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Low-Energy Neutron Shielding

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CONTENTS

ABSTRACT	1
I. INTRODUCTION	1
II. SHIELDING MATERIALS	1
III. CALCULATIONS	3
IV. RESULTS	5
V. CONCLUSIONS	7
REFERENCES	7

LOW-ENERGY NEUTRON SHIELDING

by

D.M. Lee

ABSTRACT

The attenuation of low-energy neutrons (< 20 MeV) through a 120-cm-thick slab shield of various mixtures of concrete, boron compounds, and water has been investigated. A Monte Carlo code was used to sample the neutron probability distribution and track the neutrons through the shield.

I. INTRODUCTION

In a recent study on the design of a neutral kaon beamline for a rare kaon decay experiment at Brookhaven National Laboratory,¹ one of the potentially most serious backgrounds was that from low-energy neutrons (≤ 20 MeV). The study suggested that a low-energy neutron shield upstream and around the decay section would greatly reduce the singles background, especially for higher intensity beams. This report outlines an effort to help define a low-energy neutron shield. A 120-cm-thick slab shield of various mixtures of concrete, boron compounds, and water was modeled in a Monte Carlo code to track neutrons emerging from an iron shield.

II. SHIELDING MATERIALS

Concrete, water, and boron compounds such as boron frit (50% B_2O_3) and boraxo ($Na_2B_4O_7 \cdot 10H_2O$) were considered in various combinations as a low-energy neutron shield following an iron beam stop. The elemental composition for each candidate shield configuration is shown in Table 1. The pure concrete is close to the standard CERN shielding concrete. In the boron-loaded form, the boron frit or boraxo replaces a portion of the sand aggregate in the concrete. The magnetite concrete is an ASTM-recommended mixture where the sand and gravel have been replaced by magnetite ore. This is sometimes called heavy concrete because of the increase in density. The slurry is an empirically determined mixture of boraxo and water that maximized the density.

Table 1
Elemental Composition of Candidate Shields

<u>Shield Configuration</u>	<u>Element Mass Fraction</u>									
	<u>H</u>	<u>¹⁰B</u>	<u>¹¹B</u>	<u>C</u>	<u>Na</u>	<u>^{Al}</u>	<u>Si</u>	<u>K</u>	<u>Ca</u>	<u>Fe</u>
Iron										≥1.0
Boraxo	0.053	0.022	0.091	0.713	0.121					
Pure Concrete	0.010			0.530	0.020	0.030	0.340	0.010	0.040	0.020
Borated Concrete	0.009	0.004	0.014	0.539	0.019	0.028	0.326	0.009	0.038	0.019
(400 lbs Boron frit)										
Borated Concrete	0.010	0.001	0.004	0.532	0.020	0.030	0.335	0.010	0.039	0.020
(100 lbs Boron frit)										
Borated Concrete	0.011	0.0003	0.001	0.533	0.021	0.030	0.335	0.010	0.039	0.020
(50 lbs Boraxo)										
Magnetite Concrete	0.007	0.003	0.010	0.350	0.014	0.020	0.020		0.028	0.550
(400 lbs Boron frit)										
Slurry	0.077	0.014	0.054	0.783	0.072					

III. CALCULATIONS

The Monte Carlo code, MCNP,² was used in the transport calculations. This code includes a very complete geometry package, a complete cross-section library, a generalized user-input source capability, and biasing techniques to improve sample statistics. The MCNP calculations are good for energies less than or equal to approximately 20 MeV, depending on the upper limit to the cross-section tables.

The shield geometry was 120 cm in the beam direction and infinite in the transverse direction. The shield was a completely homogenized mixture of the composite materials. Neutron tallies were recorded at depths of 30, 60, 90, and 120 cm through the shield.

The neutron-source distribution was derived from a distribution calculated by Armstrong and Alsmiller, Jr.³ This neutron spectrum was for neutrons emerging from a 220-g/cm²-thick iron shield when struck by 200-GeV incident protons. This spectrum is shown in Fig. 1. A noticeable feature of this spectrum is the enhancement of the neutron leakage at approximately 24 keV due to the transmission window in the iron cross section. Although the thickness of an iron beamstop for a neutral kaon beamline will be thicker than 220 g/cm², we expect that the probability distribution derived from this spectrum will be an adequate representation of the low-energy neutron distribution entering the neutron shield. For the calculation, neutrons of energy ≤ 10 MeV were included in deriving the probability distribution. The neutron-source probability distribution is shown in Table 2. The source consisted of monoenergetic neutrons at the energy bin boundaries, and each energy was selected with the corresponding probabilities for that bin. The source was uniformly distributed across a 1.5-meter-diameter disk located at the entrance face of the shield and directed normal to the entrance face. At each tally surface, the integral of the neutrons crossing that surface was tabulated. Biasing techniques were used at each tally surface to increase the statistical precision of the results. For a few selected shield configurations, the source shown in Table 2 was replaced with a monoenergetic 20-MeV source to show the effect of a different source distribution on the effectiveness of the shields.

Fig. 1 . Neutron Leakage Spectra at a Radius of 220 g/cm² for Iron and Iron Followed by Heavy Concrete.

Table 2
Neutron Source Probability Distribution

<u>Energy (MeV)</u>	<u>Fraction</u>
1.0×10^{-6}	0.0006
1.0×10^{-5}	0.0027
1.0×10^{-4}	0.0030
1.0×10^{-3}	0.0091
1.0×10^{-2}	0.0456
1.0×10^{-1}	0.6080
1.0×10^0	0.3040
1.0×10^1	0.0270

IV. RESULTS

Summaries of the results for the different shield configurations are shown in Tables 3 and 4. The results are quoted as the fraction of neutrons surviving per source neutron. The results in Table 3 are for the calculations with the distributed source of Armstrong and Alsmiller, Jr.,³ and in Table 4 for a monoenergetic 20-MeV source. As expected, the addition of boron to concrete increases the attenuation of neutrons by removing the low-energy portion of the spectrum. However, there appears to be no advantage to increasing the boron concentration beyond 50-100 lbs per yd of concrete. The primary reason for this is that the efficiency for removing neutrons through neutron capture on boron depends on the efficiency for downscattering in energy of the high-energy neutrons. The hydrogen content in the concrete is the primary element for downscattering the neutron energy from above 1.0×10^{-2} MeV to less than 1.0×10^{-2} MeV where the boron capture cross section is important. The concentration of hydrogen is, therefore, too small to allow a greater concentration of boron to be useful.

The slurry provides the largest attenuation of all the shield configurations. It has a large concentration of hydrogen that quickly reduces the neutron energies to values where the boron can be effective. Its low density, however, reduces the effectiveness of the shield for neutrons greater than 20 MeV.

Table 3
Surviving Neutron Fraction for Source of Armstrong and Alsmiller, Jr.¹
Depth in Shield

<u>Shield Configuration</u>	<u>30 cm</u>	<u>60 cm</u>	<u>90 cm</u>	<u>120 cm</u>	<u>Density (g/cm³)</u>
Iron	$5.7 \times 10^{-1} \pm 0.02$	$2.5 \times 10^{-1} \pm 0.02$	$9.3 \times 10^{-2} \pm 0.02$	$1.0 \times 10^{-2} \pm 0.02$	7.89
Boraxo	$1.3 \times 10^{-2} \pm 0.02$	$2.0 \times 10^{-3} \pm 0.04$	$2.9 \times 10^{-4} \pm 0.08$	$2.8 \times 10^{-5} \pm 0.13$	1.06
Pure Concrete	$1.9 \times 10^{-1} \pm 0.02$	$7.9 \times 10^{-3} \pm 0.05$	$3.5 \times 10^{-4} \pm 0.17$		2.42
Borated Concrete	$1.8 \times 10^{-2} \pm 0.02$	$1.0 \times 10^{-3} \pm 0.07$	$8.5 \times 10^{-5} \pm 0.15$		2.42
(400 lbs Boron frit)					
Borated Concrete	$2.2 \times 10^{-2} \pm 0.02$	$1.0 \times 10^{-3} \pm 0.07$	$7.1 \times 10^{-5} \pm 0.20$		2.42
(100 lbs Boron frit)					
Borated Concrete	$2.4 \times 10^{-2} \pm 0.02$	$1.0 \times 10^{-3} \pm 0.08$	$5.4 \times 10^{-5} \pm 0.20$		2.42
(50 lbs Boraxo)					
Magnetite Concrete	$1.2 \times 10^{-2} \pm 0.03$	$4.3 \times 10^{-4} \pm 0.11$	$1.7 \times 10^{-5} \pm 0.37$		3.5
(400 lbs Boron frit)					
Slurry	$3.7 \times 10^{-3} \pm 0.04$	$2.1 \times 10^{-4} \pm 0.14$			1.5

Table 4
Surviving Neutron Fraction for a 20-MeV Source
Depth in Shield

<u>Shield Configuration</u>	<u>30 cm</u>	<u>60 cm</u>	<u>90 cm</u>	<u>120 cm</u>
Pure Concrete	1.05	$2.0 \times 10^{-1} \pm 0.02$	$2.3 \times 10^{-2} \pm 0.05$	$7.4 \times 10^{-4} \pm 0.08$
Borated Concrete	$5.2 \times 10^{-1} \pm 0.01$	$7.1 \times 10^{-2} \pm 0.02$	$7.0 \times 10^{-3} \pm 0.03$	$3.4 \times 10^{-4} \pm 0.06$
(400 lbs Boron frit)				
Borated Concrete	$5.5 \times 10^{-1} \pm 0.01$	$7.5 \times 10^{-2} \pm 0.01$	$7.9 \times 10^{-3} \pm 0.03$	$3.4 \times 10^{-4} \pm 0.06$
(100 lbs Boron frit)				
Magnetite Concrete	$4.6 \times 10^{-1} \pm 0.01$	$4.1 \times 10^{-2} \pm 0.02$	$2.7 \times 10^{-3} \pm 0.05$	$9.3 \times 10^{-5} \pm 0.12$
(400 lbs Boron frit)				
Slurry	$2.8 \times 10^{-1} \pm 0.01$	$3.1 \times 10^{-2} \pm 0.02$	$2.7 \times 10^{-3} \pm 0.04$	$1.5 \times 10^{-4} \pm 0.09$

The magnetite concrete has the same amount of water and boron as standard concrete but is more efficient than standard concrete primarily because of its higher density. It will also be a better shield for neutrons above 20 MeV than standard concrete.

Pure boraxo has a high concentration of both hydrogen and boron, but its low density limits the attenuation to values less than the concrete shields and slurry. Pure iron is the poorest low-energy shield because of a low capture cross section and because elastic scattering on iron is an inefficient process in reducing the neutron energy.

The results in Table 4 for the 20-MeV source show attenuation factors that are higher than for the distributed source. This reflects the dependence of the attenuation on the source distribution. At this and higher energies, the most important parameter is the density of the shield.

V. CONCLUSIONS

The choice of the neutron shield configuration depends on the spectrum of neutrons entering the shield and on the cost and ease of manufacture. Standard shielding concrete with boron loading is an effective low-energy shield and is probably the least expensive. Magnetite concrete is better than standard concrete primarily because of the increase in density. However, the magnetite ore is a more expensive aggregate and less readily available, and consequently magnetite concrete is useful only in situations where standard concrete does not provide enough attenuation. Slurry is by far the most effective low-energy neutron shield. However, it requires a sturdy container to hold the material and a means for preventing the evaporation of the water.

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