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KERMA TRANSMISSION THROUGH STEEL

FOR A p(66)Be(49) NEUTRON BEAM, AN UPDATE.

Randall K. Ten Haken , Miguel Awschalom, Ivan Rosenberg
Fermi National Accelerator Laboratory, Neutron Therapy Facility
P. O. Box 500, Batavia, Illinois 60510.

Introduction

Steel is being considered for use as the primary shielding material for a highly penetrating neutron therapy beam comparable to the p(66)Be(49) beam in use at Fermilab. This shielding would surround a p(70)Be(45) clinical neutron source mounted on an isocentric gantry. Therefore, we are updating our previously published kerma transmission results (Aw81b) after making new measurements under better geometry, extending the measurements to include greater thicknesses of steel absorber and, to see the broad beam build-up effects, taking measurements at various points downstream from the absorber.

For 15 MeV neutrons, 50 cm thick shields comprising multilayers of steel, polyethylene and/or borated materials have been reported (Ma72) to be more effective per unit length than shields of steel alone. Also, since radioactivity is induced in steel by neutrons, the steel shield itself may become a source of exposure to medical personnel entering the area after treatment. It may, therefore, be desirable to have lead surrounding the neutron shield. An outer layer of lead may also be useful during beam-on conditions if a significant photon exposure rate is still present outside the shield. This has been the experience for a p(41)Be beam incident on a Benelex* shield with a lead outer liner (He78). Therefore, the effectiveness of multilayer shields consisting of steel, polyethylene, and lead outer liners was also investigated.

Experimental Methods

The Fermilab Neutron Therapy Facility (Co76, Aw79) and the p(66)Be(49) neutron beam (Aw81a, Ro81) have been described in detail elsewhere.

The transmission measurements were made using an air-filled 8 cm^3 spherical ionization chamber with a build-up cap. The cap, wall, and collector were made of A-150 tissue equivalent (TE) plastic (Sm77). The cap plus wall had a thickness of 1.7 g cm^{-2}. This chamber was designed and built by Paul de Luca and Richard P. Torti of the University of Wisconsin, Madison, Wisconsin. The charge collected was interpreted as being proportional to total kerma in A-150 TE-plastic at that point in air. Figure 1 shows the experimental arrangement.

For the broad beam (At76) measurements, the neutron beam was collimated to a 34 cm diameter field at the chamber position A, 174.5 cm downstream from the target (see Figure 1). Steel plates (ρ = 7.8 g cm^{-3}) measuring 40 x 40 x 2.5 cm^3 were stacked starting just upstream from chamber position A (3 cm from chamber center, nearly touching the build-up cap) with thickness increasing towards the source. The steel plates were individually measured and weighted. Measurements were also made with the chamber in positions B and C, 10 cm and 50 cm further downstream, respectively. For absorber thicknesses of 31.4 cm and 60.0 cm, additional measurements were made at chamber position A with the downstream 2.5 cm of steel (closest to the ion chamber) replaced by an equal thickness of lead. In the latter case (60.0 cm total thickness), two more measurements were made. The first was made after replacing the downstream 10 cm of steel with a sequence, in the beam direction, of 5 cm of high density polyethylene (ρ = 0.96 g cm^{-3}) plus 2.5 cm of steel plus 2.5 cm of lead. The second measurement was made by moving the 5 cm of polyethylene upstream such that only 10.5 cm of steel were upstream of the polyethylene, with 42 cm of steel plus 2.5 cm of lead downstream.

For narrow beam (At76) measurements the beam was limited by a concrete-polyethylene collimator to a 10x10 cm^2 field at the chamber position N, 316 cm from the target. The plates were stacked starting at the west wall, increasing in thickness towards the chamber.

Results and Discussion.

The broad beam results are presented in Table 1 and in Figure 2. The curves shown are drawn to guide the eye. The measurements taken at position A for the large field size most closely approximate broad beam conditions. A thickness of 469 g cm^{-2} of steel is seen to reduce the kerma transmission at this point to less than 0.6%. From previous broad beam results (Aw81b) we would expect steel to attenuate this beam more effectively than lead. In fact, for absorber thicknesses on the order of 30 cm, the last 2.5 cm of lead in a lead stack attenuate the beam approximately 7% less than the last 2.5 cm of steel in a steel stack. However, as can be seen from Table 1, replacing the last 2.5 cm of steel with lead in a steel stack decreases the attenuation by 3% at 31 cm total thickness and does not change the attenuation of a 60 cm stack. Since the A-150 detector has nearly equal sensitivity to both neutrons and photons, and since lead attenuates photons more effectively than steel, we might explain the present results in terms of the changing proportions of photon and neutron components in the beam. For steel alone, photons apparently become a larger fraction of the transmitted beam as the stack thickness increases, to a point near 60 cm total thickness where 2.5 cm of lead attenuate the total (neutron plus photon) kerma as effectively as 2.5 cm of steel. In support of this explanation, preliminary measurements (Be 82) in a neutron beam similar to ours indicate that, for thick steel stacks, replacing small downstream layers of steel with lead decreases the photon fraction but increases the neutron fraction of the transmitted beam.

It can also be seen from Table 1 that, for 60 cm of absorber, when 5 cm of steel are replaced with 5 cm of high density polyethylene, the kerma transmission changes only slightly and is nearly independent of the position of the polyethylene absorber stack. These measurements were made with 2.5 cm of lead at the end of the stack because photon production in polyethylene is expected to be as great or greater than in steel. The slightly increased transmission observed here is in contrast to the results for 15 MeV neutrons (Ma72), where the transmitted fraction actually decreased markedly when part of the steel was replaced with polyethylene at constant total thickness. Since no benefit in kerma attenuation of the present beam was seen with 5 cm of polyethylene, no other combination of steel and polyethylene was investigated. However, since the increase in transmitted kerma noted here is small, a considerable saving in weight may be achieved by replacing 5 cm of steel with 5 cm of polyethylene next to the outer layer of a shield. If lead is used as an outer liner (as proposed above for beam-off protection of personnel) savings in total weight of the primary shield become even more important.

The relative ionizations given in Table 1 with no absorber present, 1.000, 0.890, and 0.594 for positions A, B and C, respectively, are in proportion to inverse square distance from the neutron source. Consideration of the curves in Fig. 2 enables one to perceive build-up effects and illustrates the transition from semi-broad to semi-narrow beam conditions. Build-up effects are quite apparent, as indicated by the convex nature of the early parts of the broad beam curves and are more evident for the positions nearer the stack. At large stack thicknesses, the curves become concave indicating approach to background levels and/or beam hardening. Since the measurements at point C have not been influenced as much by build-up as those at point B (and likewise B versus A) the convex to concave change of its curve occurs at smaller stack thicknesses. The previously reported broad beam results (Aw81b) fall between the present point A and point B values, indicating that better broad beam conditions were achieved this time.

The narrow beam results are also presented in Figure 2, where the dashed curve has been drawn to guide the eye. An attenuation length (Aw81b) $\lambda = 37.5$ g cm^{-2} is obtained from the slope of the initial attenuation curve. This is consistent with the previously calculated value (Aw81b) of 36.8 g cm^{-2}. Point by point subtraction of the quantity $\exp(-x/37.5)$ (drawn in Fig. 2 as the tangent to the initial narrow beam curve) from the narrow beam data results in values represented by the solid line at the bottom of Fig. 2. This decreasing background level appears to be mostly related to transmission through the central portion of the front (west) shielding wall (Figure 1). As stated above, for the narrow beam measurements the steel plates were stacked starting at this wall. Therefore, as the stack thickness is increased, more and more of the central region of the front wall is shielded from the detector. In other words, the steel plates subtend a greater solid angle at the detector as they get closer to it. If the majority of the background at the detector is originating somewhat uniformly from transmission through the central portion of the front wall, as other measurements indicate, we would expect the background to decrease in proportion to the increase in that solid angle. Since the plates all have the same area, the solid angle changes as the inverse square of the distance from the detector to the nearest plate. For the distances involved, this $1/R^2$ change in residual background is very closely approximated by the solid line at the bottom of Fig. 2. As in the broad beam case, for the full 60 cm stack thickness, exchanging the downstream 2.5 cm of steel for lead leaves the total kerma transmission essentially unchanged.

Conclusions.

These measurements show that, in the design of a target shield for a therapeutic neutron beam source to be mounted on an isocentric gantry, considerable weight may be saved using 5 cm of polyethylene in place of 5 cm of steel, especially in the outer layers. Furthermore, for beam-off protection of medical personnel, the outer 2.5 cm of steel may be replaced with 2.5 cm of lead without significant loss of beam-on protection to the patient.

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Table 1

BROAD BEAM MEASUREMENTS IN STEEL

Absorber Thickness (cm)	Kerma Transmission			Absorber Thickness †($g\ cm^{-2}$)
	point A	point B	point C	
0	1.000	*1.000	**1.000	0
2.63	.923	.828	.719	20.3
5.26	.794	.673	.522	41.4
10.5	.536	.423	.280	82.1
15.7	.342	.258	.154	123.
20.9	.211	.154	.0850	163.
26.1	.127	.0912	.0485	204.
31.4	.0757	.0537	.0288	246.
39.2	.0351	.0251	.0147	307.
49.7	.0131	.0099	.0075	398.
60.0	.0053(a)	.0046	.0045	469.
31.4	.0778(b)			
60.0	.0057(c)			
60.0	.0060(d)			

† $\rho = 7.82\ g\ cm^{-3}$
* Ionization was 0.890 of reading at point A.
** Ionization was 0.594 of reading at point A.
(a) Kerma transmission essentially the same for 60 cm Fe as for 57.5 cm Fe + 2.5 cm Pb.
(b) 28.9 cm Fe (upstream) + 2.5 cm Pb (downstream).
(c) 50 cm Fe (upstream) + 5 cm $(CH_2)_n$ + 2.5 cm Fe + 2.5 cm Pb (downstream).
(d) 10.5 cm Fe (upstream) + 5 cm $(CH_2)_n$ + 42 cm Fe + 2.5 cm Pb (downstream).

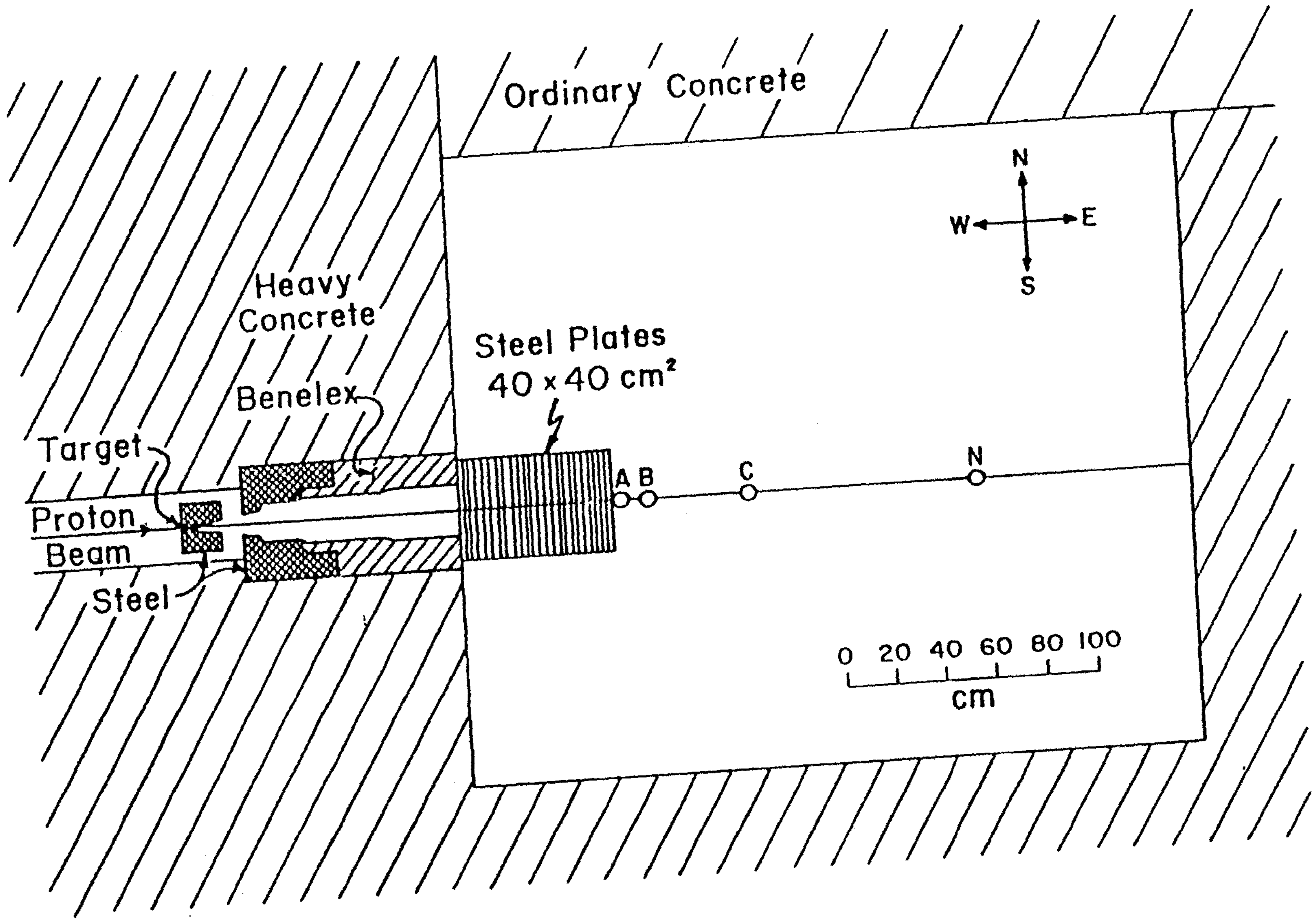
FIGURE CAPTIONS

Figure 1. Plan view of treatment room showing experimental layout. Beam enters from west. West wall is 110 cm from neutron source. Full description of collimator system and materials in Ref.(Ro81). False floor is located approximately 30 cm below beam level.

i) For broad beam measurements. Beam size at chamber position A (63 cm from west wall) is 34 cm in diameter. Steel plates are stacked in increasing thickness from east to west. Chamber positions A, B and C are 3, 13, and 53 cm downstream from the steel plates, respectively.

ii) For narrow beam measurements. Additional Benelex plus polyethylene-concrete is used to collimate the beam to 10x10 cm^2 at point N. Steel plates stacked in increasing thickness from west to east. The only chamber position used is N (206 cm from west wall).

Figure 2. Kerma fraction transmitted through steel under semi-broad and narrow beam conditions.



Ordinary Concrete
N
W
E
S
Heavy Concrete
Steel Plates
40 x 40 cm²
Benelex
Target
Proton
Beam
Steel
A
B
C
N
0 20 40 60 80 100
cm

Figure 1

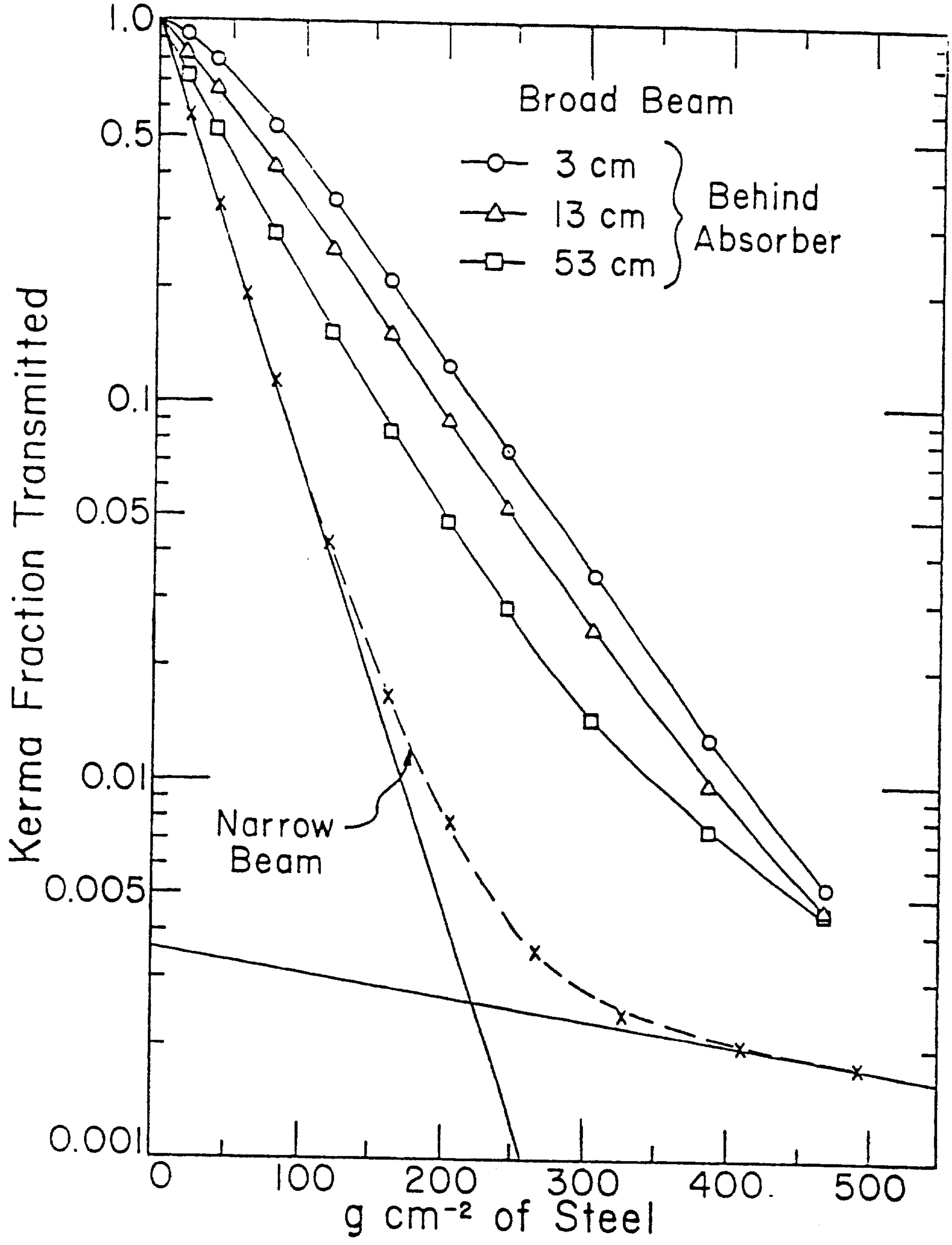

Broad Beam
3 cm
13 cm
53 cm
Behind Absorber
Narrow Beam
Kerma Fraction Transmitted
g cm⁻² of Steel
1.0
0.5
0.1
0.05
0.01
0.005
0.001
0
100
200
300
400
500

Figure 2