ICANS-XIII
13th Meeting of the International Collaboration on
Advanced Neutron Sources
October 11-14, 1995
Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

COUPLED MODERATOR NEUTRONICS

Gary J. Russell, Eric J. Pitcher, and Phillip D. Ferguson

Manual Lujan, Jr. Neutron Scattering Center
MLNSC, MS H805
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

Optimizing the neutronic performance of a coupled-moderator system for a Long-Pulse Spallation Source is a new and challenging area for the spallation target-system designer. For optimal performance of a neutron source, it is essential to have good communication with instrument scientists to obtain proper design criteria and continued interaction with mechanical, thermal-hydraulic, and materials engineers to attain a practical design. A good comprehension of the basics of coupled-moderator neutronics will aid in the proper design of a target system for a Long-Pulse Spallation Source.

1. Introduction.

Target stations are vital components of a spallation-neutron source, and target-station design plays a major role in determining the overall (neutronic and operational) performance of the facility. Many traditional notions will have to be rethought and several new concepts put forward to meet the challenge of designing a target station for the next generation spallation neutron source (5 MW of proton beam power); it is believed a target station designed for 1 MW can employ existing technology. The particulars of a target station depend on whether it is designed for a Short-Pulse Spallation Source (SPSS) or a Long-Pulse Spallation Source (LPSS).

Keywords: Target, Moderator, Reflector, Target System

In the context of this paper, the term *target station* refers to an ensemble of components needed to produce/extract neutrons for various areas of research. The major components of a target station are the *target system*, the *shield*, and the *ancillary systems*. In this paper, we will focus our discussion on the neutronic performance of the *target system*. We define the *target system* as the subset of components (targets, moderators, poisons, decouplers, liners, and reflectors) in the target station that contribute directly to the production of useful neutrons. The target system used at the Manual Lujan, Jr. Neutron Scattering Center (MLNSC) is illustrated in Fig. 1 [1].

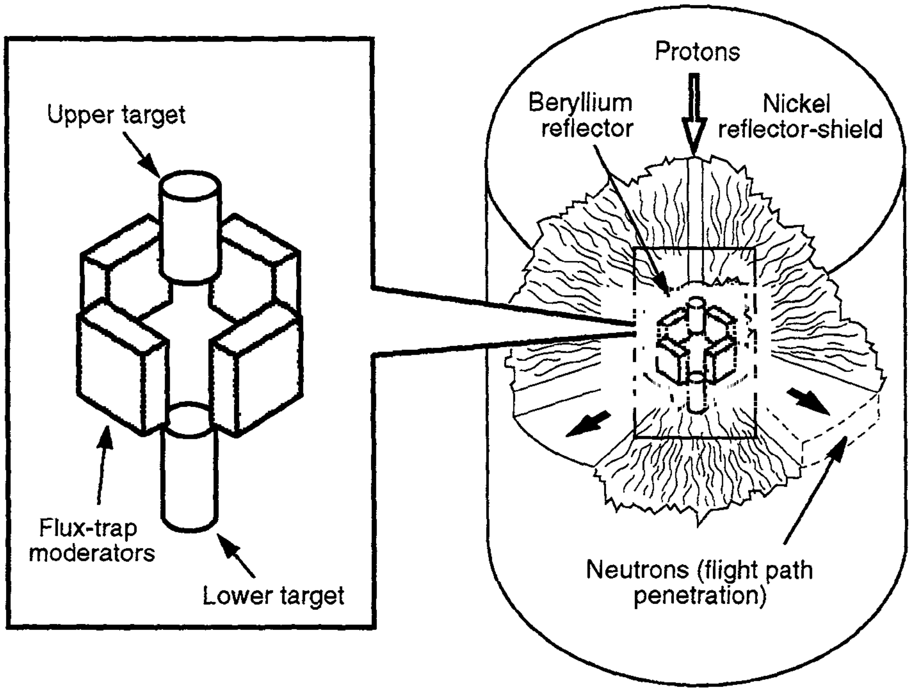

Figure 1. Illustration of the target system used at the MLNSC. The target system consists of a split target of tungsten, four flux-trap moderators of water and liquid hydrogen, an inner moderating reflector of beryllium, and an outer fast neutron reflector and high-energy neutron shield of nickel. The target system forms a right circular cylinder of about 1-m diameter and 1-m high.

We focus here primarily on coupled-moderator neutronics, where the proton pulse width and the choice of target, moderator, and reflector materials and geometry dominate the neutronic performance of moderators. This is in contrast to decoupled-moderator neutronics where the proton pulse width is kept deliberately short compared to the slowing down and thermalization times in moderators and reflectors. For decoupled systems, the intensity and pulse widths of neutrons from a moderator are controlled by the use of poisons, decouplers, and liners in addition to the choice of target, moderator, and reflector materials and geometry. The MLNSC target system in Fig. 1 is a decoupled target system because it employs poisons, decouplers, and liners, and is, therefore, a SPSS. Before we discuss coupled moderator neutronics, we will review the neutronic issues in going from decoupled moderators to coupled moderators, i.e., decoupled to coupled target systems.

2 From an SPSS to an LPSS

2.1 *Decoupled to Coupled Target Systems*

For most users of a pulsed spallation-neutron source, useful neutrons can be defined as those headed in the right direction with appropriate energy at the right time. Unfortunately, spallation neutrons produced directly in the target rarely have the desired characteristics. We must, therefore, add the necessary systems and devices to the bare neutron production target in order to tailor the neutron pulse so that its characteristics are as close as possible to the users' requirements. As mentioned above, a complete target system consists not only of target(s) for the production of neutrons, but also of moderators, reflectors, and, in the case of an SPSS, poisons, decouplers, liners.

In addition to the choice of material, temperature, geometry (*e.g.*, wing versus flux-trap moderators), and the presence or absence of a reflector, moderator neutronic performance is also strongly tied to the presence or absence of poisons, decouplers, and liners. The choice of materials and thicknesses for these target system components is a crucial part of moderator design.

2.1.1 *Poisons, Decouplers, and Liners.* The function of poisons, decouplers and liners is to tailor the temporal and energy characteristics of the neutron pulses emitted by the moderator. Fig. 2 shows the arrangement of poisons, decouplers and liners in the split-target, flux-trap moderator geometry of Fig. 1. Moderator poisons can be either spread homogeneously throughout a moderator, or introduced heterogeneously (as a discrete region) into the moderator [2]. In this paper, we confine our discussion to the use of heterogeneous poisons. For thermal neutrons, the poison neutronically defines that part of the moderator "viewed" by an experiment. Decouplers surround a moderator and both geometrically and neutronically isolate it from the reflector. Liners geometrically and neutronically isolate the moderator "viewed surface" from the reflector. We deliberately define decouplers and liners separately because they can be different materials with distinct thicknesses, as in the MLNSC target system design [3]. The goal of short-pulse moderator design is to get as much useful neutron intensity from a moderator as possible with little or no attendant degradation in the neutron pulse width.

The energy range over which poisons, decouplers, and liners "neutronically" operate is not distinct and depends on the thickness and material used. For example, gadolinium and cadmium have "characteristic" cutoff energies (roughly 0.1-0.2 eV and 0.5-0.6 eV, respectively) above which they are not as neutronically effective, whereas, a "1/v" absorber like boron has a cutoff energy that is not as distinct. For boron, one usually refers to a "1/e" cutoff energy for a given boron atom density and thickness and is usually chosen to be "1/e" in the few eV range [3].

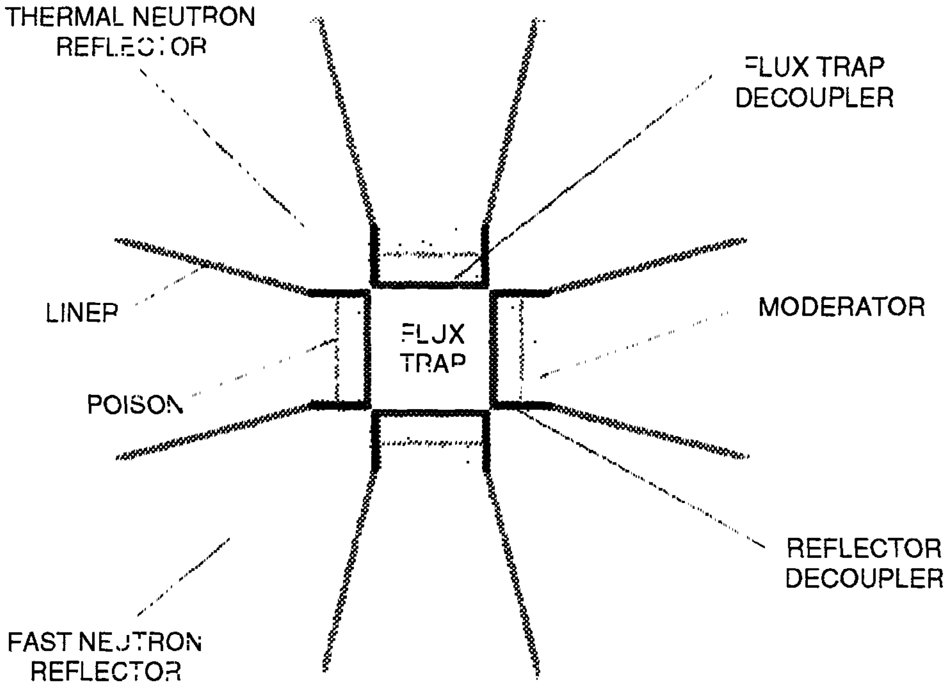

Figure 2. Arrangement of poisons, decouplers, and liners in a flux-trap moderator geometry. Poisons are typically oriented parallel to and positioned some distance (≈1 to 3 cm) behind the moderator viewed surfaces. The flux-trap decouplers neutronically insulate moderators from one another whereas the reflector decouplers neutronically isolate moderators from the adjoining reflector material. Liners neutronically insulate the reflector from the moderator viewed-surface.

2.1.2. *Decoupled Moderators.* If we employ decouplers and liners in conjunction with a moderator surrounded by a reflector, we refer to those moderators as "decoupled" moderators, and the target system as a SPSS. The choice of material and thickness of material for decouplers and liners is important in optimizing the neutronic performance of the next-generation SPSS. Adequately cooling the decouplers and liners for the next generation SPSS will be a design challenge.

2.1.3 *Coupled Moderators.* If decouplers and liners are not used when a moderator is surrounded by a reflector, we call the moderators "coupled." Coupled moderators can be significantly more intense than decoupled ones. However, the neutron pulse width from a coupled moderator is much larger than that from a decoupled one [4]. We illustrate this neutronic gain in Fig. 3 for liquid H_2 (ortho/para 50/50) moderators. For these liquid hydrogen moderators, a totally coupled moderator provides about 6.7 times greater neutron pulse intensity (for $E < 5$ meV) than a decoupled moderator. This is precisely the reason to consider an LPSS over an SPSS. However, as indicated by the standard deviation, the neutron pulses are "broader" in time from a coupled moderator compared to a decoupled one.

Figure 4 depicts the energy-dependent gain in neutron intensity and time distributions for a coupled liquid H_2 (ortho/para 50/50) moderator compared to a decoupled one.

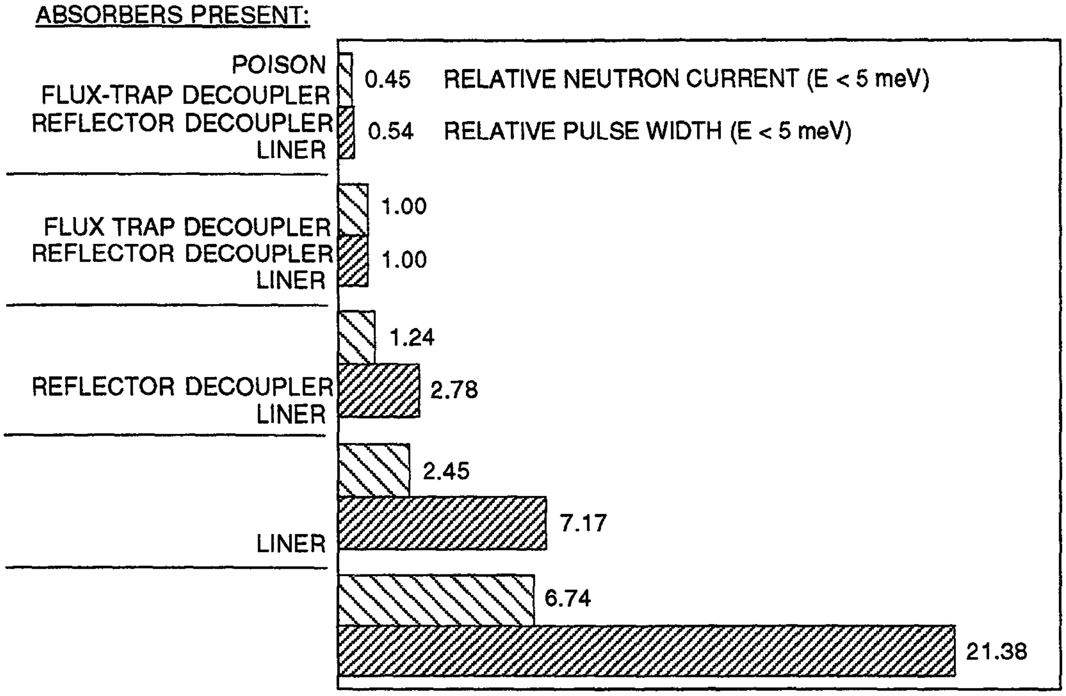

Figure 3. Effect of poisons, decouplers and liners on neutron pulse intensity and pulse width for liquid H_2 (ortho/para 50/50 v%) moderators. The labels on the left side of the bar graph indicate what items are present for the corresponding bars. The neutron pulse width is defined as the standard deviation of the time at which neutrons leak from the moderator viewed surfaces. The 22.5-cm-long, D_2O-cooled W rod-target is singly split and the four 5x13x13-cm^3 moderators are in flux-trap geometry. The poison is 0.00508-cm-thick Gd, and the decouplers and liners are 0.0813-cm-thick) Cd. The reflector is D_2O-cooled Be (D_2O/Be 15/85 v%). The proton beam energy is 800 MeV.

In Fig. 5, we show the decoupled data of Fig. 4 integrated over time; this is *the time-dependent neutron leakage gain*. The results show that the neutron gain depends on the time over which the neutrons can be utilized in an experiment. The maximum gain is the factor of about 6.7 (as $t \to \infty$).

The coupled-moderator gain will also depend on the type of reflector employed, i.e., whether or not the reflector is a "fast" or "moderating" reflector. We will now discuss the various types of reflectors we can use in a target system.

3. Reflectors

Reflectors enhance the efficiency of useful neutron production by returning neutrons that would have otherwise escaped from the target system to the moderator zones where there is another chance to change them to useful neutrons. The reflector is absolutely essential for this purpose; otherwise, the requisite intensities of useful neutrons would not be adequate [5]. However, reflectors also alter the time structure of neutron pulses from a moderator.

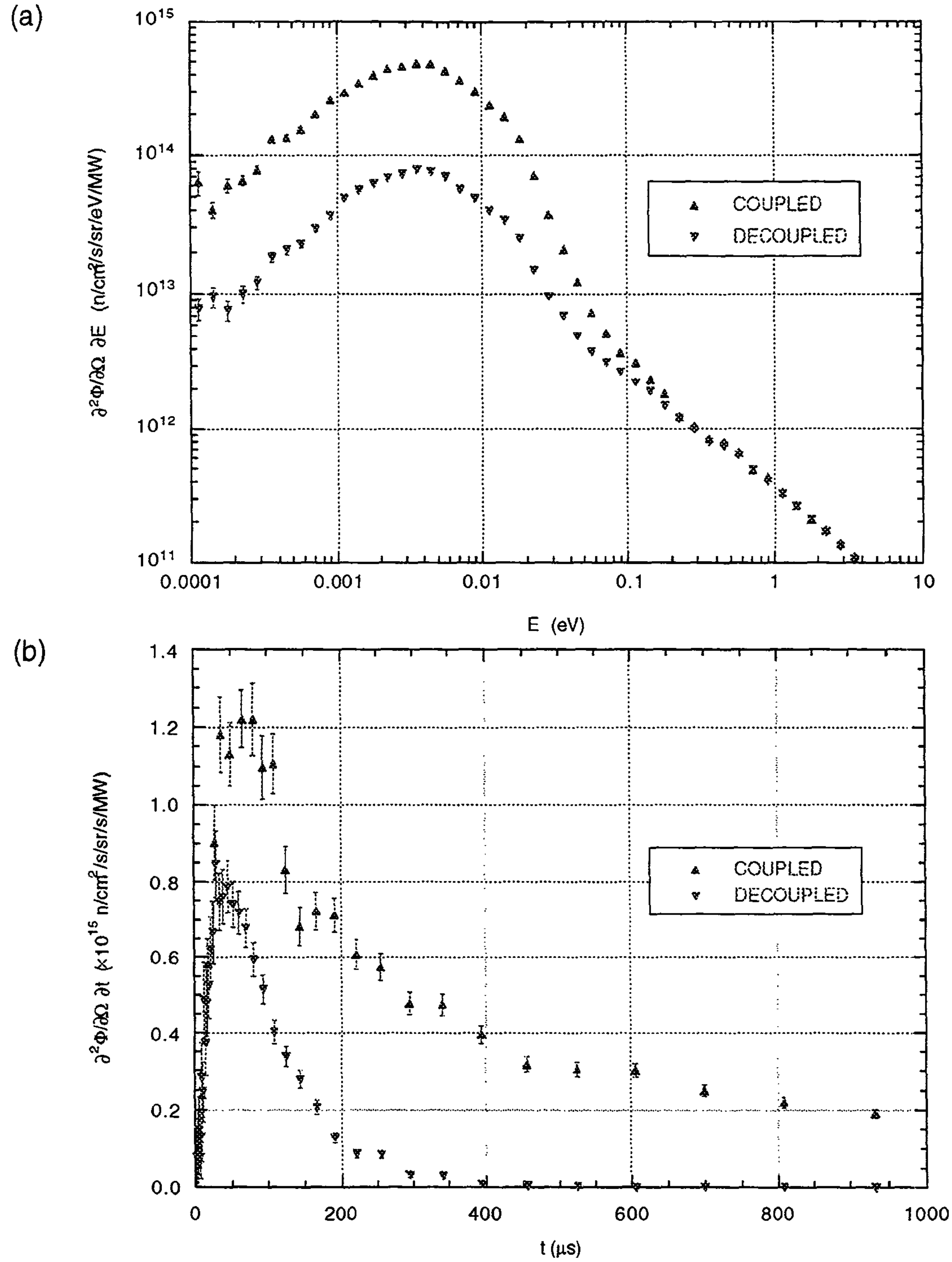

Figure 4. Flux spectrum (a) and time distributions (b) for coupled and decoupled liquid H_2 (ortho/para 50/50) moderator showing the energy-dependent and time-dependent differences, respectively, of leakage neutrons. The moderators are unpoisoned.

3.1. *One-Component Reflectors.* Beryllium has been the classic reflector material for pulsed spallation sources [1, 6-8], and heavy water for quasi-continuous spallation sources [9]. These are examples of one-component reflectors. However, it is useful to combine reflector material types into a composite reflector, and to investigate multiple uses of the components of a composite reflector.

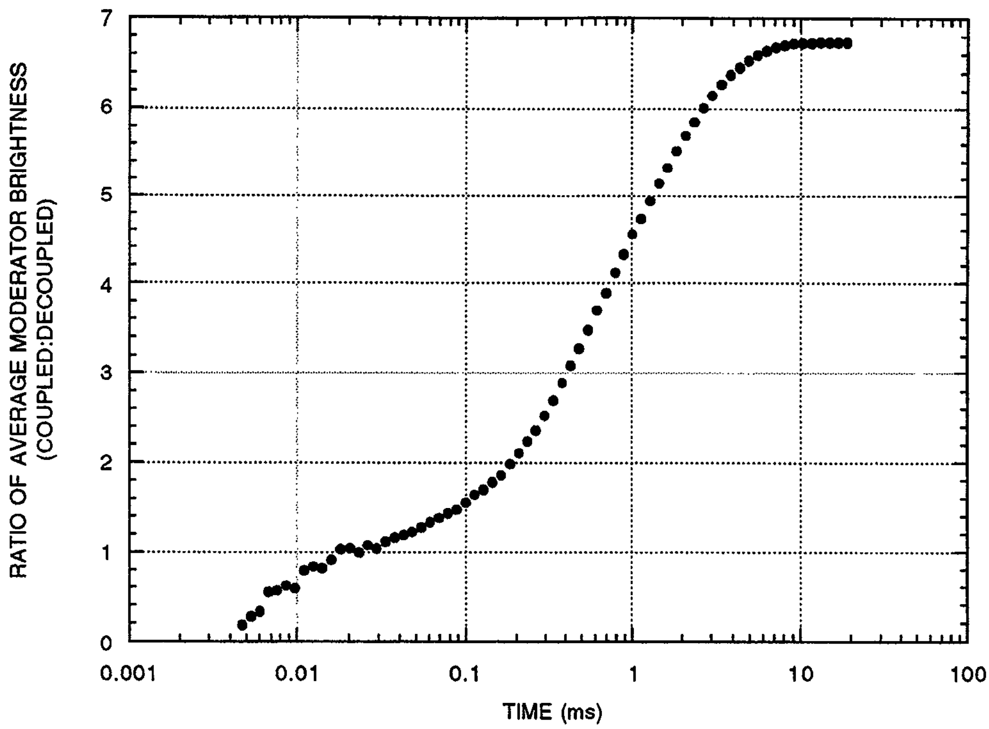

Figure 5. The time-dependent coupled/decoupled gain for unpoisoned liquid H_2 (ortho/para 50/50) flux-trap moderators with an infinite D_2O-cooled Be reflector..

3.2. *Composite (Multiple-Component) Reflectors.* In 1985, we introduced and implemented the notion of a composite reflector at the MLNSC [1]. We designed the MLNSC composite reflector to perform three distinct functions: 1) as a thermalizing and thermal neutron reflector, 2) as a fast neutron reflector, and 3) as the beginning of the high-energy neutron shield. In addition to these three functions, a composite reflector of the proper material can be looked at (from the point-of-view of neutron production) as an extension of the target, i.e., to enhance spallation neutron production and to provide additional (n,xn) neutrons. Also, in the case of the LPSS, the outer portion of a composite reflector can be used to tailor the time distribution of neutrons leaking from a moderator. Thus, a composite reflector can have several distinct neutronic functions. We will now discuss the purposes of the various components of a composite reflector.

3.2.1 *Inner Reflector.* The inner portion of a composite reflector should be a moderating/reflecting zone surrounding the moderators and performing two primary functions: 1) to moderate (thermalize) fast neutrons and redirect them back into the moderators, and 2) to reflect back into the moderators thermalized neutrons escaping from the moderators into non-useful directions. The inner reflector should have two other secondary qualities: 1) the ability to transmit neutrons from the intermediate "fast neutron" reflector back into the moderators (this requires low neutron absorption characteristics for the inner reflector material); and 2) the ability to make (n,xn) neutrons, i.e., to act as a neutron source. Materials studied to date for inner reflectors include H_2O, D_2O, C, and Be.

3.2.2 *Intermediate Reflector.* We use an intermediate reflector zone to return fast neutrons back into the inner reflector, to produce spallation and (n,xn) neutrons, and to act as a high-energy neutron shield. This material should have low or moderate neutron absorption properties. The materials studied to date include Ni, W, and Pb. Figure 1 shows the two-component composite (Be/Ni) reflector used at the MLNSC.

3.2.3 *Outer Reflector.* In our LPSS studies, we are considering an outer "fast neutron" reflector region to return fast neutrons back into the intermediate reflector zone, to produce spallation and (n,xn) neutrons, to help remove "tails" on neutron pulses in an LPSS application, and to act as a high-energy neutron shield. The materials we will be looking at are Ni and W.

4. LPSS Design Issues

There are several key issues that affect the overall neutronic performance of an LPSS. Among the most important concepts are: a) *neutron intensity vs. brightness* - this determines the moderator size; b) *temporal brightness* - this establishes the "peak" neutron intensity in time; c) *number of neutron beam lines* - this affects the absolute overall neutronic performance of the target system; d) *liquid H_2 compared with liquid D_2* - influences how "cold" one can make the neutron leakage spectrum from a moderator; e) *ortho/para- hydrogen fraction* - this affects the neutronic performance of a liquid H_2 moderator; f) *premoderator materials/thickness* - enhances the neutronic performance of a moderator and reduces the energy deposited in the moderator per se; and g) *reflector materials/size* - enhances both the neutronic performance and pulse characteristics of a moderator. We will now discuss a few of these issues in detail.

4.1 *Neutron Intensity vs. Brightness*

In addition to target-moderator-reflector materials and geometry, the total number of neutrons leaking from a moderator surface (the moderator intensity) depends on the overall size of the moderator. Generally, the larger the moderator, the higher the neutron intensity.

Average Brightness - We define the average brightness of a moderator to be the total neutron leaking from a moderator surface divided by the area of the moderator viewed-surface. Figure 6 shows neutron intensity and average brightness for wing moderators [10]. When the moderators are made larger to gain intensity, reflector material is removed, and the target system becomes less efficient (in terms of useful neutrons per incident proton). In general, average moderator brightness decreases with increasing moderator size. Therefore, a criteria for high average moderator brightness requires small moderators, whereas, a criteria for high moderator intensity behooves large moderators. Clearly, a compromise must be struck, and we need objective criteria from instrument designers on the importance issue of *average moderator brightness vs. intensity.*

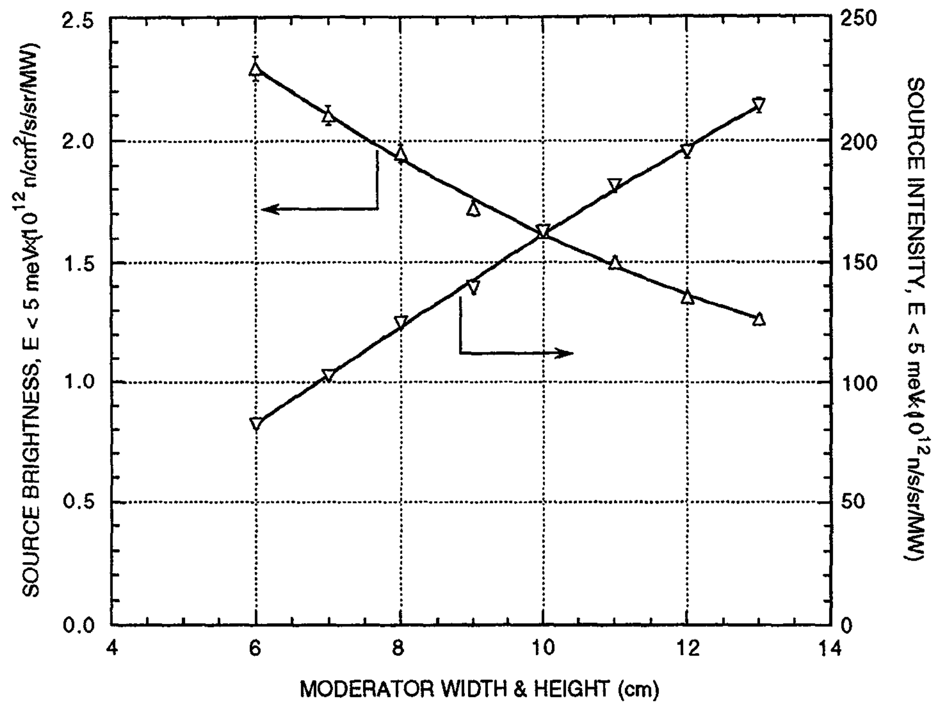

Figure 6. Average moderator brightness and moderator intensity vs. moderator size for wing moderators of liquid H_2 (ortho/para 50/50).

Specific Brightness - For a given moderator size, we define the *"specific moderator brightness"* to be the brightness over a smaller "field-of-view", i.e., over a smaller area of the moderator surface. Figure 7 shows specific brightness vs. field-of-view for both decoupled and coupled liquid H_2 flux-trap moderators. Because of "edge effects" (changes in the spatial distribution of leakage neutrons), the specific moderator brightness of a decoupled moderator is more sensitive to moderator field-of-view than is a coupled moderator.. There also appears to be spectral effects for a liquid H_2 moderator, i.e., the neutrons seem to be colder at smaller specific brightnesses [11].

4.2 *Temporal Brightness*

The *"temporal brightness"* (the peak time-dependent neutron brightness) is an important consideration in both SPSS and LPSS target system design. The temporal brightness can be altered with reflector type and by employing a composite reflector which we discussed above. We have calculated temporal brightness for liquid H_2 moderators coupled to D_2O and Be reflectors as well as for composite reflectors of Be/Ni, Be/W, and Be/Pb. The results are shown in Fig. 8 for an inner reflector size of 60 cm diam by 60 cm high. For the materials studied, D_2O exhibits the worst temporal brightness and a long-time tail. The Be/W composite reflector has slightly better temporal brightness than D_2O/Pb. Because of the moderate neutron absorption in W, the long-time tail for the Be/W composite reflector is better than the D_2O/Pb combination. The temporal brightness is further improved in going to a Be/Ni reflector with shorter long-time tails. An all Be reflector gives a high temporal

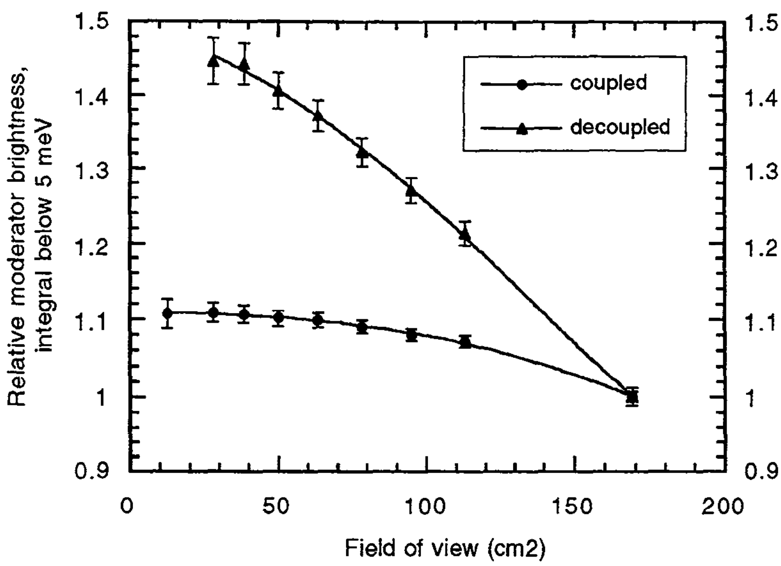

Figure 7. Specific Brightness versus moderator field-of-view for decoupled and coupled liquid H_2 (ortho/para 50/50) flux-trap moderators. The moderators were $5x13x13\ cm^3$.

brightness, but has a long-time tail. The temporal brightness is the best for the Be/Pb composite reflector; the long-time decay constant is better than that for an all Be reflector but still needs improvement. We are studying ways of keeping the temporal brightness high and decreasing the long-time tails by composite reflectors of Be/Pb/Ni and Be/Pb/W.

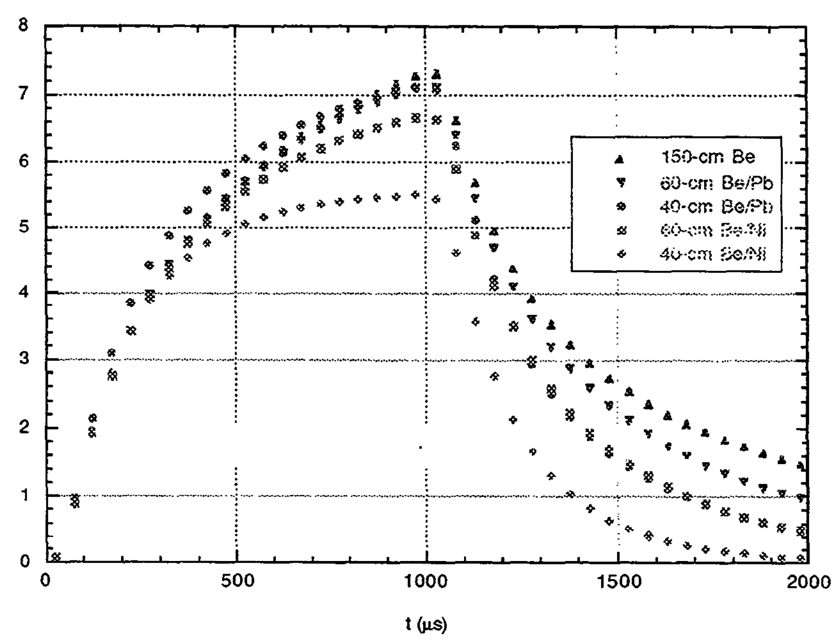

Figure 8. Temporal average moderator brightness from a liquid H_2 (ortho/para 50/50) flux-trap moderator for various reflector types.

4.3 *Liquid H_2 compared with Liquid D_2*

We have calculated the neutron flux inside spheres of liquid H_2 and liquid D_2 surrounded by a Be reflector to understand basic moderator characteristics. We placed an isotropic point source of 1-keV neutrons at the center of two concentric spheres of moderator/reflector (see Fig. 9), and calculated the neutron flux inside the moderator region. The results of the calculations are shown in Figs. 10 and 11.

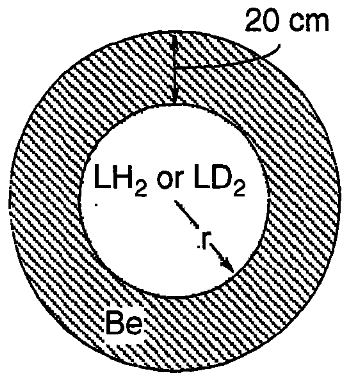

Figure 9. Geometry used to calculate neutron fluxes inside cold moderators of liquid H_2 and D_2 with ortho/para fractions of 50./50. An isotropic source of 1-keV neutrons was placed at the center of the moderator-reflector and the radius of the moderator was varied.

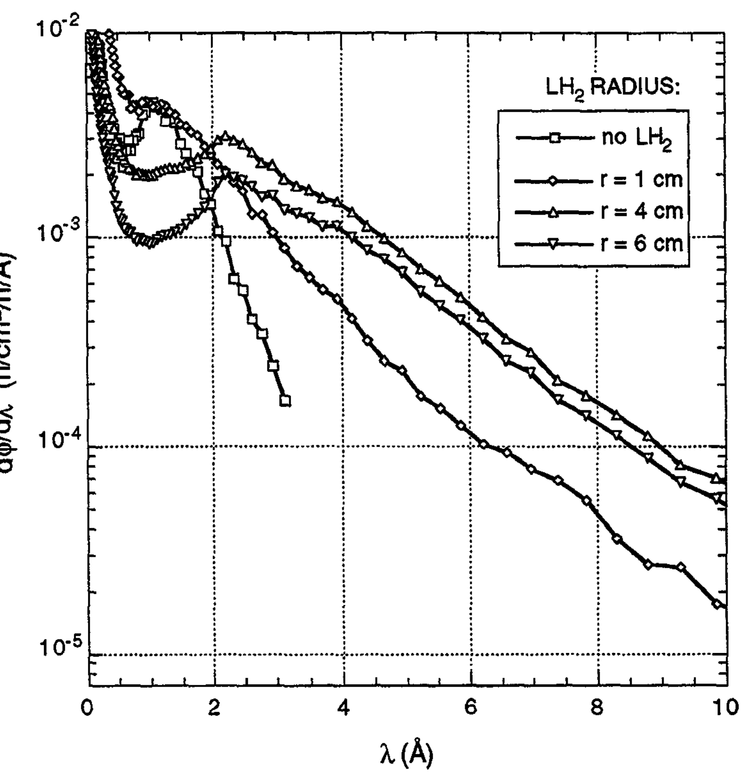

Figure 10. Neutron flux inside liquid H_2 moderator (ortho/para 50/50).

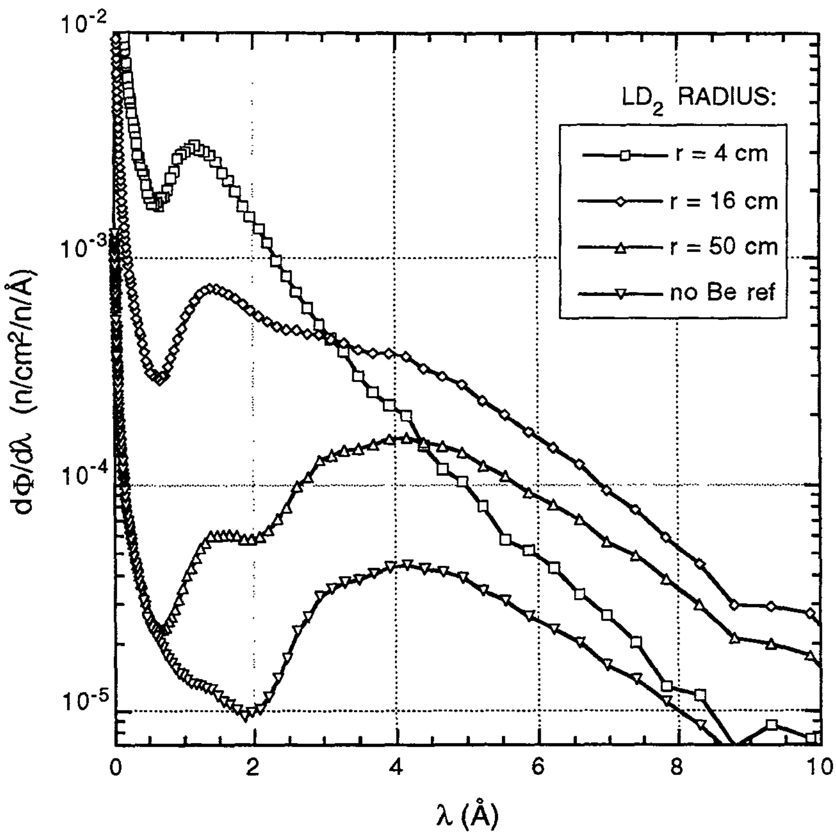

Figure 11. Neutron flux inside liquid D_2 moderator (ortho/para 50/50).

In Figure 10 we see a source of albedo neutrons from the beryllium when there is no hydrogen moderator. When the hydrogen moderator is present we see an increase in the epithermal neutrons and the beginning of the thermalization process. For these calculations, the neutron flux peaks at a radius of about 4 cm. In Figure 11, we see the effects of the beryllium reflector and a peaking in the neutron flux around 4 angstroms. The liquid H_2 doesn't show this peak presumably because of the increased absorption in H_2 compared to D_2. Thus, liquid H_2 produces the brightest cold source, but liquid D_2 produces a much larger volume of *"colder"* neutrons.

4.4 Ortho/Para-Hydrogen Fraction.

We have looked at the effect of ortho/para fraction on average moderator brightness as a function of moderator thickness and ortho/para fraction for coupled liquid H_2 moderators. The results are shown in Fig. 12. The average moderator brightness is largest for the 100% para-H_2 moderator which reaches a maximum around 10 cm. All the moderators with orth/para combinations show a "peaking" in the average brightness as a function of moderator thickness. This peaking occurs around moderator thicknesses of 5-6 cm. This study shows that it is important to know the ortho/para fraction for a liquid H_2 moderator in either a SPSS or a LPSS. Also, the pulse widths of neutrons leaking from a thick liquid H_2 moderators must be understood.

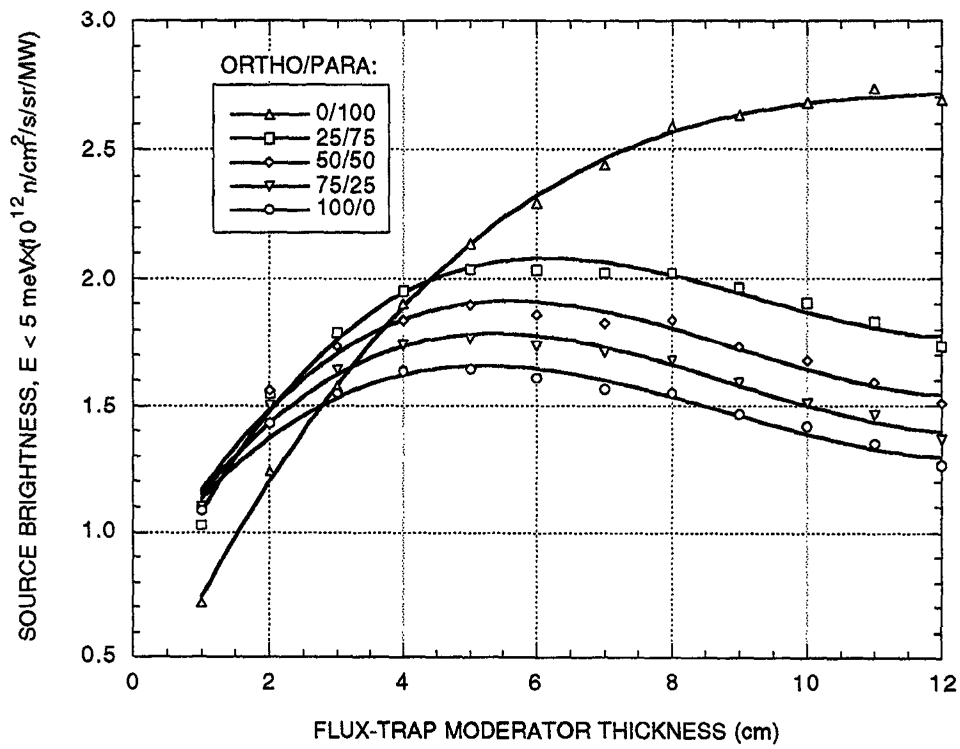

Figure 12. Average neutron source brightness from a 13x13 cm^2 liquid H_2 flux-trap moderator as a function of ortho/para concentration and moderator thickness. The target was D_2O-cooled W and the reflector D_20-Cooled Be (D_2O/Be 15/85).

Figure 13 shows the average moderator brightness of a liquid H_2 flux-trap moderator for several composite reflectors. The overall size of all the reflectors used in this work is 150 cm diam by 150 cm high. The average moderator brightness with a D_2O reflector is about 70% of that with a Be reflector. An "infinite" Be reflector is about 125x125 cm. For inner reflector sizes up to about 20 cm, the average moderator brightness for a D_2O/Pb composite reflector is the same as that of a Be/Pb composite reflector. For inner reflector sizes between about 20 and 125 cm, the average moderator brightness with a Be/Pb composite reflector is better than that of a D2O/Pb composite reflector.

Also, The average moderator brightness with an all Pb reflector is better than with an all Ni reflector and remains so up to an inner reflector size of about 125 cm. However, the neutron pulses from a moderator are shorter for a Be/Ni composite reflector compared to a Be/Pb composite reflector (see Fig. 8).

5. Conclusions

Optimizing the neutronic performance of a coupled-moderator system for a Long-Pulse Spallation Source is a new and challenging area for the spallation target-system designer. For optimal performance of a neutron source, it is essential to have good communication with instrument scientists to obtain proper design criteria, and continued interaction with mechanical, thermal-hydraulic, and materials engineers to attain a practical design. A good comprehension of the basics of coupled-moderator neutronics will aid in the proper design of a target system for a Long-Pulse Spallation Source.

Many traditional notions will have to be rethought and several new concepts put forward to meet the challenge of designing the target system for a next generation (5-MW) spallation neutron source. However, it is possible to design a high-performance target system for a 1-MW spallation source using existing technology.

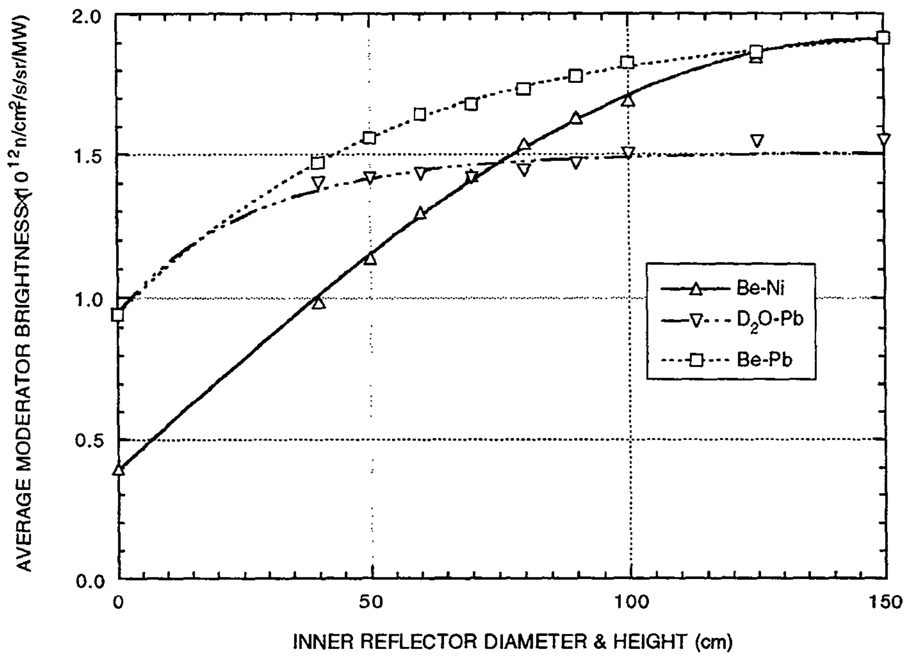

Figure 13. Average moderator brightness as a function of the inner reflector size and composition. The liquid H_2 (ortho/para 50/50) flux-trap moderators were 5x13x13 cm^3. The target was D_2O-cooled W rods.

6. Acknowledgments

We wish to acknowledge valuable discussions with Roger Pynn and Rex Hjelm. This work was supported by the U.S. Department of Energy, BES-DMZ, under Contract No. W-7405-Eng-36.

7. References

[1] G. J. Russell, C. D. Bowman, E. R. Whitaker, H. Robinson, and M. M. Meier, "LANSCE High-Power (200 μA) Target-Moderator-Reflector-Shield," in ICANS-VIII: Proceedings of the Eighth Meeting of the International Collaboration on Advanced Neutron Sources, Rutherford-Appleton Laboratory report RAL-85-110 (November 1985), pp. 272-293.

[2] G. Fluharty, F. B. Simpson, G. J. Russell, and J. H. Menzel, "Moderator Studies for a Repetitively Pulsed Test Facility (RPTF)," *Nuclear Science and Engineering,* **35**, 45-69 (1969).

[3] G. J. Russell, J. S. Gilmore, H. Robinson, G. L. Legate, A. Bridge, R. J. Sanchez, R. J. Brewton, R. Woods, and H. G. Hughes, III, "LANSCE Target System Performance," in *Advanced Neutron Sources 1988: Proceedings of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X),* Dianne Hyer, Ed. (IOP Publishing Ltd., Bristol, England), Vol. 97, pp. 483-496.

[4] G. J. Russell, "LANSCE Upgrade Cold Sources," in "Proceedings of the International Workshop on Cold Neutron Sources," Los Alamos National Laboratory report LA-12146-C (August 1991), pp. 471-489.

[5] G. J. Russell, H. Robinson, G. L. Legate, R. Woods, E. R. Whitaker, A. Bridge, K. J. Hughes, and R. D. Neef, "The LANSCE Target System," in *ICANS-IX: Proceedings of the Ninth Meeting of the International Collaboration on Advanced Neutron Sources*, F. Atchison and W. Fischer, Eds., Swiss Institute for Nuclear Research report ISBN 3-907998-01-4 (April 1987), pp. 177-244.

[6] N. Watanabe, S. Ikeda, and Y. Ishikawa, "KENS Target Station, " in *ICANS-IV: Proceedings of the Fourth Meeting of the International Collaboration on Advanced Neutron Sources*, Y. Ishikawa, N. Watanabe, Y. Endoh, N. Niimura, and J. Newsam, Eds., National Laboratory for High Energy Physics report KENS-II (March 1981), pp. 181-199.

[7] A. Carne, "Review of the SNS Target Station," in *ICANS-IV: Proceedings of the Fourth Meeting of the International Collaboration on Advanced Neutron Sources*, Y. Ishikawa, N. Watanabe, Y. Endoh, N. Niimura, and J. Newsam, Eds., National Laboratory for High Energy Physics report KENS-II (March 1981), pp. 136-153.

[8] J. M. Carpenter, C. W. Potts, and G. H. Lander, "Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL): A Status Report as of June 1982," in *ICANS-VI: Proceedings of the Sixth Meeting of the International Collaboration on Advanced Neutron Sources*, Argonne National Laboratory report ANL-82-80 (January 1983), pp. 77-101

[9] W. E. Fischer, "Status Report of SINQ: A Continuous Spallation Neutron Source," in *Advanced Neutron Sources 1988: Proceedings of the Tenth Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-X),* Dianne Hyer, Ed. (IOP Publishing Ltd., Bristol, England), Vol. 97, pp. 67-78.

[10] E. J. Pitcher, G. J. Russell, P. A. Seeger, and P. D. Ferguson, "Performance of Long-Pulse Source Reference Target-Moderator-Reflector Configurations," these proceedings.

[11] P. D. Ferguson, private communication.