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STUDIES OF A LEAD REFLECTOR FOR A PULSED NEUTRON SOURCE

by

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1. INTRODUCTION

Many of the new generation of accelerator based neutron sources have adopted a target-moderator geometry in which the neutron beam is tangential to the target (wing geometry). Such an arrangement significantly reduces the high energy (up to several hundred MeV) neutron background compared with the radial configuration (slab geometry). This improvement in background is accompanied by a severe reduction in solid angle between target and moderator, thus reducing the neutronic coupling. Some compensation may be achieved by using a fast neutron reflector [1]. These reflectors fall into two classes: moderating reflectors such as water, polyethylene, heavy water, graphite and beryllium; and non-moderating reflectors such as iron, copper, nickel and lead. Both experiment and Monte Carlo simulation show beryllium to be the superior moderating reflector. In this paper, we examine the consequences of adopting a non-moderating reflector and compare its performance to that of beryllium.

Reflector studies on a time modulated source [2] have shown lead to be an excellent reflector, maintaining the structure of the long time pulse (500 μs) marginally better than beryllium and with a slightly superior yield. Engineering, fabrication and cost factors as well as improved gamma and fast neutron shielding properties further favour lead as a reflector for these sources. Even for truly pulsed sources which rely primarily on time of flight for energy selection, Monte Carlo studies have shown that a lead reflector maintains an excellent time structure in hydrogenous moderators in the slowing down region [3]. In this paper, we describe the experimental comparison of lead and beryllium reflectors for the case of a pulsed spallation source. The target-moderator-reflector configuration used was a mock-up of the Rutherford Appleton Laboratory's SNS geometry. The experiments were performed in the low current target area of the Los Alamos National Laboratory's spallation source, the WNR. This work was complemented by Monte Carlo calculations using the TIMOC code[4].

2. EXPERIMENTAL MEASUREMENTS AT THE WNR

The capabilities of the low current target area of the WNR for time structure and spectral measurements on the neutron beams produced by pulsed spallation target-moderator-reflector assemblies have been described previously [5]. In this study, the normal WNR reflected 'T' configuration, figure 1a, was modified to simulate the geometry of the SNS assembly [6], figure 1b. Only one moderator was used and it was open on both faces. The decoupler and void liner (which was removable) were cadmium; and a neutronic approximation to SNS's heavy water cooling wings was incorporated. The reflector, which could be either lead or beryllium, formed a 40 cm cube around the system. Both ^{238}U and Pb targets were used to study the effect of the harder spectrum from the small Pb target.

Using the pyrolytic graphite crystal analyser arm, the time structure of moderated neutron pulses from a lead reflected and a beryllium reflected moderator were compared. The 100 ns long proton pulses used make a negligible contribution to these data and the 0.4% resolution of the spectrometer is small in comparison with the observed widths. Semi-logarithmic plots of these data (unnormalized) are shown in figures 2a and 2b. In both cases, there was a cadmium decoupler between moderator and reflector and a cadmium void liner in the neutron beam port through the reflector. The FWHM of the time pulses were found, within experimental error, to be identical. Further, it was possible to superimpose the time pulses from both reflectors over two orders of magnitude showing that the <u>shape</u> was the same.

The overall efficiency of the two reflectors was compared by measuring the spectral distribution by time of flight over a 5.58 m flight path. Each data set was normalized, corrected for detector efficiency and attenuation factors and converted to an energy distribution (see [5] for details). The overall spectrum is then described by a maxwellian region:

$$\phi_{max}(E) = \phi_m \frac{E}{T^2} \exp(-E/T)$$

and an epithermal region

$$\phi_{epi}(E) = \frac{\phi e}{E^{\gamma}}$$

joined together by a switch function

$$\Delta(E) = \left[1 + \exp\left(\frac{W_1}{\sqrt{E}} - W_2\right)\right]^{-1}$$

thus

$$\phi(E) = \phi_{max}(E) + \Delta(E)\,\phi_{epi}(E)$$

In these equations, ϕ_m is the integrated maxwellian intensity, T is the effective neutron temperature, ϕ_e is the differential intensity at 1 eV, γ is a measure of the leakage of the system and W_1 and W_2 parameterize the switch from slowing down to thermalization behavior. Using ϕ_m, T, ϕ_e, γ, W_1 and W_2 as parameters, a fit is made to the data*. A typical fit is shown in figure 3. The results of this analysis are summarized in Table I for studies with a Pb target and in Table II for studies with the ^{238}U target. The latter table contains data from coupled as well as decoupled systems. The yield parameters ϕ_m and ϕ_e indicate that although a lead reflector performs well, it is not as efficient as a beryllium reflector. At this point the question of reflector dimensions must be raised: although both reflectors were physically identical in size, their neutronic dimensions were not the same. A 40 cm beryllium reflector is close to its optimum size [3]; the Monte Carlo technique was employed to establish the optimum size of a lead reflector.

*NOTE: The values of $\gamma > 1.0$ indicate that a high energy background has not been accounted for. This background is less then 7% at 1.257 eV (the rhodium resonance) and may be large at high energies. In the thermal region, it is negligible.

3. MONTE CARLO OPTIMIZATION

Variation of the reflector cube dimensions experimentally would have been costly in time and effort, difficult to achieve because of the experimental set up and hazardous to personnel involved because of the radiation levels around the target. A very good estimate of the functional dependence of performance on cube size is readily achieved by Monte Carlo simulation. Such an optimization has already been described for the case of a beryllium reflector. We now report results for a lead and a heavy water reflector. The geometry used to optimize the reflector dimensions is shown in figure 4. A 10 x 10 x 5 cm^3 moderator is located centrally in a cube of reflector of side 2L and decoupled by a variable density B^{10} layer. An isotropic point source is located below the moderator. The coupling efficiency, as measured by neutrons leaking down the beam tube, is determined for a variety of dimensions, 2L. These data are given in figure 5 for beryllium, lead and heavy water reflectors. We observe that a 40 cm beryllium reflector (L = 20 cm) is within a factor 1.08 of the saturation value whereas the performance of a 40 cm lead reflector may be enhanced by up to a factor 1.3.

We note that the absolute performance of beryllium in this simple geometry (figure 4) is significantly better than that of lead or heavy water. Calculations on realistic geometries (with a target source rather than a point source) do not support this result. It would appear to be an artifact of the extremely tight source to moderator coupling employed. The saturation of the coupling with increasing moderator size is, however, quantitatively supported by realistic calculations and by experiment [5].

Using the information of figure 5 to scale the experimental data on a 40 cm cube reflector to a reflector of optimal size gives 11.4 and 3.9 for the thermal and epithermal coupling parameters when lead is the reflector (Pb target) and 11.5 and 3.8 for a beryllium reflector (Pb target). With the softer spectrum from a U^{238} target the thermal and epithermal parameters become 24.1 and 8.46 with a lead reflector and 25.3 and 8.45 with a beryllium reflector.

We may conclude that for pulsed neutron moderators a lead reflector is as efficient as a beryllium reflector. On the question of decoupler, some differences appear. As expected a coupled beryllium system has an effective neutron temperature of 25 meV, indicating the highly moderated nature of the spectrum, in comparison with some 34 meV when decoupled. It is known from other work that this increase in moderation is accompanied by a degradation in time structure. In the case of the lead reflector, some lowering in the neutron temperature did occur for the coupled case. No time measurement was made on the coupled lead reflector but it is reasonable to infer that some pulse degradation has occured and that even a non-moderating reflector such as lead may need to be decoupled for use in a truly pulsed source.

Two secondary aspects of the reflector's performance should be discussed, namely the fast neutron shielding effect and the distribution of energy within the moderator-reflector system.

4. FAST NEUTRON SHIELDING

For a tightly coupled target-moderator system in wing geometry, the collimation is usually set such that no neutron may leak out of the target directly into the experimental area. Table III summarizes the high energy attenuation lengths for some common shielding materials. For very high energy neutrons some rays exist with only a few mean free paths of attenuation [7], see figure 5. Such a problem may be eased (at the expense of flux) by increasing the target-moderator distance, by minimizing the collimator void or by adding additional shielding external to the bulk shield or internal to the target crypt. The reflector is the first material that such neutrons encounter and it is highly desirable to maximize their attenuation within the bulk shield. We see from Table III that lead is far superior in this aspect to beryllium.

5. NEUTRONIC HEATING

A disturbing feature of non-moderating reflectors is the redistribution of neutronic heating in the target-moderator-reflector assembly. As neutrons moderate in the reflector, they deposit energy which might otherwise be added to the moderator's heat load. In a non-moderating reflector neutrons entering the moderator after several collisions in the reflector still carry a large fraction of their initial energy. Figure 6 shows the Monte Carlo results for the fraction of the total energy available in the test geometry that was deposited in the moderator and reeflector as a function of the size of reflector, for all three reflector materials. Both heavy water and beryllium reflectors absorb substantial fractions of this energy (~80%) whereas even the largest size of lead reflector takes up less than 40%. The result is a factor 2 increase in heat deposited in the moderator. This calculation is idealized and the presence of a target is expected to reduce the effect. Although such a factor may not be significant for ambient or 90°K moderators, a substantial financial penalty would be incurred in the case of a liquid hydrogen moderator operating at 20°K. In such a case, a composite reflector[9] with a beryllium blanket (or other moderating reflector) surrounding the cryogenic moderator would be desirable.

6. CONCLUSION

This study illustrates the complementarity of experiment and Monte Carlo simulation. Neither technique on its own would have been able to answer the questions raised; for example, thermal pulse shapes from a reflected configuration are extremely difficult to compute and heat loads in the reflector and moderators impossible to measure at currents which are low enough to keep induced radiation at a level which would allow the experiment to be performed. There are many practical advantages to using a lead reflector. We find no degradation in the quality or intensity of moderated neutron pulses. The shielding advantage may be somewhat offset by the higher moderator heat loads, especially if cryogenic moderators are used.

References

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Table I

Pb TARGET

Reflector	Decoupler	ϕ_e	ϕ_m	T	γ	W_1	W_2
Be	Cd	3.54	10.7	33.6	1.05	90	8.5
Pb	Cd	3.01	8.8	33.8	0.99	97	9.3

Table II

U TARGET

Reflector	Decoupler	ϕ_e	ϕ_m	T	γ	W_1	W_2
Be	Cd	7.82	23.4	34.0	1.05	91	8.5
Pb	Cd	6.51	18.5	33.9	1.00	93	8.9
Be	--	8.08	35.4	25.0	1.07	132	14.6
Pb	--	6.88	24.7	28.6	1.02	118	12.4

Table III

High Energy Neutron Nuclear Mean Free Paths (MFP) [8].

Material	Be	H_2O	Concrete	Fe	Cu	W	Pb	U
MFP(cm)	50.0	90.3	46.1	17.3	15.8	10.1	17.8	11.1

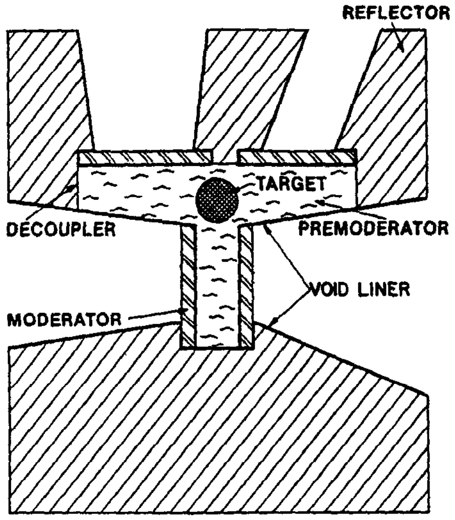

Fig. 1a

Section through the standard reflected 'T' shape moderator/premoderator configuration used at the WNR.

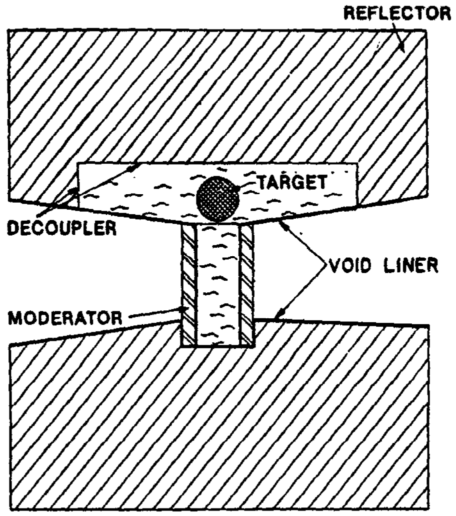

Fig. 1b

Section through the modified configuration simulating a single moderator SNS wing geometry.

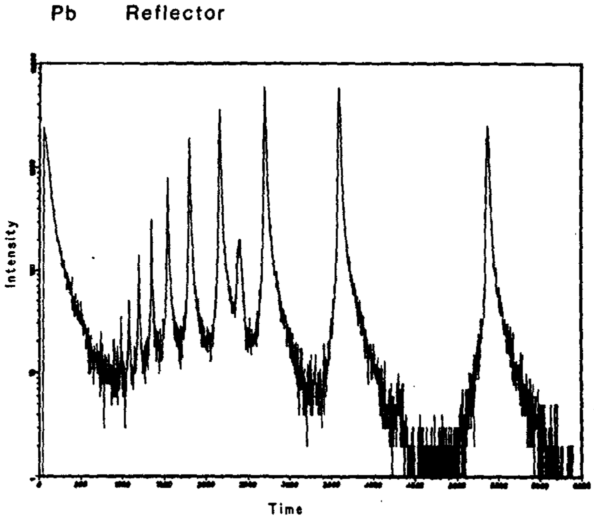

Fig. 2a

Semi-logarithmic plot the moderated pulse shapes of a lead reflected system. The moderator was cadmium decoupled polyethylene, poisoned at a depth of 1.27 cm by 0.025 mm of gadolinium. The peak at 5500 μs is the 004 reflection from pyrolitic graphite. The spurious peak at 2400 μs is the 002 reflection, viewed in frame overlap.

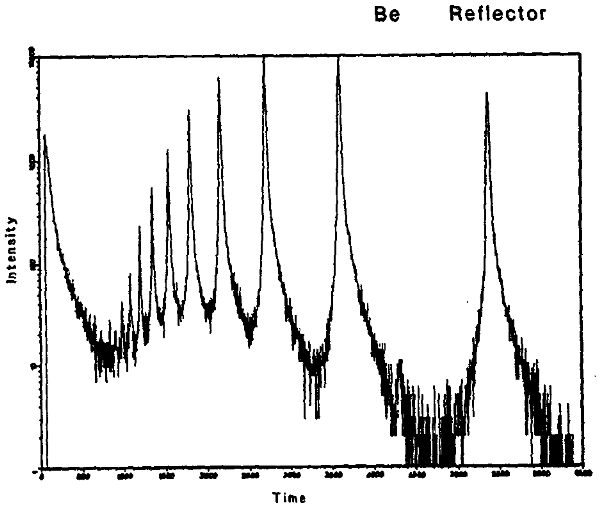

Fig. 2b

The corresponding data to figure 2a with beryllium as reflector. These data were taken at 60 Hz, thus eliminating the frame overlap problem.

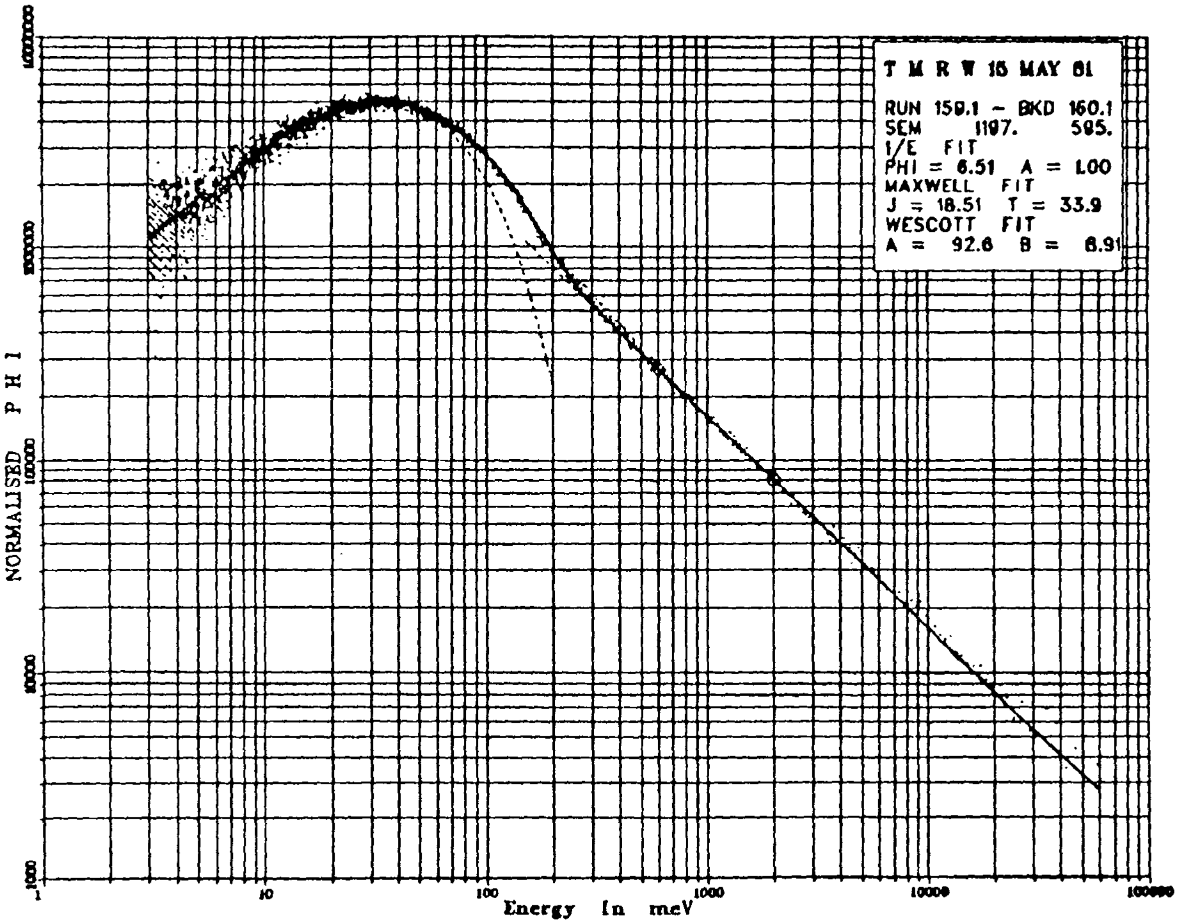

Fig. 3. A fit of a spectral measurement to the function described in the text. The dashed lines are independent fits to the maxwellian and slowing down regions. The solid line is the overall six parameter fit using the switch function.

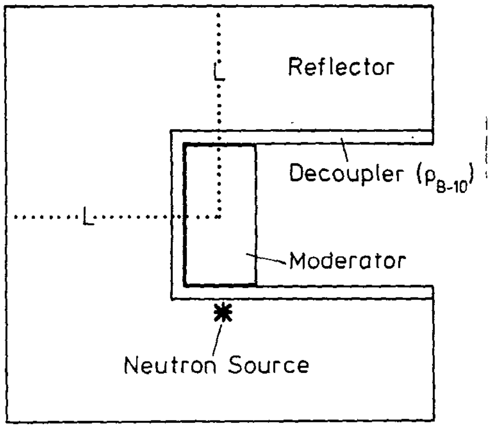

Fig. 4

The Monte Carlo geometry used to optimize the reflector dimension, L. The decoupler density for these studies was fixed at 0.5 eV(1/e).

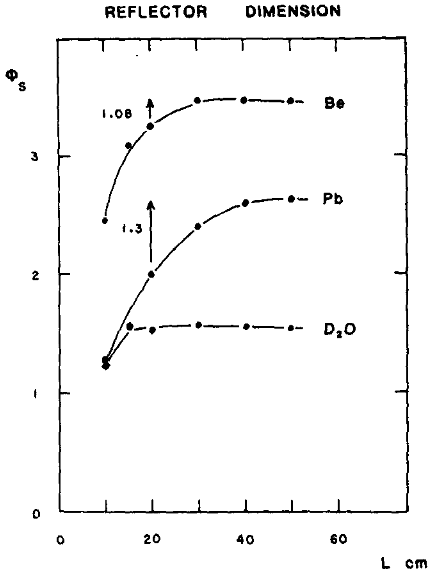

Fig. 5

The two steradian average of the surface flux from the moderator as a function of reflector dimension for beryllium, lead and heavy water reflectors. The numbers shown are the scaling factors required to convert a 40 cm cube of reflector to the asymptotic performance.

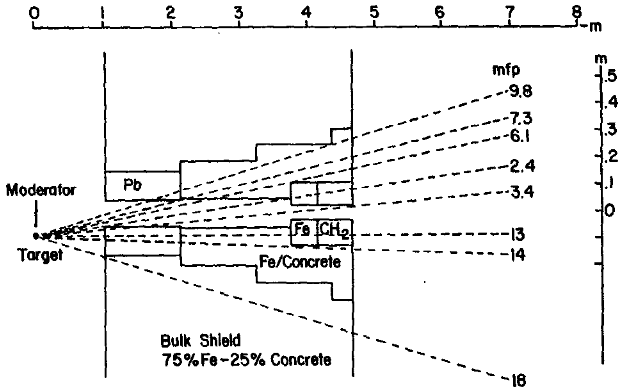

Fig. 6

The ray diagram for fast neutron collimation for a typical beam. The numbers opposite each ray correspond to the number of mean free paths seen by a 100 MeV neutron. Calculations [8] indicate that some 14 mean free paths are required to shield a 5 μA, 800 MeV source.

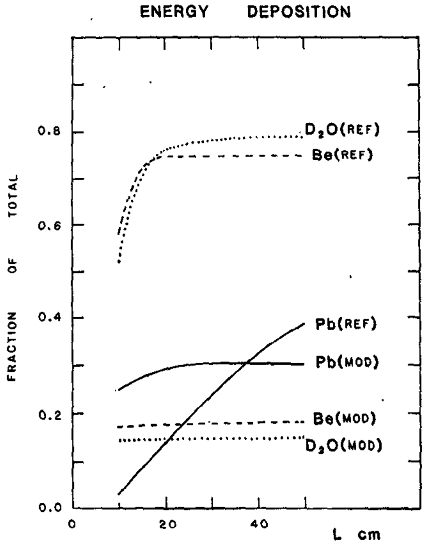

Fig. 7

The fraction of initial neutron energy deposited in the reflector and moderator of Figure 4 for beryllium, lead and heavy water reflectors.