Burnup of Cadmium Decoupler Material in the Spallation Neutron Source Moderators

B. D. Murphy and P. D. Ferguson
Oak Ridge National Laboratory
Oak Ridge, TN 37830-6370
(865)574-5441
murphybd@ornl.gov

ABSTRACT

At the Spallation Neutron Source being constructed at Oak Ridge National Laboratory, power levels will be greater than at any other operating pulsed spallation neutron scattering facility. Some of the moderators at the facility will contain cadmium that will be used to tailor neutron time distributions by absorbing low-energy neutrons. Because of the higher operating power levels, indications are that there will be considerable burnup of this cadmium during the lifetime of the moderators. Cadmium burnup rates have been calculated for locations around the moderators. Assumed operating conditions for these calculations were a 2-mA beam of 1-GeV protons on the mercury target for 5,000 operating hours per year and a three-year lifetime for the moderators and inner-plug assembly. With the present proposed cadmium thickness in the moderator region (0.05 cm), Monte Carlo calculations indicate considerable depletion of the active cadmium isotope. In places, the calculations indicate complete depletion. An obvious solution to the problem would be to increase the cadmium thickness with a concomitant increase in heat load. Results from some cadmium heating calculations are also presented for a cadmium thickness of 0.05 cm.

I. INTRODUCTION

For many experiments at a pulsed spallation neutron source facility it is desirable to have neutron pulses of short duration and in such cases one may be willing to sacrifice neutron intensity for better resolution (i.e. shorter pulses). For other experiments, neutron flux or current may be of prime importance and time-pulse characteristics may be a secondary consideration. To a large extent, the long tails in the neutron time pulses come from slow neutrons that return to the moderator from the reflector and, therefore, will exit the moderator at later times. Consequently, one way to avoid such time-delayed neutrons within a pulse is to place material with a high absorption cross section for slow neutrons between the moderator and the surrounding reflector material. Moderators with such an arrangement are known as decoupled moderators meaning that for these time-delayed neutrons they are decoupled neutronically from the surrounding reflector. Conversely, moderators without this arrangement are called coupled moderators. A good summary and comparison of coupled and decoupled moderator neutronics was completed by Russell, et al.[1] At the Spallation Neutron Source (SNS)[2] being built at Oak Ridge National Laboratory it is envisaged that two of the four moderators will be decoupled. The decoupling material will be cadmium and currently it is proposed that it have a thickness of 0.05 cm. The nominal neutron cutoff energy for cadmium is approximately 0.4 eV.

Some of the moderators in the SNS will also contain gadolinium poison plates for pulse-shaping purposes. Recent calculations[3] have indicated that these poison plates will suffer significant burnup of their neutron absorbing isotopes during the course of a typical moderator lifetime. This realization prompted us to investigate the possibility that burnup of the cadmium decoupling material might also be significant.

Until recently, burnup of cadmium had not been envisaged as a problem. This has not been seen to be a problem at other pulsed spallation facilities, but neutron currents at the SNS will be approximately an order of magnitude higher than at any existing facility. The solution selected for the gadolinium issue was to increase the thickness of the poison plates so that they remain effective throughout the lifetime of the moderator (approximately three years). This must be balanced with the effect it has on moderator leakage and the neutron spectral characteristics early in the life of the moderator. Similarly, if cadmium burnup were a problem, an obvious solution would be to increase the decoupler thickness. However, this must also be balanced with other design considerations (reduced neutron flux early in the lifetime of the unit and increased heat load).

II.   SNS MONTE CARLO MODEL

For reference, the Monte Carlo model of the SNS target system is shown in Fig. 1. For the remainder of this paper, we will focus on the two upper moderators, the upstream, decoupled, supercritical hydrogen moderator and the downstream, coupled, supercritical hydrogen moderator. A similar analysis has been carried out for the lower moderators. The cadmium decoupling material for the SNS moderators is divided into two pieces due to the moderator geometry. One piece is placed on the vacuum vessel inside the cooling water and the other piece surrounds the outer part of the decoupled moderator, including a portion of the water premoderator for the downstream moderator. If cadmium burnup is a concern, then the distribution of cadmium within these two regions needs to be studied in more detail. In addition, heat deposition consequences must be considered if overall cadmium amounts need to be increased.
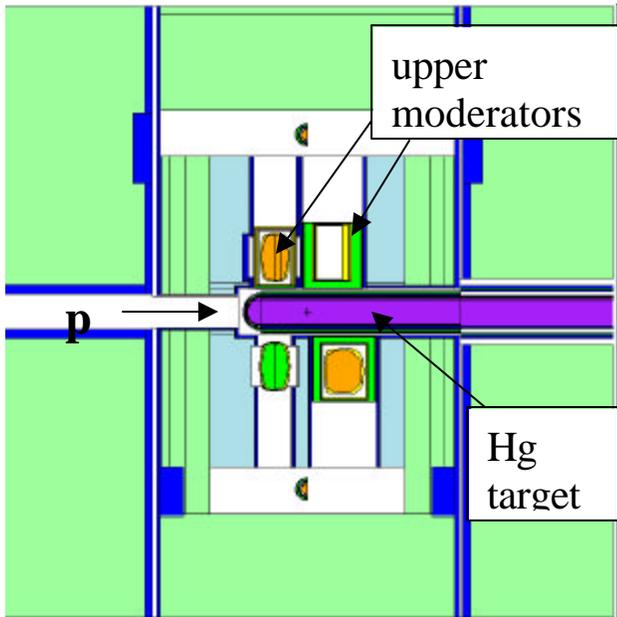

Figure 1. Elevation view of the SNS target system Monte Carlo model used for the analysis.

Cadmium liners also exist along the neutron flight paths from the decoupled moderators. The flight paths have a 0.0762-cm layer of cadmium on top of a layer of stainless steel covering the Be/D_2O reflector material of the inner plug. Cadmium burnup in this location could be compensated for by an increase in thickness and the heat deposition consequences are not likely to be as critical as in the case of the moderators themselves. Cadmium is also covering the well in which the moderator sits within the reflector material. Each piece of cadmium was needed at the time it was included in the model but design changes have made some of it redundant. Some redundancy can be tolerated because it is important that

decoupled moderators be completely decoupled from the reflector to retain the pulse characteristics desired by the instrument scientists.

III.   BURNUP ANALYSIS

All calculations reported here used the MCNPX code.[4] The most recent calculations, leading to the more detailed analyses reported below, used version 2.1.5 of MCNPX.   Interaction rates in cadmium cells were determined from the track-length estimate of neutron flux (type f4 tally in MCNPX), the cadmium density, and the (n, gamma) cross section.   The majority of capture reactions occur in ^{113}Cd and for burnup calculations, all interactions were assumed to occur in ^{113}Cd. Output from MCNPX will be in terms of absorptions per unit volume per proton. With ^{113}Cd being 12.2% of the cadmium and assuming a 2 mA beam of protons, 5000 hours running time per year, and a three-year lifetime, the cadmium burnup values were estimated. Heating rates in cadmium were estimated from the +f6 tally in MCNPX (track-length estimate of energy deposition).

Figures 2 and 3 show the locations of the cadmium associated with the top upstream decoupled moderator. In Fig. 2 the area covered by the side cadmium is shown as one looks down on the unit. The side cadmium strips are shown as exaggerated arcs. The cadmium at the top and bottom on the outside of the unit extends across the regions shown by the double-headed arrows above and below the flight paths so as to shield against neutrons exiting the reflector in those regions.

Figure 3 shows the same moderator unit from a location in front of the viewing face, but this particular slice shows only the cadmium inside the water cooling layer.

Scoping calculations for the cadmium decoupling material around the top upstream decoupled supercritical hydrogen moderator indicated two regions susceptible to burnup.   These regions were the cadmium decoupler along and near the bottom of the moderator (high moderated neutron flux close to the target) and the start of the cadmium that lines the neutron flight path from this moderator. Our calculations indicate that a large fraction of the ^{113}Cd, the dominant absorbing isotope, could be depleted during the course of the moderator and inner-plug lifetime.   Preliminary estimates indicated that (depending on the thickness of this cadmium and its location) the depletion rate could be anywhere from a lower limit of 40% to possible total depletion of the ^{113}Cd. Recall that on the moderator itself there is cadmium decoupling material inside the cooling water (on the sides and top but not on either viewing face) and also on the outside surface of the moderator. As expected, the

cadmium inside the cooling water is where most neutron-cadmium interactions occur. And, the cadmium towards the bottom of the unit (i.e., nearest to the target) experiences the highest interaction rates. For the outer cadmium, the bottom component sees the higher reaction rates, as expected.
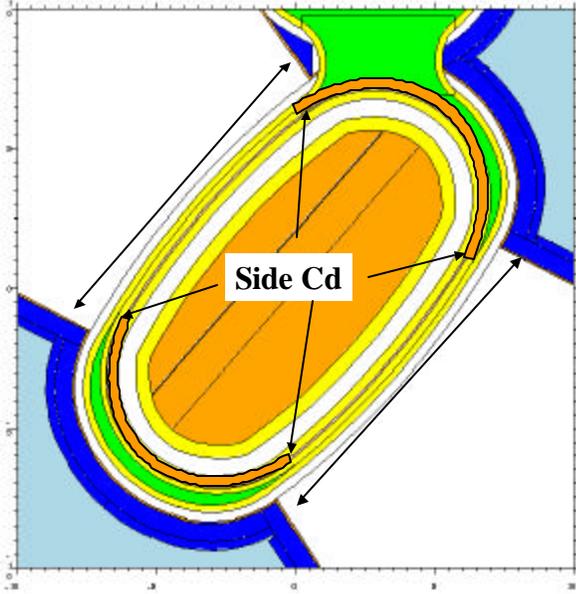

Figure 2. Plan view of the top upstream decoupled moderator Monte Carlo model. The side cadmium decoupler material is shown (not to scale) and the location of the cadmium lining the flight path is shown with double-headed arrows.
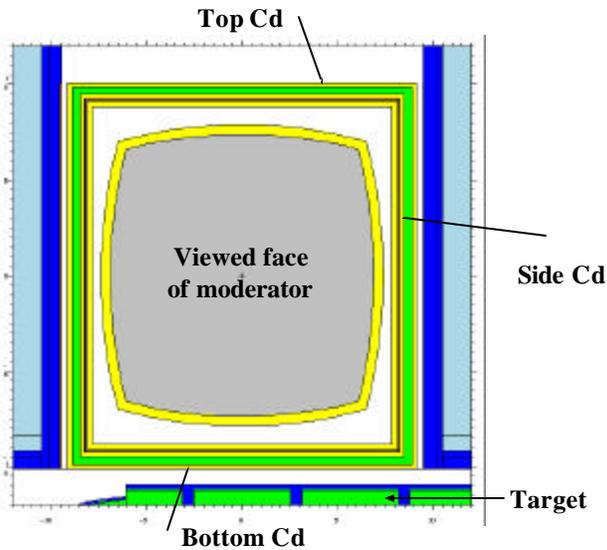

Figure 3. The top upstream decoupled moderator viewed from the front/back. The cadmium inside the cooling water compartment is shown.

An early neutronic model of the moderators used a cadmium thickness of 1 mm and some of our preliminary burnup calculations used this model. The latest design, however, calls for 0.5 mm (0.02 inches) of cadmium decoupler for the moderators. For the flightpath liners, the cadmium thickness is 0.762 mm (0.03 inches). Table 1 presents the cadmium burnup results using these latest values for the cadmium thickness. The numbers quoted in the table are the percentages of ^{113}Cd lost by neutron absorption over a period of three years assuming 5000 hours running time per year.

Table 1. Percentage burnup of ^{113}Cd

Location of Cd	% of ^{113}Cd destroyed
lower outside of moderator	58
first cm of flight path liner	35
side Cd inside water cooling	88
top Cd inside water cooling	75
bottom Cd inside water cooling	134

The calculations that produced these results were conceptually quite simple. We used a steady-state calculation (MCNPX) followed by a linear extrapolation to estimate the burnup, which is changing over the course of time. MCNPX calculates the instantaneous burnup rate of the ^{113}Cd for the initial configuration of fresh material and this estimate is then extrapolated forward in time. Of course, the cadmium composition changes with time, which should be taken into account by approaching the calculation via a succession of appropriately chosen time steps spanning the life of the moderator. This was the approach used in the study that was conducted for the gadolinium poison.[3] Such a calculation is considerably more time consuming and will be carried at a later date. But with the more simple calculations being reported here, the results in Table 1 do indicate that there is a serious issue regarding cadmium burnup for the decoupled moderator. In particular, the prediction that the ^{113}Cd would be completely exhausted inside the premoderator on the bottom of the unit (134%) is a matter for concern.

Following the calculations that produced the results shown in Table 1, a separate calculation was carried out to determine the variation of the burnup rate as a function of height in the side cadmium inside the water cooling layer. The 88% ^{113}Cd burnup for the decoupler along the side of the moderator shown in the table is the average rate, but it can be expected to vary noticeably as a function of moderator height. Our calculation shows that the rate varies from 100% at the bottom to 50% at the top and that it peaks at 114% roughly one-third the distance up from the bottom. This cadmium burnup rate, as a

function of moderator height, is shown in Fig. 4. Figure 4 also shows heat deposition rates as a function of height.
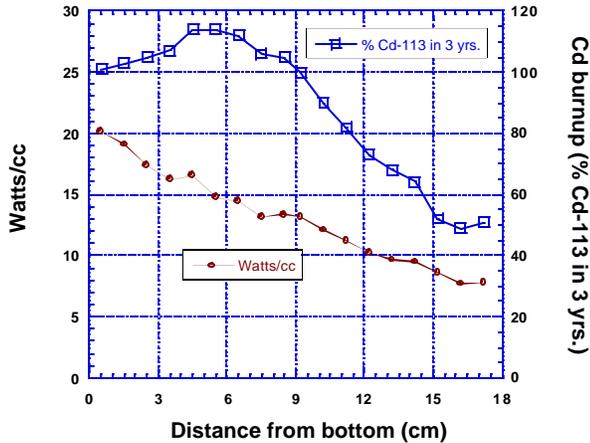

Figure 4. Heating and burnup rates in the inside cadmium decoupler as a function of moderator height.

I. COMPARISON OF CADMIUM BURNUP AND HEATING RATES

The earlier model of the moderators, containing 0.1 cm of cadmium decoupling material, had been used to estimate heating rates in the moderator cadmium. It predicted about 15 Watts/cm^3 for the cadmium decoupler inside the premoderator water and about 13 Watts/cm^3 for the decoupler on the outside surface of the decoupled unit. These values are just volume averages and spatial variations are expected to be significant throughout the volumes in question.

As an adjunct to the burnup calculations discussed here, the spatial variability in the heat-deposition rates for cadmium was also investigated. And, for these newer heating studies, the later design cadmium thickness of 0.05 cm was used. Results are reported per unit volume.

Recall that the cadmium outside the unit is composed of two parts: one at the top and one at the bottom. Using the most recent MCNPX model, heat deposition rates are predicted to be about 7 and 18 Watts/cm^3 respectively for these regions. Again, using the most recent model for the cadmium inside the water cooling layer, the top and bottom surfaces have calculated heat deposition rates of about 8 and 23 Watts/cm^3 respectively.

Heat deposition rates in the cadmium along the sides (inside the water cooling layer) and cadmium burnup as a function of height are shown in Fig. 4. Notice that the heating rate decreases with height as one moves away from the target. However, although the cadmium burnup rate, in general, decreases with height, it peaks at about

one third the distance from the bottom. Peaking is caused by the increase in cold neutron flux as one moves towards the wider part of the liquid-hydrogen compartment. By comparison, heat deposition is caused by more energetic neutrons (and photons) and is therefore not dominated by the cold neutron flux.

II. SUMMARY AND CONCLUSIONS

At the proposed operating power levels at SNS there will be significant depletion of cadmium decoupling material. Simple calculations indicate that with the proposed thickness for cadmium decoupler there will be parts of the decoupled moderator unit where the active cadmium isotope will be completely eliminated over the course of the moderator's lifetime (three years). More detailed time dependent depletion calculations are needed to narrow the uncertainties in these estimates and the heat deposition consequences of increased decoupler thickness need to be assessed.

VI. ACKNOWLEDGEMENTS

REFERENCES

1) Gary J. Russell, Eric J. Pitcher, and Phillip D. Ferguson, Coupled Moderator Neutronics, Proceedings of the Meetings ICANS-XIII and ESS-PM4, PSI Proceedings 95-02, 495 (November 1995).

2) National Spallation Neutron Source Conceptual Design Report, Oak Ridge National Laboratory, NSNS/CDR-2/VI, 1997.

3) E. B. Iverson and B. D. Murphy, Burn-up of Moderator Poison in Pulsed Neutron Sources, Proceedings of the Fourth Topical Meeting on Nuclear Appl. of Accel. Tech., Washington, DC, November 12-15, 2000, ISBN: 0-89448-653-5, pp. 101-108.

4) H. G. Hughes, et al., Recent Developments in MCNPX, Second International Topical Meeting on Nuclear Applications of Accelerator Technology, September 20-23, 1998, Gatlinburg, Tennessee, p. 281.