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Neutronics for the SNS Long Wavelength Target Station

E. B. Iverson,[1]* B. J. Micklich,[2] J. M. Carpenter [3]

[1]Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, TN 37831
[2]Technology Development, Argonne National Laboratory, Argonne, IL 60439
[3]Intense Pulsed Neutron Source, Argonne National Laboratory, Argonne, IL 60439
*E-mail: iversoneb@sns.gov

1 Introduction

The Long Wavelength Target Station (LWTS) is being developed as an addition to the Spallation Neutron Source (SNS) Project. The SNS Project has always planned that a second target station will be an eventual addition to the SNS facility. The LWTS design effort taking place now explores the possibility of this target station being constructed at the beginning of the facility life, permitting greater flexibility in design and implementation on both LWTS and the original target station, the High Power Target Station (HPTS). Further discussion of the philosophy behind this design effort may be found elsewhere. Here we describe the neutronic design and the design studies underway for the LWTS effort.

Section 2 describes the neutronically-relevant aspects of LWTS and the fundamental performance characteristics we expect, Section 3 outlines some of the optimization studies we have performed during our design process, Section 4 discusses high-energy neutron aspects of the LWTS design, and Section 5 lists various research and development efforts underway or planned for the LWTS design project.

2 LWTS Configuration

We have calculated detailed neutronic performance characteristics for what we have denoted the "base case" LWTS configuration. These characteristics are more completely documented elsewhere, [1] although we summarize them here. We employ both the MCNPX code package and the Lahet Code System for our simulations, both with ENDF cross section libraries and state-of-the-art scattering kernels from the ACoM collaboration.

2.1 Description

The LWTS base case configuration includes three moderators, of which two are "slab" moderators and one is a "front wing" moderator. Each of these moderators is viewed from one side only. All moderators have fully viewed faces of 120 mm (horizontal) by 200 mm (vertical) and are 50 mm deep. The reflector (out to a radius of $\approx$500 mm) is beryllium and is cooled with heavy water. This reflector is surrounded by a shield of iron cooled with heavy water. Table 1 summarizes relevant characteristics of the target station configuration defined as our base case. Although nominal operation is considered to be at 10 Hz (and thus 340 kW), the actual repetition rate has yet to be determined; 34 kJ per pulse is the value to be considered constant. Figure 1 shows the general layout of target and moderators for this LWTS configuration.

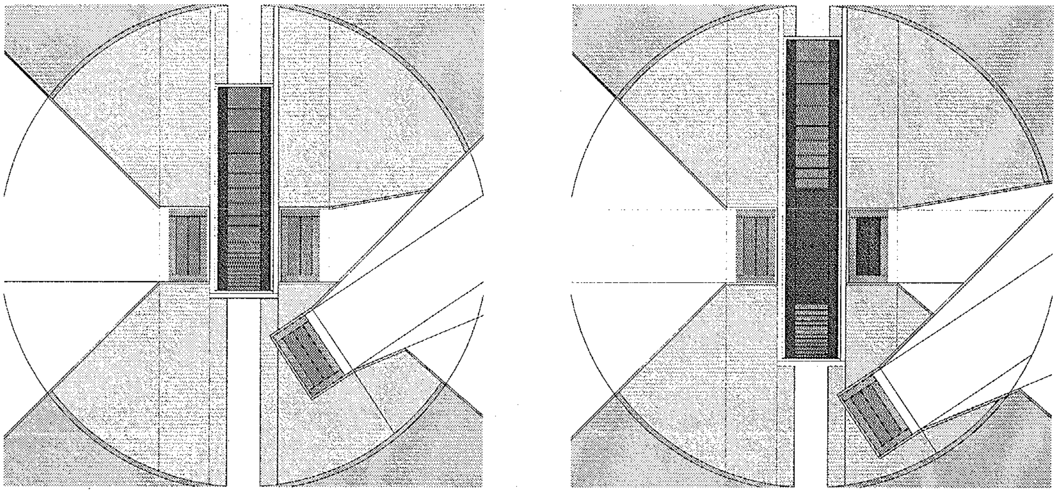
Table 1: LWTS parameters used in calculations. Normalizations are performed per 34 kJ-pulse.

Proton Energy	1 GeV
Pulse Rate	10 Hz
Average Power	340 kW
Energy per pulse	34 kJ
Proton Beam Shape	rectangular
Proton Beam Size	50x150 mm^2
Proton Pulse	$\delta(t)$
Target	W
Inner Reflector	Be
Inner Reflector Coolant	D_2O
Outer Reflector	Be
Outer Reflector Coolant	D_2O

The "port slab" moderator is the slab moderator to the left of the target, when viewed from the direction of the incoming proton beam. This moderator is fully coupled to the reflector, and is composed of solid methane at 22 K (90% by volume) and aluminum (10% by volume). The "starboard slab" moderator is the slab moderator to the right of the target, when viewed from the direction of the incoming proton beam. This moderator is decoupled from the reflector with cadmium, is composed of solid methane at 22 K (90% by volume) and aluminum (10% by volume) and is poisoned with gadolinium 25 mm beneath the viewed surface. The "front wing" moderator is upstream (for the proton beam) of the target, decoupled with cadmium, composed of liquid methane at 100 K, and is poisoned with gadolinium 25 mm beneath the viewed surface. Table 2 summarizes this moderator configuration. Note that in our current judgment, the slab moderators must be viewed indirectly, i.e., through a curved guide or compact beam bender. This defines our "base case" configuration. Many of our detailed calculations, including all of those discussed here, were performed for a configuration in which the two decoupled moderators were exchanged, with the front wing moderator being solid methane, and the starboard slab moderator liquid methane. Because our results and discussions for the decoupled moderators

Table 2: LWTS moderator summary. Solid methane is mixed with aluminum at 10% by volume.

Moderator Location	Moderator Material	Temperature (K)	Decoupling Material	Poison Material	Poison Depth (mm)
Port Slab	CH_4	22	–	–	–
Starboard Slab	CH_4	22	Cd	Gd	25
Front Wing	CH_4	100	Cd	Gd	25



(a) Solid target-slab moderator configuration.

(b) Split target-flux trap configuration.

Figure 1: Top view of LWTS moderator and target layouts discussed. The moderators to the right of the target are decoupled. The slab moderators are solid methane. Protons enter from the bottom of the figure.

discuss only the 1 eV coupling, as described below, or the high-energy neutron emission, this change has no significant impact on our present conclusions.

2.2 Quantities Calculated

The spectral intensity $i(E)$ of a moderator is a measure of the number of neutrons leaving the moderator at a particular energy E, and is related to the differential flux $\phi(E)$ at a point some large distance L from the moderator by a "$1/r^2$" relationship, that is,

$$i(E) = L^2 \, \phi(E)|_L \,, \tag{1}$$

where the flight path is normal to the viewed moderator face. This intensity characterizes the moderator independently of flight path length from which it is viewed. If the flight path is not normal to the moderator surface, the intensity observed is scaled by the cosine of the angle between the flight path and the normal to the moderator surface. The intensity is usually separated into a shape factor and an overall scale factor, with the overall scale factor equal to the intensity evaluated at 1 eV, referred to as the "moderator coupling,"

$$I_{\mathrm{epi}} = Ei(E)|_{1\mathrm{eV}} \,, \tag{2}$$

which is the epithermal intensity per unit lethargy. Note that we assume that slab moderators require indirect views of the moderator, and thus 1 eV neutrons would likely not be available from those moderators; we nonetheless use I_{epi} as a metric for characterizing the moderator performance. We calculate spectral intensities both by point detector tallies, which give rapid convergence, absolute scaling, and directional sensitivity, and by leakage current tallies, which provide intensities for neutrons of high energy (the way in which the point detector tally in MCNP functions does not permit high energy neutrons to contribute to the next event estimator).

Our proposed use of slab moderators requires careful examination of the high energy neutron source term, and therefore we calculate the spectral intensities up to some 500 MeV using leakage current tallies, which we normalize using point detector results in an energy range where both tallies function properly.

The emission time distribution of the moderator specific to a given neutron energy, also called the pulse shape, is simply the intensity distribution as a function of the time (after the initial proton pulse strikes the target) at which neutrons cross the moderator surface. It is related to the spectral intensity by

$$i(E) = \int_0^\infty i(E,t)dt. \tag{3}$$

The emission time distribution of the neutrons leaving the moderator depends upon the viewing angle only in the scaling of the overall intensity. The energy binning and time binning for the Monte Carlo calculations provide 10 energy bins and 20 time bins per decade, such that $\Delta E/E \approx 23\%$ and $\Delta t/t \approx 11\%$. The predictions reported are differential values averaged over such bins. We calculate emission time distributions by surface-averaged leakage current tallies, normalized by point detector intensity tallies.

2.3 Results

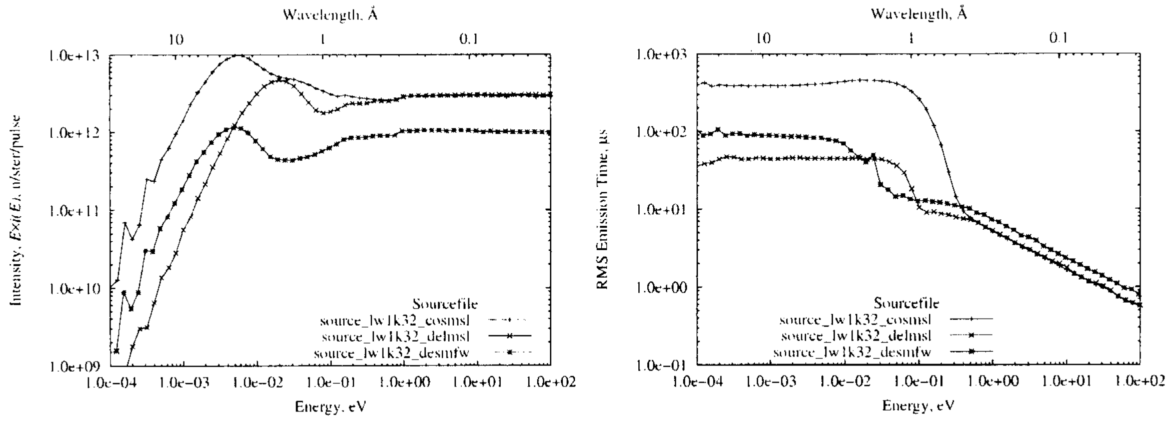
The detailed performance as predicted by the simulations appear elsewhere in great detail. [1] Recall that slab moderators must be viewed indirectly, implying a cut-off wavelength below which neutrons are unavailable due to the characteristics of the viewing optics. We summarize some of the more relevant results in graphical form only in Figures 2 and 3.

3 Optimization Studies

We have performed a number of calculations intended to optimize the configuration of the LWTS target-moderator-reflector assembly. We report here the following main studies:

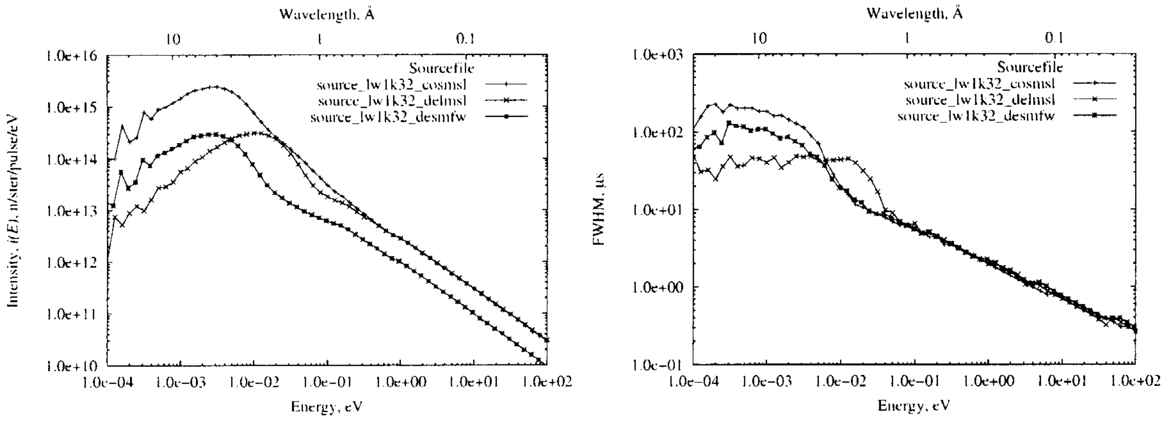
1. target position relative to moderators for the slab moderator configuration,
2. beam void open angle for the slab moderator configuration,
3. target gap for the flux trap moderator configuration, and
4. target division for the flux trap moderator configuration.

We have also examined the impact on the slab moderator performance due to the inclusion of the front wing moderator and the effect of filling the "flux trap gap" in a split target with water (in an effort to more closely approximate the idealized flux trap). We use the techniques described above to calculate the moderator coupling I_{epi} as a general metric of performance. We further use the spectral intensity at 1 meV as a measure of the thermalization in a moderator. If we assume that there is no change in the spectral temperature of the thermalized neutron beam, then the flux at any low energy, or integrated over a range of low energies, provides a metric for the "thermalization coefficient." This coefficient could also be obtained by fitting a suitable parametric form to the spectral intensity. We use the intensity at 1 meV, as it requires less manual data post-processing. In all cases we here report, the spectral temperature of the neutron beams in question was unaffected by the geometry changes. The thermalization coefficient is of course not expected to change for a decoupled moderator, but does for a coupled moderator in differing geometric arrangements.



(a) Intensity per unit lethargy

(b) Pulse Width (RMS)



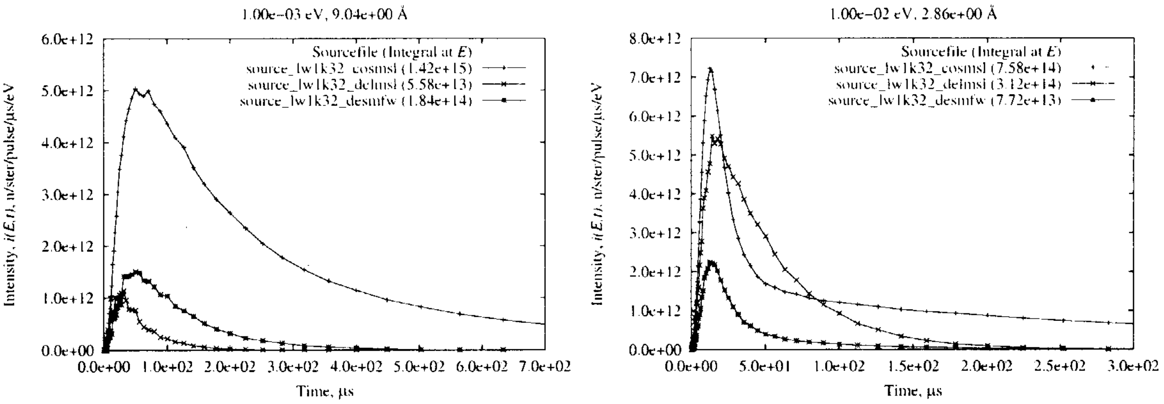
(c) Intensity per unit energy

(d) Pulse Width (FWHM)

Figure 2: Intensities and pulse widths as functions of energy for compared moderators. Recall that slab moderators must be indirectly viewed. The coupled moderator is denoted **source_lw1k32_cosmsl**, the decoupled liquid methane slab moderator **source_lw1k32_delmsl**, and the decoupled solid methane front wing moderator **source_lw1k32_desmfw**.

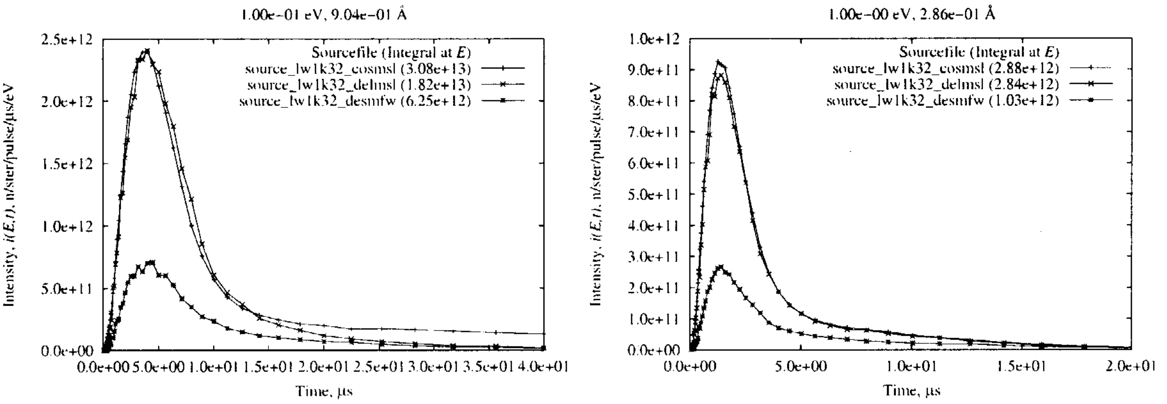
3.1 Target Position

We have examined the effect of target-moderator position by varying the position of the target. The slab moderators for this study are centered within the reflector, and the target shifted to maximize performance. Figure 4(a) shows the coupling for both decoupled and coupled moderators, as well as the degree of thermalization expected for the coupled moderator as a function of target position. We deduce from Figure 4(a) the optimum position for the target (which is the position we have defined as our base case), and the sensitivity of beam intensity to that position (around 5% loss in coupling at most for a shift of up to ±5 cm). This sensitivity will be considered later, when we position the third, front wing moderator, and when we evaluate the high-energy neutron component of the neutron beams. We also see that the thermalization in a coupled moderator is less sensitive to large variations in target position than is the moderator coupling. This follows the intuition that the reflector storage component is a very significant



(a) 1 meV

(b) 10 meV



(c) 100 meV

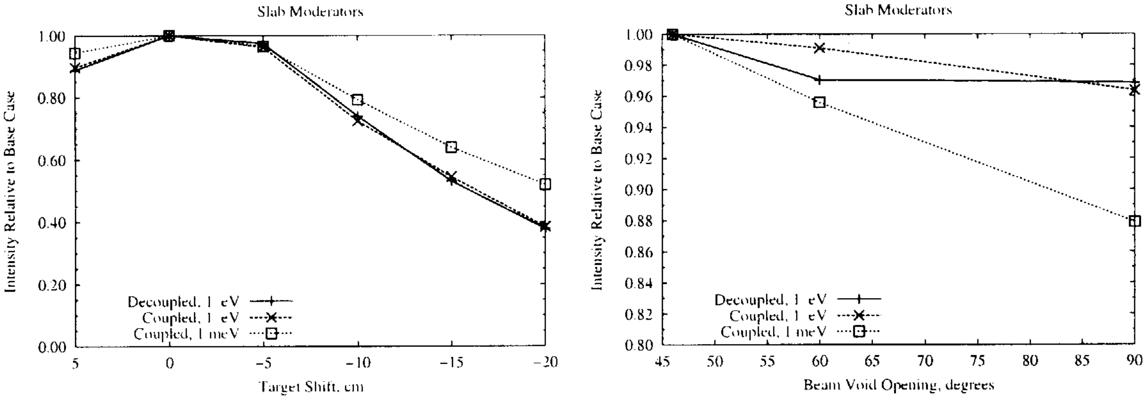
(d) 1 eV

Figure 3: Emission time distributions. The coupled moderator is denoted **source_lw1k32_cosmsl**, the decoupled liquid methane slab moderator **source_lw1k32_delmsl**, and the decoupled solid methane front wing moderator **source_lw1k32_desmfw**. $\Delta E/E \approx 23$ %. Recall that slab moderators must be viewed indirectly.

component in the coupled moderator performance.

3.2 Beam Void Open Angle

The LWTS configuration has a small number of moderators, and is intended to maximize the efficiency of those moderators for use through curved guides. There is always a desire, however, to maximize the number of beams, and thus instruments, as well. Together, these two desires lead us to consider broad angular coverage of the high-performance slab moderators. We have therefore studied the impact of opening the beam void, immediately outside the moderator, to a larger angle—specifically, as large as 90°. Figure 4(b) shows the impact of opening this void to such an angle, that might permit as many as nine closely spaced beams to come off a single moderator. There is a minor penalty in the moderator coupling, perhaps as much as 4%, and a larger penalty, as much as 12%, on the low-energy intensity from the coupled moderator.



(a) Target position (+ values move target toward proton beam).

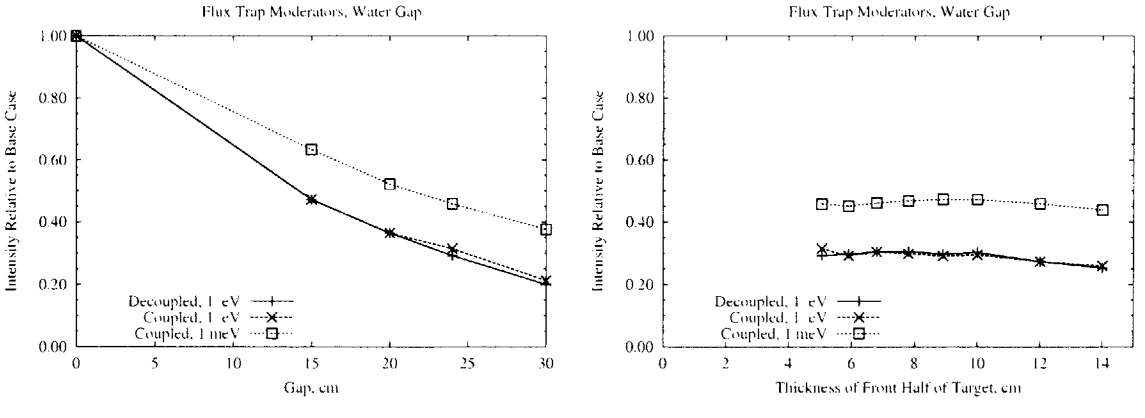
(b) Beam void open angle (note suppressed zero).

Figure 4: Results of optimization studies of slab moderator configuration.

3.3 Split Target Configuration

A split target configuration permits the use of "flux trap" moderators—moderators which do not have to be viewed through a curved guide because the beamlines are not directly illuminated by target material and the primary neutron source. This flexibility comes at a significant penalty, as seen in Figure 5(a), which shows the intensity from the two moderators as a function of the gap between the split target sections, where a gap of zero implies a solid target and slab moderators. Any gap large enough to actually avoid having target material illuminate all beamlines (a minimum of 15 cm) results in a factor of two reduction in moderator coupling, while a gap large enough to avoid illuminating any beamlines (24 cm) results in a factor of three reduction. Note that this particular flux trap configuration is one in which the gap between target segments is filled with water. Similar studies, with a more conventional vacuum gap, indicate a somewhat smaller penalty, namely a factor of two intensity reduction for the 24-cm gap realistic case; still very significant. The value of the H_2O-filled gap is clearly seen in the improved thermalization on the coupled moderator, giving a significantly higher thermalization than might be expected with an equivalent void gap, however this higher thermalization is not enough to overcome the lower initial coupling; the net result is that the low-energy flux on the coupled moderator with a split target wyth H_2O-filled gap is roughly 20% lower than that for a conventional split target with a void-filled gap.

Finally, we have examined the effect on moderator intensity of the division of the target into two regions—that is, the length of the "upstream" or first target section relative to the "downstream" or second target section, assuming a constant total length. Figure 5(b) shows that the coupling of both moderators, as well as the thermalization of the coupled moderator, is relatively insensitive to the exact partitioning of target material between the first and second sections, with anywhere between 5 and 10 cm for the first section offering the best performance. This parameter might therefore be adjusted to optimize the front moderator performance or the high-energy neutron background.



(a) Gap size (15 cm gap clears some beamlines, 24 cm gap clears all beamlines).

(b) Division of target material between front and back sections.

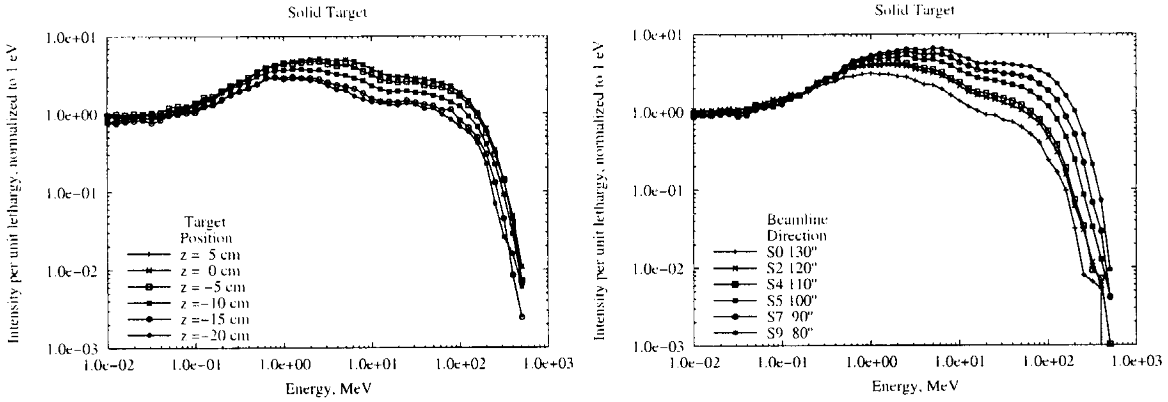
Figure 5: Results of split target optimization studies.

4 High-Energy Neutron Source Term

One of the most significant and adventurous aspects of the LWTS design concept is the use of slab moderators, historically considered to be awkward due to the high contamination of the neutron beams with fast (0.1–10 MeV) and high energy (10+ MeV) neutrons. Concern over this contamination is the reason behind our proposition that none of the beams on a slab moderator should be viewed directly, that is, without a curved guide, compact bender, or other fast and high energy neutron filter. Figure 6 shows the results of a large number of calculations concerning fast neutron source terms. All fast and high-energy neutron spectra will be reported as lethargy spectra, normalized to 1 eV, except where otherwise noted. In this way, we will attempt to define the "cost" of using slab moderators as a function of the payoff gained from their use. We report these data for general information and discussion, and further draw the conclusions discussed below. Figure 6(a) indicates that there is only marginal benefit to shifting the target position around the location optimum for performance.

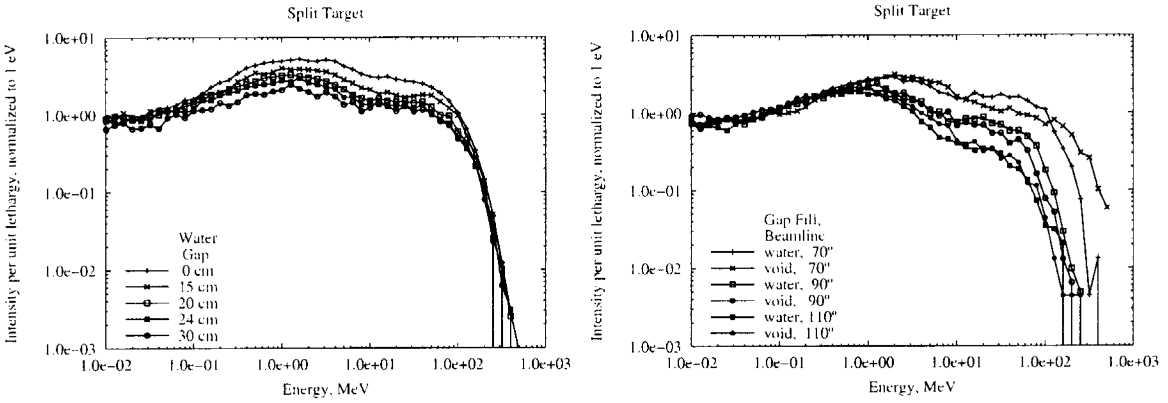
Figure 6(b) indicates that there is a "worst-case" beamline angle, around 77° from the proton beam, where reduced shielding and increased source term are least desirably matched, although the highest energy neutrons are still most problematic at the lowest angles relative to the proton beam. Furthermore, there is an enormous difference between neutron beams depending on the exact value of this angle. This may have significant implications regarding the choice of beamline for a given instrument, as some instruments will have restrictions on background and on feasible shielding configurations.

Finally, Figures 6(c) and 6(d) indicate that the neutron beamline angle more strongly influences the fast neutron component than does the presence or absence of water in the flux trap gap, or even than the size of this gap. This last point is further demonstrated in Figure 7(a) which shows that the flux trap 70° beamline has similar quantities of the highest energy neutrons to the 90° beamline for a slab moderator, although the fast neutron contribution is lower. Thus we see that, depending on the beamline angle, slab and flux trap moderators have different energy ranges over which each displays a higher fast and high energy neutron component. Finally, Figure 7(a) does confirm that our use of slab moderators does result in more fast and high-energy



(a) Moderator-target position relative to base case.

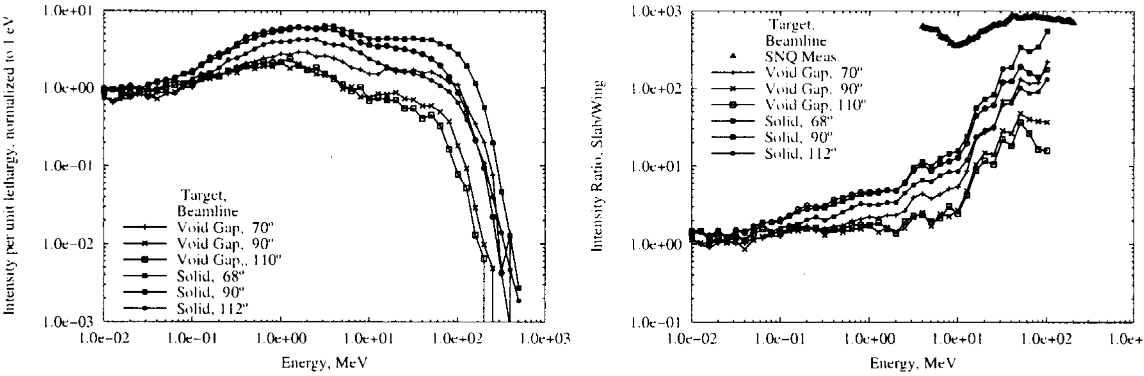
(b) Neutron beam direction relative to the direction of the proton beam.



(c) Size of water gap for a split target.

(d) Void- and water-filled gaps and neutron beam direction.

Figure 6: Fast and high energy spectra for a variety of optimization studies. All angles are relative to proton beam. Neutron beams are normal to moderators (90° from proton beam) unless otherwise specified.



(a) Slab and flux trap moderators.

(b) Wing moderators.

Figure 7: Fast and high energy spectra for various neutron beam angles for a solid target-slab moderator configuration a split target-flux trap moderator configuration, and a wing moderator configuration.

neutrons in a given beam, when compared to a wing moderator. The ratio of the fast neutron spectrum from our slab moderator to our front wing moderator appears in Figure 7(b). Our results comparing the LWTS slab to the LWTS front wing moderator are roughly consistent at the highest energies ($\geq$ 100 MeV) with measurements carried out some time ago for the SNQ project. [2] Those measurements indicate a factor of approximately 300–1000 greater fast neutron intensity from a "slab" moderator configuration than from a "wing" configuration, as shown in Figure 7(b). However, our calculations indicate substantially lower ratios at lower energies, 3–10 MeV, for the LWTS slab-wing comparison than for the SNQ measurements. We feel that measurements in the LWTS configurations are needed to resolve this apparent discrepancy.

However, the increase in the undesirable neutron component is not tremendously larger for a slab moderator than it is for a flux trap moderator (which has been successfully employed at the Lujan Center), and is still reasonably similar in shielding requirements to the High Power Target Station beamlines (once proper accounting is made for the different repetition rate of the two target stations). The new upstream moderator at the Lujan Center will provide further valuable information. Moreover, experience and measurements at ISIS and SINQ indicate that feasible guide and bender shielding adequately controls the fast neutron component.

5 R&D Efforts

Numerous issues have arisen in the course of the LWTS concept development which require more information than is now in hand to provide the basis for detailed design and for potential design innovations. Some of the R&D issues are listed here, along with proposed efforts to fill design needs.

Our current LWTS configuration calls for monolithic solid methane cold moderators, which have yet to be realized at high-power spallation sources. In addition to developing and exploring engineering solutions to permit using monolithic solid methane moderators, we are also involved in the ACoM collaboration, the members of which seek to develop a pelletized methane moderator system. We are involved in this effort via the tracking of and collaboration with a

DOE-sponsored pelletized moderator development effort at Cryogenic Applications F, Inc., by the co-sponsoring of the "URAM" series of measurements at Dubna, and by supporting a calculational effort at the University of Illinois. We also seek to explore other moderator materials, most especially ammonia, for which scattering kernel measurements and model development would need to be done, as would experimental tests of the proposed moderators.

We are investigating the possibility of using metal hydrides, perhaps in deuterated form, as reflectors—an old idea that has become more practical with the development of an industrial infrastructure surrounding the use of metal hydrides as battery material and for hydrogen storage. This too will require development of suitable scattering kernels for simulation, perhaps requiring in turn scattering measurements on candidate materials.

There are a great many optical components required for LWTS as envisioned to be successful, both due to the heavy emphasis on low-energy neutrons and due to the reliance on indirect viewing of slab moderators. We will explore guide and compact beam bender effectiveness both computationally and experimentally, drawing on experience at ISIS and SINQ, the ongoing ASTE tests at AGS, and perhaps additional prototyping tests. We are deeply involved in ongoing prototyping of focusing optics, polarization equipment, and energy filters at IPNS. Finally, we are also heavily involved in the development and prototyping of new neutron detectors and new instrument concepts.

6 Conclusions

We have devised a highly effective "base case" conceptual design for LWTS, which we are still evaluating and optimizing. LWTS will provide distinctly unique capabilities complimentary to the SNS HPTS. The configuration of LWTS is strongly coupled to instrument requirements through close interaction with scientists formulating the science case and instrument suite.

References

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[2] G. S. Bauer, H. Sebening, J.-E. Vetter, and H. Willax, "Realisierungsstudie zur Spallations-Neutronenquelle," tech. rep., Arbeitsgemeinschaft Spallations-Neutronenquelle, 1981.