JAERI-Conf 2001-002

ICANS-XV
15th Meeting of the International Collaboration on Advanced Neutron Sources
November 6–9, 2000
Tsukuba, Japan

18.4 Neutronic Performance Issues for the Spallation Neutron Source Moderators

E. B. Iverson,* B. D. Murphy

Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, TN 37831
*E-mail: iversoneb@sns.gov

1 Introduction

We address recent progress in the continued neutronic design of the Spallation Neutron Source Target Station as regards moderator performance. The Spallation Neutron Source Target Station will receive 2 MW of 1 GeV protons at 60 Hz. This level of proton power offers unprecedented neutronic performance for pulsed neutron production for time-of-flight neutron scattering, as well as unprecedented challenges in providing said performance. We report on the predicted performance of the moderators for SNS, the results of recent design optimization studies, and some of the special design challenges that have come about for this target station, such as poison burnup in poisoned moderators and composite moderators.

2 SNS Moderators

The Spallation Neutron Source moderator suite has changed somewhat recently. We have replaced the (bottom upstream) composite moderator with a conventional water moderator, and replaced the existing (bottom downstream) water moderator with an additional coupled hydrogen moderator. These changes are partially in response to evolving instrument demands, and partially due to a greater understanding of the composite moderator performance. Table 1 shows intensity metrics for the moderator suite, both before and after this most recent change.

The composite moderator was found to be an undesirable match to the neutron scattering instruments currently being designed for SNS. We have therefore replaced it with a more conventional liquid water moderator in the bottom upstream position, where it will serve eight beamlines (four off of each side). As our design progresses, this moderator may be assymetrically poisoned. We discuss the composite moderator in greater detail below. The existing (bottom downstream) water moderator has been changed to a coupled liquid hydrogen moderator, reflecting the ever-increasing demands on the SNS instrumentation design efforts for lower-resolution flux-limited applications requiring cold neutrons.

3 Composite Moderator Performance

High-power spallation neutron sources such as SNS have large radiation damage rates on most of the neutronically significant components, including the moderators. This fact is espe-

Table 1: Intensities from the previous and current SNS moderator configuration.

Moderator	$Ei(E)\|_{1eV} = I_{epi}$ (n/ster/pulse ± %)	kT (eV ± %)	R (Ratio ± %)
previous			
H_2O BD	0.86×10^{12} ± 2.1	0.0394 ± 1.2	4.89 ± 2.8
Composite BU	1.66×10^{12} ± 3.6	0.0168 ± 2.7	4.16 ± 4.9
Coupled TD	0.94×10^{12} ± 4.3	0.0066 ± 2.2	9.80 ± 5.2
H_2 TU	1.10×10^{12} ± 2.0	0.0067 ± 2.3	1.28 ± 3.6
current			
Coupled BD	0.94×10^{12} ± 4.3	0.0066 ± 2.2	9.80 ± 5.2
H_2O BU	1.70×10^{12} ± 3.6	0.0344 ± 0.9	4.18 ± 1.3
Coupled TD	0.94×10^{12} ± 4.3	0.0066 ± 2.2	9.80 ± 5.2
H_2 TU	1.10×10^{12} ± 2.0	0.0067 ± 3.1	1.05 ± 3.6

cially significant for moderators composed of liquid methane. In the liquid state (around 100 K) methane suffers from severe problems with radiation-induced polymerization, to such a level that the highest-power existing spallation sources must significantly limit the lifetime of their liquid methane moderator vessels, imposing significant constraints on operational strategies for the facility. [1] At damage rates present in SNS the use of liquid methane does not currently appear to be practical, even though it provides performance characteristics generally agreed to be highly desirable. As no practicable means to use liquid methane at SNS-like damage rates is known, we have explored an alternative moderator concept, the hydrogen-water composite moderator, as a surrogate for liquid methane on high-power spallation neutron sources which would be tolerant of radiation, given that neither hydrogen nor water are significantly subject to radiation damage. Although the inspiration and initial goal of our explorations was to investigate the composite moderator as a surrogate for liquid methane, we also consider it as a new type of moderator, one which has its own unique performance characteristics, and may be desirable in its own right.

In general, we can then list a number of characteristics we would like to obtain from a composite moderator intended as a surrogate for liquid methane:

- narrow pulse shapes in the slowing down region ($\delta t \cdot v \approx 28$ mm for both water and liquid methane),
- narrow pulse shapes, relatively invariant with energy, in the thermalized region, for which the width is controllable with appropriate poisoning ($\delta t \approx 30$–60 μs for water and liquid methane, depending on poison depth),
- slowing-down-to-thermal transition energy similar to that of liquid methane (30 meV),
- pulse shapes with sharp rising edges,
- exponentially decaying tails no worse than water or liquid methane ($\tau \approx 20$–40 μs for water and liquid methane, depending on poison depth), and
- more low-energy neutrons.

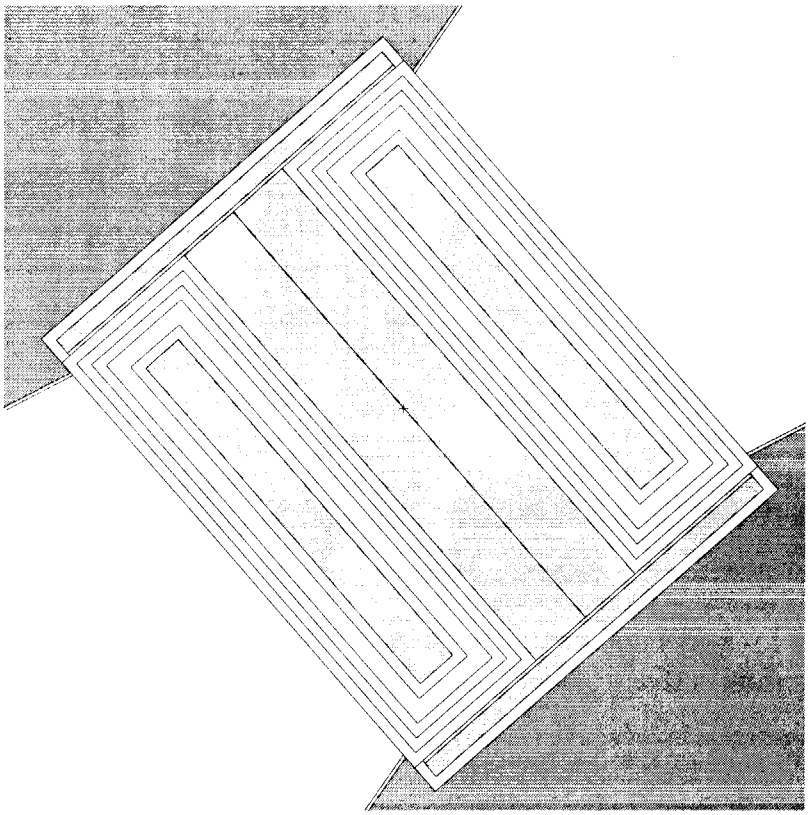
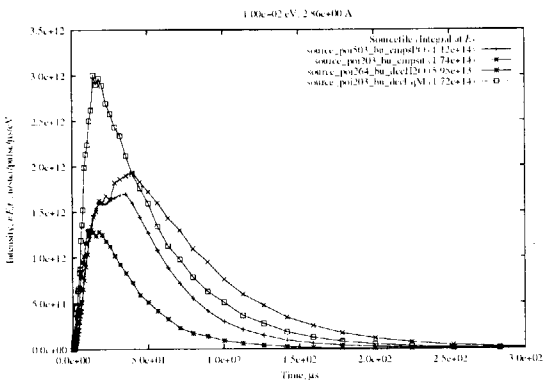


Figure 1: Composite moderator configuration. The viewed layers are supercritical hydrogen, the central region is liquid water. The central line shows the base configuration poison location.

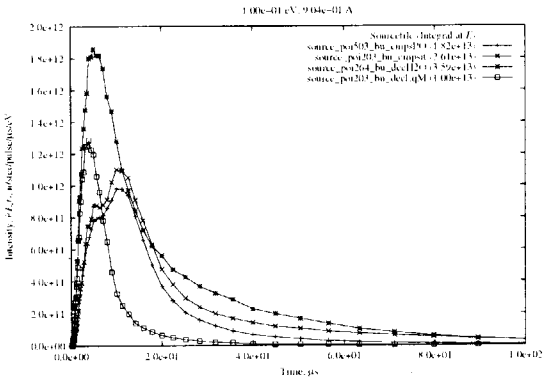
3.1 Composite Moderator Description

Our concept for a hydrogen-water composite moderator is one in which the viewed face of the moderator is a thin layer of hydrogen at 20 K, closely backed by a fairly thick layer of water at 300 K. As this water layer is optically thick, and would quite likely be poisoned for pulse width control, the moderator can be arranged symmetrically, as shown in Figure 1, where hydrogen layers form each viewed surface.

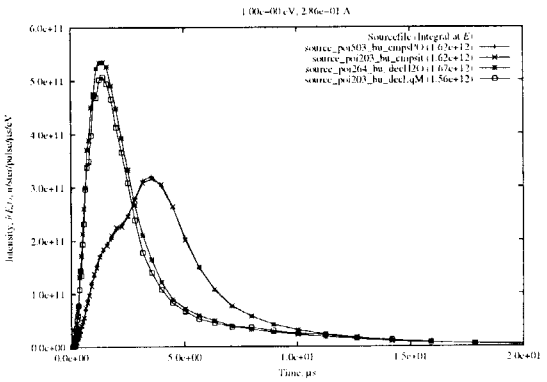
In the composite moderator configuration shown in Figure 1 each viewed face is a 12.5 mm-thick layer of supercritical hydrogen. Each hydrogen layer is closely backed by a central layer of water 37.5 mm thick at 300 K. The moderator is decoupled with cadmium from the reflector. The studies reported here examine two poisoning configurations, one without poison, and one with poison in the center of the water region, some 18 mm beneath the surface of the water layer, and thus some 31 mm within the "moderator material region" of the assembly. Other poison configurations have been studied; comparisons between different poison scenarios for the composite moderator appear elsewhere. This geometry of hydrogen and water was developed as part of an optimization process in which the spectrum of the composite moderator was made, as much as possible, similar to that of a nominal liquid methane moderator. [2]



(a) 10 meV; all moderators thermal.



(b) 100 meV; composite/H_2O thermal, CH_4 slowing-down.



(c) 1 eV; all in slowing-down region.

Figure 2: Emission time distributions. Poisoned composite is **cmpsPO**, unpoisoned composite **cmpsit**, water **decH2O**, and methane **decLqM**. $\Delta E/E \approx 23$ %.

3.2 Simulation Results

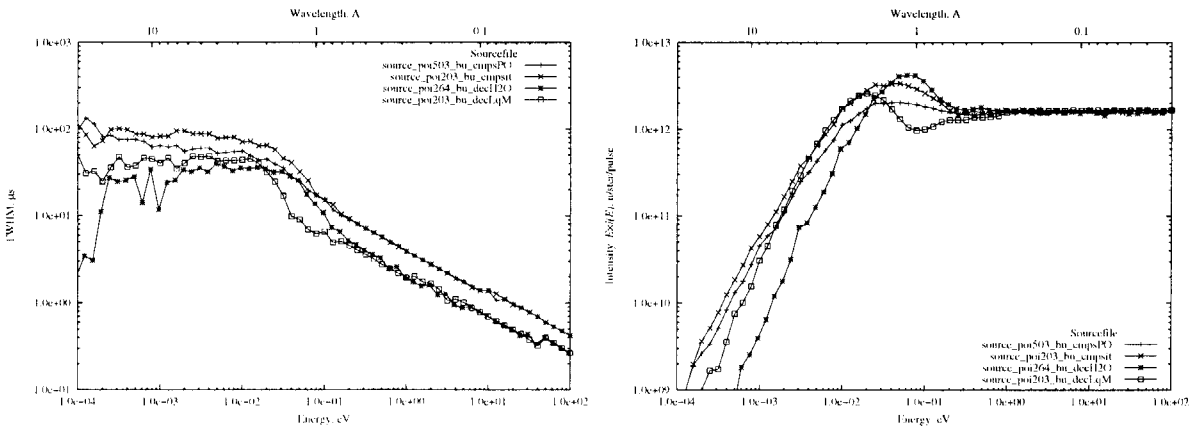
Figure 2(a) shows the pulse shapes calculated for 10 meV neutrons, well within the thermalized region for both water and methane moderators. It is immediately apparent that the composite moderator has a significantly broader pulse shape than either water or methane, although the degree of that increase depends upon the poisoning. Although the unpoisoned composite moderator intensity at 10 meV is identical to that of the methane moderator, the increased width also implies a decrease in peak intensity, by definition an undesirable effect. Furthermore, the nature of the peak intensity is somewhat different for the composite, in that there is a broad plateau region, not very useful for precise position location.

Figure 2(b) shows pulse shapes calculated for 100 meV neutrons, within the thermalized region for a water moderator but not for a methane moderator. The composite moderator, whether poisoned or not, seems to clearly display the undesirable characteristic signs of thermalization—a relatively broad, slowly decaying pulse, along with significantly less intensity, both peak and averaged, than the also-thermalized water moderator. Even though the composite has 2–3 times the averaged intensity as the methane moderator, the peak intensity for methane is still higher.

Finally, we see that the plateau in the peak intensity region observed at lower energies has now resolved itself into a "double-peak" structure, representing an extremely difficult pulse shape to parametrically describe.

Figure 2(c) shows the pulse shapes calculated for 1 eV neutrons, within the slowing-down region for all moderators. The water and methane pulse shapes appear to be functionally identical, as expected. The composite pulse shape on the other hand is extremely unpleasant. At 1 eV the (gadolinium) poison is of course no longer relevant. Although the time-averaged intensity is equivalent for all moderators, the pulse shape for the composite is significantly broader than for water or methane, leading to a significant reduction in peak intensity. This is somewhat un-intuitive, as one might think of a composite moderator in a homogenized sense, having a hydrogen density somewhat between that of water and liquid hydrogen, and thus a slowing-down time behavior somewhat between that of water and hydrogen. However, the oddly-shaped pulse shape observed above is still present. Furthermore, we can now easily note that the rising edge of the pulse shape is significantly slower than that of water or methane; in fact, it is nearly identical to that of liquid hydrogen.

Figure 3(a), showing the pulse width (FWHM) as a function of energy, further demonstrates the onset of thermalization in the composite moderator, as indicated by the sharp increase in pulse width, at energies very similar to that for water rather than methane. Additionally, the composite moderator in general gives significantly broader pulse shapes overall, even in the typically narrow slowing-down region. Finally, we can see that the low-energy-asymptotic behavior of the pulse width provides additional indication that the composite moderator is a "thermalizing" moderator. Figure 3(b), however, shows that the composite moderator, while



(a) Pulse widths.

(b) Intensity per unit lethargy.

Figure 3: Characteristics of compared moderators. The poisoned composite is denoted source_poi503_bu_cmpsPO, the unpoisoned composite source_poi203_bu_cmpsit, the poisoned water source_poi264_bu_decH2O, and the poisoned liquid methane source_poi203_bu_decLqM. Statistics are poor at low energies.

having quite good time-averaged intensity (always superior to methane while competing very well with water), does not have a characteristic Maxwellian shape, and thus might not be considered a thermalizing moderator by most definitions.

3.3 Experimental Verification

In many ways, the simulations of the composite moderator are probably the most challenging pulsed moderator simulation that we've ever attempted. Furthermore, the importance of the composite moderator for SNS is quite large, even though it is somewhat untested technology. We have performed experiments [3] at the Hokkaido University in Japan on a prototype composite moderator with the goal of answering two main questions:

- The composite moderator simulations show very broad pulse shapes, even at slowing down energies. Current tallies (such as we use to calculate pulse shapes) are known to artificially broaden the pulse shapes when they are significantly displaced from the moderator material surface. Could the broader pulses we observe be due to an artifact of an unusually complicated moderator geometry?
- The composite moderator seems to display an unusual "double pulse" behavior. Broad energy bands in the simulation (necessary to achieve reasonable statistics) are known to smear high-resolution features. Could the double pulse behavior in a real system be even worse than our prediction?

While in general we would like to validate or benchmark our overall simulation strategy, our specific needs, met by the work described in [3], is to gain insight into these two characteristics we predict for the composite moderator. Our experiments, while they do point out some deficiencies in our calculations, do provide answers to the questions above. First of all, the composite moderator pulse shapes are indeed quite broad. Second, we find no evidence of a double pulse shape at energies that would be propagated through a curved neutron guide, given the finite proton pulse width expected in a high-power spallation source. We refer the reader to [3] for further details.

3.4 Discussion

If we consider again the desiderata mentioned earlier, we find that the composite moderator performance is not particularly satisfactory. Although it does match the low-energy intensity of liquid methane, and even further provides (at least in the design phase) some capability for tuning of the spectral intensity as a function of energy, the characteristic performance of the moderator is much more like that of water, with some of the undesirable characteristics of liquid hydrogen, as well as some unique undesirable tendencies.

The composite moderator:

- displays broader pulse shapes at all energies than either water or methane,
- transitions to a thermalization regime like water,
- has slow rise times like liquid hydrogen, and
- displays a moderately bimodal pulse shape at medium-to-high energies.

As a result, higher resolution information (in scattering experiments using a composite moderator) will not be present, and the pulse shapes at shorter wavelengths will be very difficult to fit.

Although a detailed analysis of the serviceability of the composite moderator is beyond the scope of this document, there are some conclusions that seem inescapable. First of all, the composite moderator does not mimic liquid methane. The slowing-down properties, thermalization

properties, and general pulse shape characteristics are fundamentally different. Furthermore, the composite moderator performance displays very few canonically desirable features, and even then only the somewhat less important ones. It seems likely that any scattering instrument design effort seeking moderate-to-high resolution would choose water or liquid hydrogen, already available elsewhere in the SNS facility, rather than choosing the composite moderator.

4 Poison Burnup

The moderators in a pulsed spallation neutron source are by design the locations with the highest thermal neutron flux in the entire system. At the same time, these moderators often include poisons, such as cadmium or gadolinium, in order to tailor the dynamic performance of the moderators to meet desired characteristics. The Spallation Neutron Source, currently under construction at Oak Ridge National Laboratory, will have thermal neutron fluxes more than an order of magnitude greater than any existing pulsed spallation source, and thus the depletion rate within these high-cross section absorbers becomes of significant interest in the design process.

Existing pulsed source moderators have poison plates that might typically be on the order of 40 μm of gadolinium metal or the equivalent. These poison plates serve to tune the time-response characteristics of the moderator to match the applications served by that particular moderator. Design calculations for SNS indicate that such a poison plate will be significantly depleted after some 1000 hours in a megawatt-class spallation source. Of course, consistency of performance is a watch-word in a large facility of this sort, and significantly less than total burn-up might still be enough to lead to significant performance changes. Thus, realistic lifetimes, given a nominally desired poison thickness of 40 μm, might be far less than the quoted 1000 hours. Such a short lifetime presents a problem for facility usability. As an example, the ISIS facility methane moderator is typically changed on the order of every 2000 hours (although for different reasons); this rapid replacement schedule is regarded by ISIS operations and instrument personnel as a rather significant drawback. Furthermore, the moderator vessels in SNS are part of the "inner plug" assembly, which also includes some portion of the reflector, and has desired lifespan of three years (15000 operational hours). Reducing the lifetime of the inner plug assembly (at greater than one million dollars per copy) so dramatically would be a very significant engineering decision.

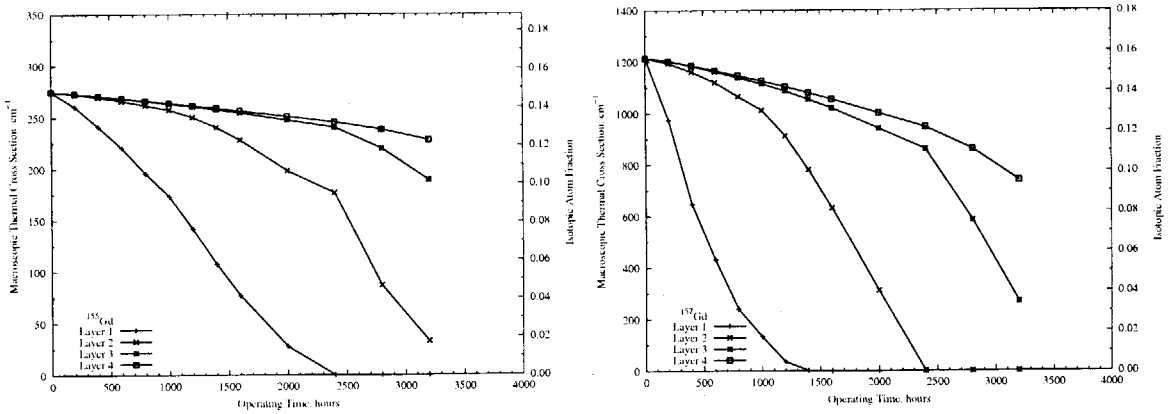
The obvious answer—to increase the thickness of the poison plate to meet the desired lifespan characteristics—may present significant compromises in performance. Preliminary estimates have indicated that a reduction in moderator intensity of some 30% may accompany the thickening of the gadolinium poison layer by the amount required. While this is, to be sure, undesirable, it is perhaps more important to consider the change over time in the performance of the moderator. If the thicker poison sheet can be designed to have constant, although reduced, performance over the life of the moderator, then such a compromise might be acceptable.

All of our calculations for this study are based on the top upstream (hydrogen) moderator. Our conclusions can be extended to other moderators (for example, a decoupled poisoned water moderator) via simple scaling factors. For these calculations, the poison plate in the top upstream moderator is separated into seven layers, each one 20 μm thick, for a nominal poison plate thickness of 140 μm. The top upstream moderator is cadmium-decoupled hydrogen at 20 K and has curved viewed surfaces. The moderator material has a maximum thickness of 65 mm, and an average thickness of about 55 mm. The moderator is poisoned with the afore-mentioned gadolinium at the centerline and is viewed from both sides.

4.1 Poison Depletion Calculations

Following the levels of the poison isotopes in a gadolinium poison plate is a fairly standard buildup-depletion process. In this particular case, it is especially simple, as there is no meaningful buildup of neutronically significant material, nor is there any radioactive decay with which to be concerned. Thus calculating the change over time in the isotopic makeup of the poison plate is merely a matter of calculating burn-up rates for the neutronically-significant isotopes in gadolinium (^{155}Gd and ^{157}Gd), multiplying these reactions by a reasonable length of time, substituting the product isotopic abundances for the poison abundances in the appropriate amount, and iterating over the length of time of interest. For the SNS characteristics, we chose a layer thickness of 20 μm and an initial time-step of 200 operating hours.

The isotopic makeup of the resulting poison plate layers appears in Figure 4, and the neutronic properties in Figure 5. The data clearly show that, over the course of about 1500 hours of



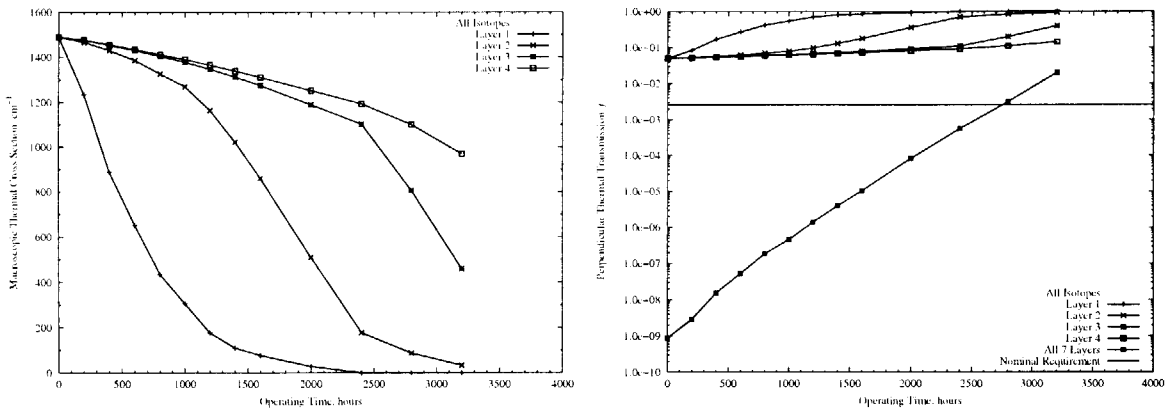
(a) ^{155}Gd abundance and macroscopic cross section.

(b) ^{157}Gd abundance and macroscopic cross section.

Figure 4: Abundances and cross section contributions in depleted gadolinium plates. Cross sections for 0.0253 eV.

operation, the outermost 20 μm of the poison plate is completely depleted in ^{157}Gd and mostly depleted in ^{155}Gd. In fact, closer examination of Figure 5(b) indicates that there is a "burn-in" period, during which the isotopic profile of the "surface layer" of the poison changes from the natural abundances as different isotopes burn at different rates. This burn-in period, which lasts about 800 hours, is followed by more uniform loss in effective thickness (as measured by the nominal perpendicular transmission, defined here as f). This uniform loss in effective thickness appears to persist for long times, as long as the depleted poison plate can be considered black. Figure 5(b) dramatically shows this depletion. Extrapolating the perpendicular transmission of the 7-layer structure, we can predict that a poison plate of 140 μm original thickness will become less effective than the 40 μm nominally required after about 2800 operating hours, and will be essentially gone within 4000 operating hours.

This rate of burn-up could be interpreted as a reduction in effective poison plate thickness by a constant amount per unit time. The above numbers would indicate that 50 μm of thickness is effectively lost off of each face of the poison plate after 2800 hours. Thus, if we wish to have a poison plate last 15000 hours, each face will lose 270 μm, and the initial thickness must be at least 580 μm in order to provide the equivalent of 40 μm at the end of life.



(a) Total macroscopic cross section.

(b) Nominal perpendicular transmission.

Figure 5: Neutronic characteristics of depleted gadolinium layers. Cross sections are for 0.0253 eV.

Formalizing this relationship, an exponential fit

$$f(T) = f_{\mathrm{b}} e^{\left(\frac{T - T_{\mathrm{b}}}{\tau}\right)} \tag{1}$$

to the latter portion of the transmission of all seven layers of the depleting poison plate, as shown in Figure 5(b), gives an e-folding time of $\tau = (206 \pm 4)$ hours. The transmission at the end of the burn-in period $T_{\mathrm{b}} = 800$ hours is $f_{\mathrm{b}} = (1.8 \pm 0.4) \times 10^{-7}$, and the effectiveness of the poison plate decreases over the burn-in period T_{b} by a factor of $f_{\mathrm{b}}/f_0 = (195 \pm 10)$. We can outline a simple procedure for predicting the thickness required to reach a certain lifetime over which the poison effectiveness meets a certain requirement. Given a required effectiveness f_{r} and a required lifetime T_{r}, the effectiveness at T_{b} must be

$$f_{\mathrm{b}} = f_{\mathrm{r}} e^{-\left(\frac{T_{\mathrm{r}} - T_{\mathrm{b}}}{\tau}\right)}, \tag{2}$$

and the initial effectiveness

$$f_0 = \left(\frac{f_0}{f_{\mathrm{b}}}\right) f_{\mathrm{r}} e^{-\left(\frac{T_{\mathrm{r}} - T_{\mathrm{b}}}{\tau}\right)}. \tag{3}$$

The ratio of the initial thickness t_0 to the nominally required thickness t_{r} is

$$\frac{t_0}{t_{\mathrm{r}}} = \frac{\ln f_0}{\ln f_{\mathrm{r}}}. \tag{4}$$

If we seek a 15000 hour lifetime for the poison plate, we then require an initial poison plate thickness 13.4 times that of the nominal minimum thickness of 40 μm; that is, we require an initial poison thickness of 540 μm, very similar to the 580 μm from our less formal estimation.

We have so far assumed that the conventional 40 μm thickness represents a requirement—a minimum below which we dare not go. It is also possible that the typical 40 μm thickness historically used at pulsed neutron sources is overly conservative. If we were to instead assume that a poison plate entirely depleted in ^{157}Gd and nearly depleted in ^{155}Gd would still provide

the necessary neutronic effect we could claim, based on Figure 4, that the first layer of poison is adequate until around 2000 hours, when the ^{155}Gd abundance has fallen to approximately one eighth of its original value and the ^{157}Gd abundance is negligible. If each 20 μm layer is adequate for 2000 hours, we would require 7.5 such layers for the initial half-thickness of the poison plate; a total thickness of 300 μm.

Our most conservative depletion calculations show that the gadolinium poison plate suffers a loss in effective thickness of 180 μm (90 μm from each face) over the course of 5000 hours (the nominal operating time in one calendar year). Given a desired lifetime for the moderator of three years, this implies that an initial poison thickness of 580 μm will provide the equivalent effectiveness of 40 μm of un-depleted gadolinium at the end of the moderator lifetime. A less conservative, perhaps more realistic analysis might indicate that an initial thickness as low as 300 μm would serve our purposes. In either case, it is clear that the three-year lifetime desired for the moderator will require significantly thicker poison plates than have conventionally been used. As mentioned previously, these calculations are for a decoupled, poisoned hydrogen moderator. Moderators with different spectral temperatures or different thermal integrals would deplete poison plates at different rates, even in the same nominal position relative to the spallation target. We suggest that a scale factor of the thermal flux integral, weighted by a non-$1/v$ factor to account for differences in spectral temperature, would adequately predict depletion rates in other moderators. For any reasonable poisoned moderator, such a factor will likely never exceed five or so. We note that a factor of five, say for a high-intensity water or liquid methane moderator, would represent another enormous jump in required poison lifetime.

4.2 Performance Impacts of Poison Plate Depletion

The initial gadolinium poison plate thickness required, as determined by the calculations described in the previous section, is more than an order of magnitude larger than what is typically used in pulsed spallation source moderators. As gadolinium does have substantial resonance absorption, as well as a cutoff energy which is somewhat dependent on the exact thickness of a poison plate, conventional wisdom has dictated that the poison plate should be kept as thin as possible. We have therefor calculated the effect of thicker poison plates on the performance of the moderator in question.

Figure 6 shows the spectral intensity of the moderator for different poison thicknesses at the beginning of life, overlaid with the microscopic cross section for natural (i.e., fresh) gadolinium. The thickness of the poison plate ranges from the nominal minimum of 40 μm to 1400 μm, thicker than we hope will be necessary to meet the desired three year lifetime. It is clear that resonance capture in the poison material significantly depresses the flux near resonance energies, resulting in a significantly reduced moderator brightness at the energies below said resonances. In other words, each time the mean energy of the neutron field within the system "passes" the energy of a resonance as the neutrons slow down, resonance absorption bleeds off a certain fraction. By the time the neutrons have slowed down past the last distinct resonances in the gadolinium cross section, this effect has resulted in a loss of more than 10% in moderator brightness for a 1400 μm poison plate as compared to a 40 μm poison plate (at 1 eV). Increasing the thickness of the poison plate also shifts the effective cutoff energy slightly higher, resulting in the most significant impact on the spectral intensity occurring at energies near that cutoff, nominally around 200 meV. Again for the case of 1400 μm and 40 μm poison plates, this results in an intensity loss of more than 20% at 200 meV. Finally, at energies well below the gadolinium cutoff, the moderator suffers a fairly uniform loss in intensity of 16–18%. The specifics of the gadolinium cross section thus dictate not only a loss in intensity, but an energy-dependent loss.

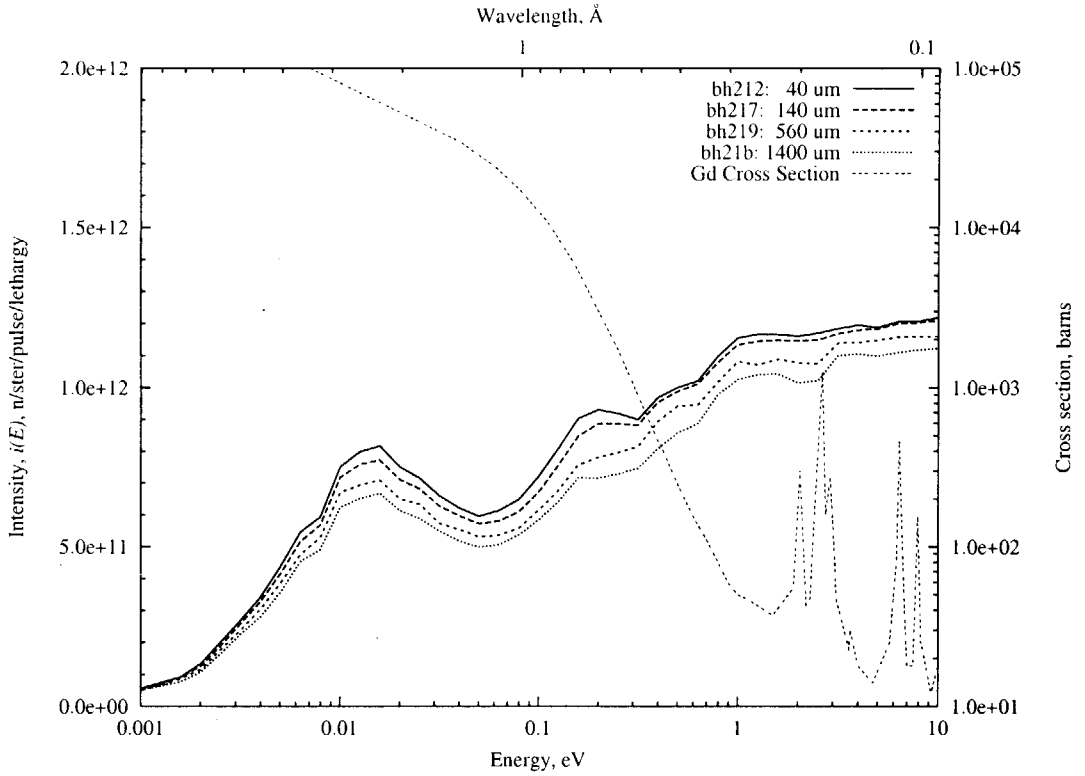


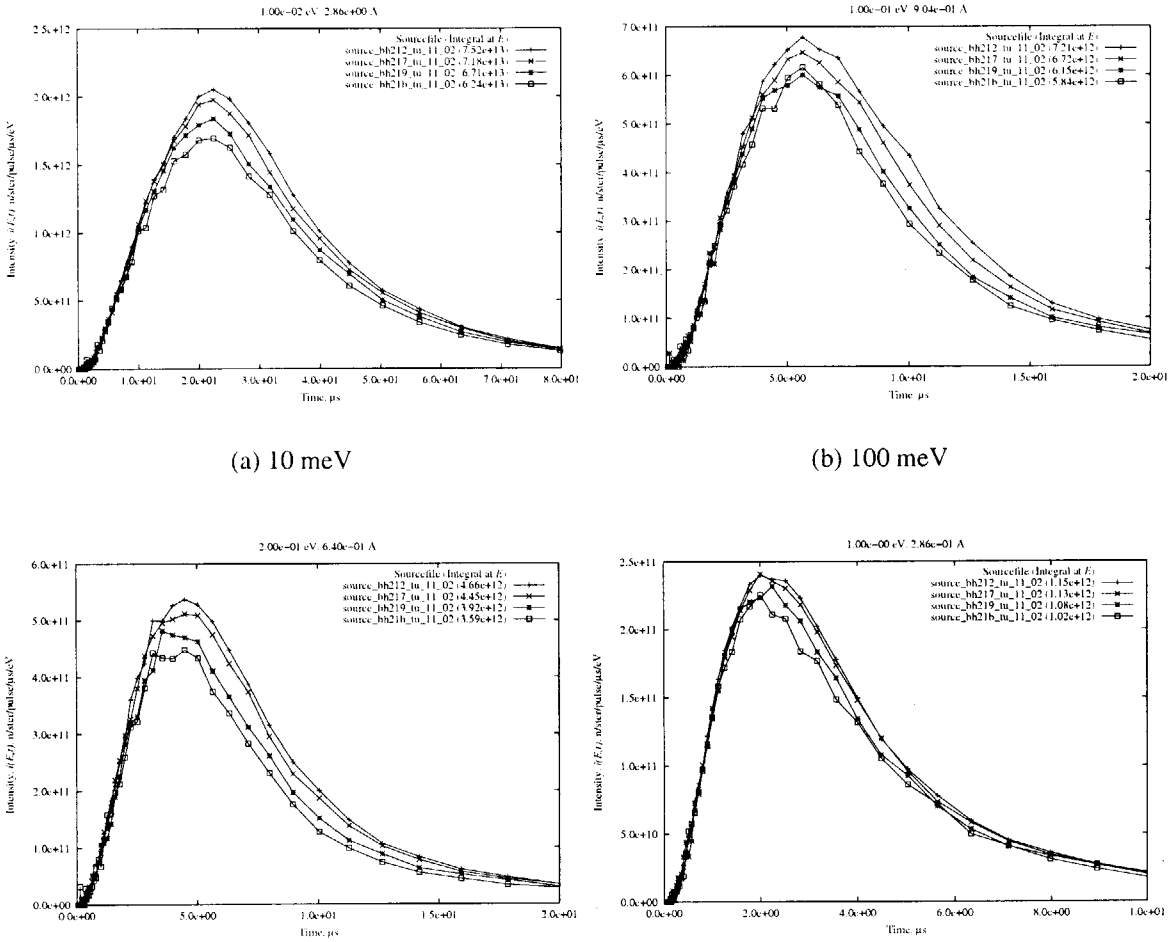
Figure 6: Moderator spectra for different (fresh) poison plate thicknesses and poison cross section. Note linear scale for spectra, logarithmic for cross section.

That is, the spectral shape changes in addition to the intensity.

Figure 7 shows the absolutely normalized pulse shape as a function of fresh poison plate thickness for various energies. At higher energies (Figure 7(d)), we see the same 10% decrease in the overall intensity between the thinnest and thickest poison plates. The shape of the distribution does not change—only the amplitude. At lower energies (Figures 7(a) and 7(b)) the decrease in intensity is again around 16–18%, with the additional decrease (over and above the 10% due to increased resonance absorption) coming from the increased cutoff energy, while at the cutoff energy (Figure 7(c)) we see the most significant decrease, nearly 25%. There is also a small change in pulse shape around 200 meV, while at the lower energies the pulse shape is again constant, with only the amplitude changing.

We emphasize that the penalties quoted above represent the thickest poison plate studied; a bounding case for consideration. A more reasonable, less conservative initial thickness of 600 μm results in losses of around 6% at 1 eV, 16% at 200 meV, and 10–15% below 200 meV. The analysis above (leading to the thickness required to provide a specified lifetime) also seems to indicate that the change in moderator performance over a given period will be similar to the change resulting from the thickening of the initial poison plate. Thus we might expect that a moderator which started with a 580 μm poison plate would provide 10–15% fewer neutrons at low energies than that same moderator after the poison plate had depleted to the equivalent of 40 μm of fresh gadolinium, barring other changes within the system.

Our analysis clearly indicates that poison plate depletion in megawatt-class pulsed spallation sources is a significant issue, and that long poison plate lifetimes come with significant neutronic compromises. For now, we feel it likely that the SNS project will accept these compromises as



(a) 10 meV

(b) 100 meV

(c) 200 meV

(d) 1000 meV

Figure 7: Emission time distributions for different (fresh) poison plate thicknesses; case bh212; 40 μm, case bh217; 140 μm, case bh217; 560 μm, case bh21b; 1400 μm.

part of the cost of pushing the envelope of spallation source design. We will, however, continue to explore methods by which we might extend reasonable component lifetimes and reduce the negative effects of those extended lifetimes.

Rapidly depleting absorbers are also used in decouplers on pulsed neutron sources. These decouplers generally surround a moderator quite closely, and thus will likely experience fluxes from the direction of the moderator similar to, although somewhat smaller than, those depleting the poison plate. The main purpose of the decoupler, however, is to prevent the return of very long-lived thermal neutron populations from the reflector. This long-lived reflector population is significantly larger than the corresponding moderator population, as is demonstrated by a comparison of thermal integrals from coupled moderators with those from decoupled moderators—factors of 5–10 are not uncommon. On the other hand, decouplers traditionally have somewhat higher cutoff energies, changes in which are likely to affect only moderator intensities, not spectra or pulse shapes. Furthermore, typical decoupler thicknesses might be more like 1 mm of cadmium, already significantly thicker than typical poison layers. We therefor feel it likely that poison depletion, rather than decoupler depletion, will be the driving force in lifetime con-

siderations.

5 Moderator Configuration Optimization

In our original moderator configuration, the (top upstream) decoupled hydrogen moderator was placed over the location of maximum neutron production in the target. The (top downstream) coupled moderator was then fit in downstream and thus was somewhat removed from the point of maximum neutron production, giving it a significant disadvantage. We felt it more important that the decoupled unit be located at the maximum of the neutron production peak because this moderator yields considerably less intensity overall, and because this moderator served twice as many instruments as did the downstream moderator. With the two cryogenic units located in this manner, and with reflector material between them, their centers were 21.5 cm apart.

We have determined that there should be premoderating light water on the bottom and sides of both cryogenic units, as this tends to increase the neutron intensity and decrease the heat load. In addition, we have designed the downstream coupled moderator with premoderator water on the back face as well (it is viewed from one side only whereas the upstream moderator is viewed from two sides). On the basis of our optimization studies, the values chosen for premoderator water thickness were as follows. There is 2 cm of water on the bottom of the decoupled moderator (toward the target) but negligible amounts on the sides, while on the coupled moderator there is 2 cm of water on the bottom, back, and sides. There is also a thin water jacket on the sides of the decoupled moderator and on the tops of both moderators. However, these small amounts of premoderator were not important neutronically; their purpose was to facilitate water flow throughout the system as this water is also used for cooling purposes.

In general, premoderators have two beneficial effects; they increase neutron yields and decrease the heat load on the cryogenic system. The increase in neutron yield is most noticeable in the case of the coupled unit. Of course, the neutron yield from the coupled unit could be further increased by moving that unit upstream towards the neutron production peak in the target. In fact, there was no apparent reason why the two units could not be positioned so that they essentially touched one another. Furthermore, if the objective is to move the downstream (coupled) unit as far as possible upstream, then one might consider dispensing with the side premoderator so as to position it as close as possible to the upstream unit. In this way, the liquid-hydrogen compartment will be closer to the area of maximum neutron production in the target.

We performed an optimization study that started with a downstream moderator containing minimal side premoderator and placed as close as possible to the upstream moderator. In a series of calculations, this downstream moderator was then moved in the downstream direction while at the same time increasing the amount of side premoderator such that the upstream side of this entire unit remained as close as possible to the upstream moderator. Because of constraints imposed by the locations of the beam channels, the downstream movement of the coupled unit in the course of these studies also required a small amount of lateral movement.

Our studies show that the neutron production rate peak as seen by the upstream (decoupled) moderator is quite flat. This means that it is possible to move the decoupled moderator slightly upstream to increase neutron production in the coupled (downstream) moderator by allowing the latter to be closer to the neutron production peak in the target. Our calculations showed that a 5 cm upstream translation would reduce the upstream moderator intensity by only 5%, while giving a much higher benefit to the coupled downstream moderator intensity. A separate set of optimization calculations was therefore carried out in which both cryogenic units were situated a further 5 cm upstream. However, in this configuration the penalty to the upstream moderator

then became unacceptably high.

6 Summary

We continue to develop the neutronic models of the Spallation Neutron Source target station and moderators in order to better predict the neutronic performance of the system as a whole and in order to better optimize that performance. While we are not able to say that every model change leads to more intense neutron beams being predicted, we do feel that such changes are advantageous in either performance or in the accuracy of the prediction of performance.

We have computationally and experimentally studied the neutronics of hydrogen-water composite moderators such as are proposed for the SNS Project. In performing these studies, we find that the composite moderator, at least in the configuration we have examined, does not provide performance characteristics desirable for the instruments proposed and being designed for this neutron scattering facility. The pulse width as a function of energy is significantly broader than for other moderators, limiting attainable resolution-bandwidth combinations. Furthermore, there is reason to expect that higher-energy (0.1–1 eV) applications will be significantly impacted by bimodal pulse shapes requiring enormous effort to parameterize. As a result of these studies, we have changed the SNS design, and will not use a composite moderator at this time.

We have analyzed the depletion of a gadolinium poison plate in a hydrogen moderator at the Spallation Neutron Source, and found that conventional poison thicknesses will be completely unable to last the desired component lifetime of three operational years. A poison plate 300–600 μm thick will survive for the required length of time, but will somewhat degrade the intensity (by as much as 15% depending on neutron energy) and the consistency of the neutron source performance. Our results should scale fairly easily to other moderators on this or any other spallation source. While depletion will be important for all highly-absorbing materials in high-flux regions, we feel it likely that the poison plate represents a bounding case. We continue to explore new methods for extending absorber lifetimes and improving the resulting neutron source performance.

Finally, we continue to optimize the configuration of the moderators as a whole, resulting for example in premoderators around the cryogenic moderators, and in slight tweaking of moderator position in order to provide performance benefits, as well as providing (undiscussed here) ease of manufacturing.

References

[1] G. M. Allen, T. A. Broome, R. A. Burridge, D. Craig, D. Evans, R. Hall, D. Haynes, J. Hirst, J. R. Hogston, H. J. Jones, J. Sexton, and P. Wright, "The ISIS cold moderators," in *Proceedings of the International Workshop on Cold Moderators for Pulsed Neutron Sources* (J. M. Carpenter and E. B. Iverson, eds.), pp. 43–54, OECD, 1998.

[2] L. A. Charlton, J. M. Barnes, J. O. Johnson, and T. A. Gabriel, "Neutron moderator design for the Spallation Neutron Source (SNS)," in *AccApp'98: 2nd International Topical Meeting on Nuclear Appliations of Accelerator Technology*, pp. 41–45, American Nuclear Society, 1998.

[3] E. B. Iverson, J. A. Crabtree, A. T. Lucas, T. Tahara, M. Ooi, H. Iwasa, and Y. Kiyanagi, "Neutronic studies of a liquid hydrogen-water composite moderator," in *Proceedings of ICANS-XV, the 15th meeting of the International Collaboration on Advanced Neutron Sources*, Tsukuba, Japan, November 2000. to be published.