison sheets in the bottom upstream moderator.

between 1 meV and 1 eV. But this increase does not come at the sacrifice of energy resolution. The ratio plots in Figs. 11 and 13 show that the full-width-at-half-maximum (FWHM) values are nearly the same in the energy range from 1 meV to 1 eV for the Gd and Cd poison sheets in both moderators. Figs. 14 and 15 show the pulse shapes for 20 meV neutrons due to the Gd and Cd poison sheets for the top and bottom upstream moderators, respectively. In both figures, the rise time and the decay time of the 20 meV neutrons are nearly the same for the two poison sheets.

As discussed earlier, the moderator performance improvement for the Cd poison design lies in the fact that compared to Gd, Cd has a significant thermal neutron absorption cross section, but a much lower resonant absorption cross section between ∼1 eV and ∼10 keV. Fig. 16 shows neutron absorption as a function of energy for Gd and Cd poison sheets in the top upstream moderator. The absorption spectra are divided into three energy regions: (1) $E_n < 1$ eV, where major thermal neutron absorptions occur, (2) 1 eV $< E_n <$ 10 keV, where major resonant absorptions occur, and (3) $E_n > 10$ keV. The integral number of absorptions in each region is also noted in the figure for each poison sheet. For each thermal neutron captured, Cd captures only 0.08 neutrons in the resonant region. Gd, however, captures 0.38 neutrons in the resonant region for each captured thermal neutron. Therefore, fewer epithermal neutrons are fed into the moderation process in the Gd poisoned moderator. For both poison sheets, absorption in the region $E_n > 10$ keV is insignificant.

It can be concluded from the moderator performance comparisons in Figs. 10–16 that the current thick Gd poison sheets in the decoupled moderators at the SNS can be replaced with thicker Cd poison sheets. The new poison sheets are expected to have a

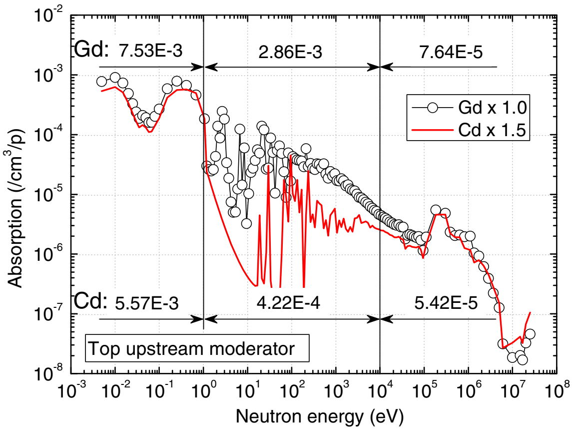

Fig. 16. Comparison of neutron absorption between Gd and Cd (1.5 times thickness of Gd) poison sheets in the top upstream moderator.

lifetime of 4 SNS years and to improve the moderator performance by ~5%.

5. Summary

The moderator system at the SNS is integrated with the inner reflector plug, which costs ~$2 million to procure. The poison sheet defines the inner reflector plug lifetime. To prolong the inner reflector plug lifetime, thick Gd poison sheets are adopted in the current SNS target system.

Using an as-built model recently developed for the SNS target system, we re-examined the lifetime of the current poison sheet. The poison sheets were divided into segments vertically and were sliced into layers along the thickness. In such a way the worst locations for poison sheet burnup were detected and the accuracy of the calculations was ensured. Our investigation confirmed that the lifetime of the poison sheets is 3.2 SNS years for the bottom upstream moderator and 4.2 SNS years for the top upstream moderator. The thick Gd poison sheet incurs at least a loss of ~13–16% in moderator brightness at the beginning of the service life compared to a fresh conventional Gd poison sheet of 40–50 μm.

Replacing Gd with Cd can improve the moderator performance and extend the poison sheet lifetime due to the lower resonant absorption cross section of Cd. The Cd poison sheets must be made thicker than the Gd poison sheets to make a lifetime of four years, but the benefit of the moderator performance gain is still ~5%.

However, Cd may produce high energy photons, which may increase background at some detectors down the neutron beamlines. Experiments for measuring the Cd poison sheets are planned to verify the new poison sheet design. Additionally, the thermal hydraulics impact of replacing Gd with Cd must be studied. Other methods of extending the poison sheet lifetime and improving the moderator performance are still under investigation.

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