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ABSTRACT

The Spallation Neutron Source (SNS)[1] to be built at the Oak Ridge National Laboratory will provide an intense source of neutrons for a large variety of experiments. It consists of a high-energy (1-GeV) and high-power (~1-MW) proton accelerator, an accumulator ring**,** together with a target station and an experimental area. In the target itself, the proton beam will produce neutrons via the spallation process and these will be converted to low-energy (<2-eV) neutrons in moderators located close to the target. Current plans are to have two liquid-hydrogen (20-K) moderators and two room-temperature H_2O moderators. Extensive engineering design work has been conducted on the moderator vessels. For our studies we have produced realistic neutronic representations of these moderators. We report on neutronic studies conducted on these representations of the moderators using Monte Carlo simulation techniques.

I. INTRODUCTION

The work reported here concerns the updated moderator designs for the SNS target, and it discusses estimates of the neutron flux and energy-deposition rates for these moderators. These updated designs were those in effect in the fall of 1998. Further updates to those designs are being considered. The updates should not change these results in principle. All results discussed in this paper were obtained from Monte Carlo calculations using the code MCNP.[2] The study area for the Monte Carlo simulations included the target material itself (mercury), the reflector and cooling materials (lead and heavy water), the moderator containers, the beam channels, and the beam tubes.

Calculations reported here are based on a 1-mA beam of 1-GeV protons on target (i.e., 1-MW). Where neutron fluxes are discussed, they are quoted as neutrons per proton per eV per cm^2. Thus, they are independent of beam current, and the actual fluxes at various beam currents can be calculated by using the appropriate normalization factor. These results would not apply, however, if the proton beam energy is different than 1 GeV. Where energy-deposition rates in moderator vessel materials are discussed, they are specifically for a 1-mA beam of protons on target. For different beam currents, calculated energy-deposition rates should be multiplied by the beam current in milliamperes.

The following subject areas are discussed below:

1. The addition of "engineering-relevant" moderators to the target design. Engineering-relevant refers to moderators whose neutronic geometry design closely matches current engineering designs. These designs are to be contrasted with earlier moderator designs where more schematic rectangular box designs were used.

2. Calculated neutron fluxes from the front faces of the new moderators and their comparisons with fluxes from the earlier moderator designs.

3. Calculated energy deposition rates in the new moderators.

II. ENGINEERING-RELEVANT MODERATORS

The SNS target area contains two liquid-hydrogen moderators above the mercury target and two ambient water moderators below the mercury target.

The liquid-hydrogen moderators are more complicated than the ambient water moderators. The liquid hydrogen itself is contained in an inner aluminum vessel. This inner vessel is surrounded by a vacuum jacket, which is then surrounded by a helium-containing compartment and, finally, by a water premoderator. The water premoderator does not cover any surfaces through which cold neutrons are viewed. It covers the bottom, top, and side surfaces only. The upstream hydrogen moderator can be viewed from two opposing directions; therefore, premoderator is located on the top, bottom and side surfaces, but there is none on either the front or back surfaces. The downstream hydrogen moderator is of similar construction. Because only one face of the downstream cryogenic moderator is viewed, a design update will include water premoderator on the other face. The work described here was begun prior to this design update.

Figure 1 shows the liquid-hydrogen moderator container (i.e., the moderator vessel itself, together with the surrounding vacuum, helium and premoderator water vessels). The metal containers surrounding these various vessels are composed of aluminum. At the center of the moderator itself is a 0.005-cm-thick gadolinium sheet used to "poison" the moderator. This sheet is vertical and parallel to the long axis of the container. The model also allows for a 0.1-cm-thick sheet of cadmium decoupler on the outside wall of the container. This decoupler is used to cover all except those faces through which neutrons are viewed. It is used to decouple the moderator from neutrons that are slowed down outside the moderator and would likely lengthen the neutron time pulse as a result. The upstream cryogenic moderator is decoupled and poisoned. The downstream cryogenic moderator is neither decoupled nor poisoned. The dimensions of the container shown in Fig. 1 are as follows: 21.6 cm in height (ignoring the various feeder tubes), 18 cm wide, and with a maximum depth of 9 cm between the front and back faces.

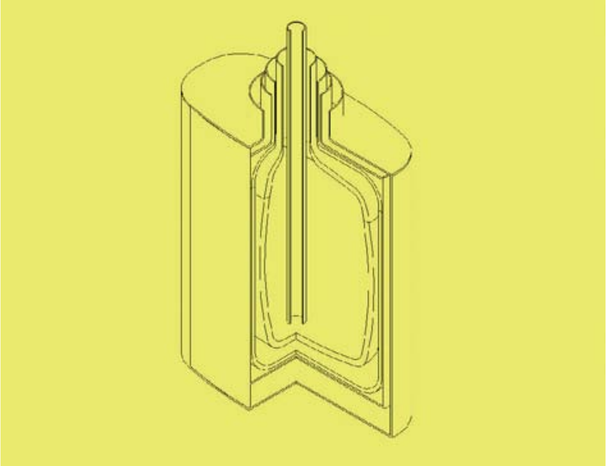

Figure 1. The liquid-hydrogen moderator container. The cutaway section shows the inner cryogenic vessel surrounded by vacuum, helium, and water containers, in order.

This new moderator vessel is larger than that studied previously (see below). Because of the vacuum jacket surrounding the inner liquid-hydrogen container, the latter has curved surfaces, and the front and back surfaces of the outer container are curved in one direction. This new design is also noteworthy in that it includes a water premoderator. Most of the water, as can be seen in Fig. 1, is contained at the bottom of the vessel and therefore sits between the target and the cryogenic moderator material. The bottom premoderator is 2 cm thick. A 0.55-cm layer of water premoderator resides on each side of the vessel, and 0.48 cm of premoderator is located on top. The effect of premoderator thickness is currently being studied.

The ambient water moderators are just replicas of the inner hydrogen vessel shown in Fig. 1. They are also covered with a cadmium decoupler on all surfaces, except those through which neutrons are viewed. Both the upstream and downstream water moderators are decoupled and poisoned.

III. NEUTRON FLUX FROM NEW MODERATORS

In an earlier design configuration,[3] the moderator vessels were of smaller volume than the present designs and the shapes were rectangular. In the earlier design, the volume of the moderating material was 900 ml in all cases. The volume of the new moderator material is 1228 ml for all four cases.

Figures 2 through 5 show the calculated neutron flux through the viewed face of the four moderators. The figures refer respectively to the upstream-cryogenic, the downstream-cryogenic, the upstream-water, and the downstream-water moderators. Simulation results are shown for both the older and the newer moderator designs. Previous studies with the earlier moderator design[3] employed beryllium as the reflector material. In all studies reported here, the reflector material is lead. We do not believe that the trends that are seen in this work would be different with a beryllium reflector.

Note that the ordinate scales are different in Figs. 2 and 3. The coupled unit (Fig. 3) produces considerably more neutrons, and the scales were adjusted for clarity. Both of the ambient moderators (Figs. 4 and 5) are decoupled, and it is therefore appropriate to present them on the same scale. When the moderators are similar, the upstream moderator produces more neutrons; when one is coupled and another is decoupled, the coupled unit produces significantly more neutrons.

Comparisons of Figs. 2 and 3 with Figs. 4 and 5 show that the cryogenic moderators, as expected, produce softer neutron spectra than do the ambient (water) moderators. Because the new moderators are larger, there are larger surfaces facing the beam ports through which neutrons can be viewed and, for this reason, flux per unit area is shown. The new moderators are also thicker than the older ones and, as a result, they may produce higher fluxes per unit area. But, in the new design the moderator vessel itself is not of uniform thickness. The average thickness in the new design is about 11% greater than in the older design. Given the numerical accuracy of the calculations, the increased neutron fluxes seen for the new updated ambient moderators (Figs. 4 and 5) can probably be attributed to the added thickness. The values in Fig. 2 for the new moderator calculation show calculational uncertainties (1 standard deviation). All other calculations have similar uncertainties (as a percentage of the calculated value) at corresponding energy values.

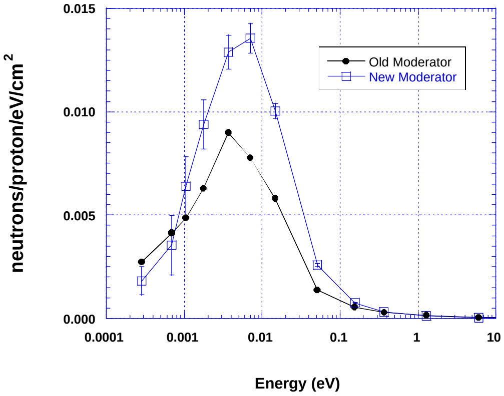

Figure 2. Neutron flux from the front face of the upstream (decoupled) cryogenic moderator vessel. The new design is the one shown in Fig. 1, and it is compared with a previous older design that did not include premoderator material. The uncertainty in the calculations (1 standard deviation) is indicated for the new moderator, which is typical of the uncertainties in all other cases.

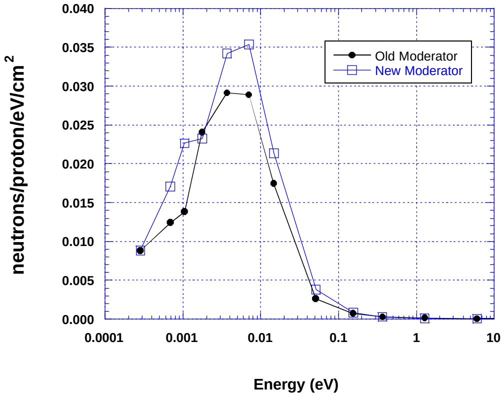

Figure 3. Neutron flux from the front face of the downstream (coupled) cryogenic moderator vessel. Results for both old and new designs are shown.

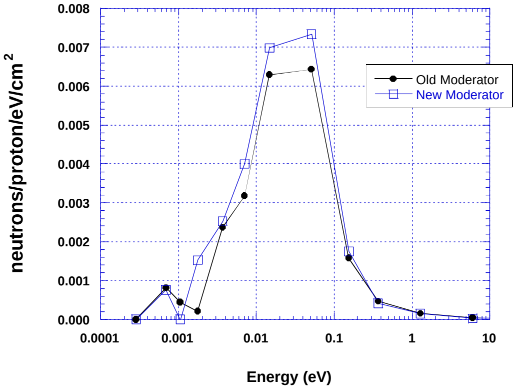

Figure 4. Neutron flux from the front face of the upstream ambient (water) moderator in the case of both the old and new designs.

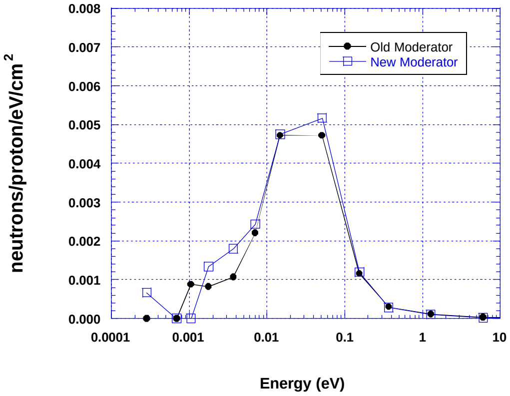

Figure 5. Neutron flux from the front face of the downstream ambient moderator for both old and new designs.

The cryogenic moderators present a more complex set of results. Figures 2 and 3 show clearly that the new designs produce larger neutron fluxes; however, the flux increase seems larger than might be expected from the moderator size effect alone. This is certainly true in the upstream case (Fig. 2). The downstream case is not as marked. Much of the increase in neutron flux is likely caused by the presence of the premoderator. This premoderator is expected to increase the efficiency of these moderators, and, indeed, this increase is evident for the upstream unit (Fig. 2). In the downstream case (because it is coupled) the situation is more complicated. In the coupled case, the side premoderator is likely to be of greater importance; and in the design it is only about 25% the thickness of the bottom premoderator. In summary, it seems that the new designs produce more neutrons because of their added size and the premoderators in the cryogenic units are noticeably increasing the efficiency of those particular moderators.

IV. ENERGY DEPOSITION IN MODERATOR VESSEL MATERIALS

For purposes of determining the heat load on the moderators, energy-deposition calculations were carried out for the components of the moderator containers. The energy- deposition results presented here (from both neutron and gamma radiation) are for a 1-mA beam of 1-GeV protons incident on the mercury target.

Recall that the cryogenic moderators are constructed as follows as one proceeds from the inside outwards: the liquid hydrogen moderator material, a surrounding aluminum wall, a vacuum compartment, a surrounding aluminum wall, a helium compartment, a surrounding aluminum wall, the water premoderator and a final surrounding aluminum container. The water premoderator is on the top, bottom and sides of the structure so that, on the front- and back-viewed faces, the aluminum wall surrounding the helium is also the outside wall of the container. Parts of the outside of the container are also covered with cadmium decoupling material. The cadmium does not cover any of the viewed faces, and there is no cadmium decoupler in use on the downstream cryogenic moderator. In the case of the upstream cryogenic unit, there is also a strip of gadolinium poisoning material inside the liquid hydrogen container itself.

The ambient (water) moderator vessels are composed of the water moderator material surrounded by an aluminum wall, and this structure is an exact replica of the inner moderator compartment in the cryogenic units. Both the upstream and downstream ambient moderators are surrounded by cadmium (but not on any of the viewing faces), and both have a strip of gadolinium poison in the water moderator.

Tables 1 and 2 give energy-deposition rates for the cryogenic and ambient moderators, respectively. They show energy-deposition rates in the various components of the moderator vessels. The energy-deposition calculations are stochastic. To emphasize this fact we quote, at most, two significant figures in reporting the results. From Tables 1 and 2, the following general conclusions can be drawn: The energy-deposition rate in any one moderator vessel is at most on the order of a few kilowatts. Comparison of upstream and downstream units for both the cryogenic and ambient cases shows that, to a rough approximation, about twice as much energy is deposited in each upstream structure component as compared with its downstream counterpart. Where cadmium shields exist, they account for a significant fraction of the total energy deposition. We note in Table 2 that there is roughly 50% more energy deposited in the cadmium shield in the downstream case as opposed to the upstream case. This would seem to contradict the statement that, component-for-component, the upstream structures experience more heat deposition. Recall, however, that the cadmium decoupler on the downstream water moderator is larger than its upstream counterpart. Specifically, because the back face of the downstream water moderator is not a viewing face, it is covered with cadmium, with reflector material located directly behind.

Table 1. Energy-deposition rates in cryogenic moderator vessels

Structure component	**Upstream unit (kW)**	**Downstream unit (kW)**
Liquid hydrogen	0.6	0.36
Gadolinium poison	0.01	NA
Aluminum	0.15	0.07
Vacuum	NA[a]	NA[a]
Aluminum	0.14	0.07
Helium	0.03	0.02
Aluminum	0.08	0.04
Water premoderator	0.9	0.4
Aluminum	0.05	0.03
Cadmium	2.2	NA

[a] Not applicable.

Table 2. Energy-deposition rates in ambient moderator vessels

Structure component	**Upstream unit (kW)**	**Downstream unit (kW)**
Water	1.6	0.94
Gadolinium poison	0.01	0.01
Aluminum	0.2	0.1
Cadmium	1.9	2.9

The total heat deposition in the upstream cryogenic moderator unit is about 4 kW, and in the downstream unit it is about 1 kW. However, of the 4 kW going to the upstream unit, about 2 kW is accounted for by the cadmium decoupling material, which is not present in the downstream unit. The total heat load in the case of the upstream water moderator is about 3.7 kW and in the case of the downstream water unit it is slightly higher at about 4 kW.

However, almost 3 kW of the 4 kW going to the downstream unit is accounted for by the cadmium. In the case of the upstream water unit, almost 2 kW is accounted for by its (somewhat smaller) cadmium decoupler.

Heat deposition in the liquid hydrogen and the surrounding aluminum wall will be handled by the liquid-hydrogen refrigeration system. The heat load in the remainder of each cryogenic unit will be handled by the circulating premoderator water. Heat loads in the ambient units will be handled by the circulating moderator water. The calculated heat loads shown above are within the capabilities of the cooling systems envisioned for these moderator designs.

V. DISCUSSION

Updated moderator-vessel designs have been investigated for the Spallation Neutron Source to be built at Oak Ridge National Laboratory. Specifically, the low-energy neutron spectra and energy-deposition rates in moderator-vessel materials were examined. Results are consistent with expectations and previous experience. The addition of water premoderator material appears to increase the efficiency of the cryogenic moderators. Heat loads in the moderators can be handled with current cooling system designs.

ACKNOWLEDGEMENTS

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