SLAC-PUB-7695
February 1998

Shielding of Radiation Fields Generated by Cf-252 in a Concrete Maze, Part 1- Experiment

N.E. Ipe et al.

Stanford Linear Accelerator Center
Stanford University
Stanford, CA 94309 USA

Presented at the 1998 ANS Radiation Protection and Shielding Division
Topical Conference, Technologies for the New Century, 4/19/98—4/23/98,
Nashville, TN, USA

Work supported by Department of Energy contract DE–AC03–76SF00515.

SLAC-PUB-7695

SHIELDING OF RADIATION FIELDS GENERATED BY ^{252}Cf IN A CONCRETE MAZE, PART I - EXPERIMENT

N. E. Ipe[1], R. C. McCall[2], T. M. Jenkins[3] and E. Benson[4]
[1]Stanford Linear Accelerator Center, P.O. Box 4349, Stanford. CA 94309
[2]McCall Associates, Woodside, California
[3] Palo Alto, California
[4] ICF Kaiser, Richland, Washington

ABSTRACT

A concrete room with a single-legged maze was constructed in order to simulate a medical accelerator room. Gamma and neutron measurements were performed along the maze with a) a ^{252}Cf source and b) a tungsten-moderated ^{252}Cf source placed inside the room. The measurements were repeated after placing an inner borated polyethylene door of varying thickness (2.54 -10.16 cm) at 2 different locations. Measurements were also performed after lining the inside of the maze with different neutron moderating materials .The following results are reported: 1) the variation and contributions of individual components of the radiation fields as a function of distance along the maze 2) the attenuation of neutron dose equivalent and reduction of capture gamma rays as a function of borated polyethylene (BPE) inner door thickness and location of the inner door; and 3) the effect of lining the maze corner with different neutron moderating materials.

1. INTRODUCTION

Most radiation therapy rooms are designed with a basic or single-legged maze or labyrinth. [1]. This avoids the use of massive doors which have to be opened or closed by hydraulic systems. A well-designed maze provides significant attenuation, so that the door at the entrance to the maze (outer door) acts primarily as a security barrier. Sometimes however, due to the lack of sufficient space or lack of consideration of neutron shielding in the original design, mazes are ineffective.

Neutron production in medical accelerators can result in doses to both patients as well as operating personnel. Unlike photons, neutrons can scatter through large angles with minimal loss in energy. Thus the transport of neutrons through the maze can lead to undesirable radiation fields at the entrance to the maze. In addition to fast, intermediate-energy and thermal neutrons, the radiation fields in the maze also include gamma rays produced as a result of neutron capture in concrete and other shielding materials.

Several years ago, under the leadership of McCall, we performed experiments in which a single-legged concrete maze was constructed and a ^{252}Cf source was used to simulate the spectrum emanating from an accelerator head. The objectives of the experiment were:

1) to study the variation and contributions of individual components of the radiation fields (including capture gamma rays) as a function of distance along the maze.
2) to determine the attenuation of neutron dose equivalent and reduction of capture gamma rays as a function of both borated polyethylene (BPE) inner door thickness and location of the inner door.
3) to study the effect of lining the maze with different neutron moderating materials

Even though the results of this experiment have been used in the shielding design of medical accelerators over a period of 9 years, they have not been published to date. A recent decision by the National Council on Radiation Protection and Measurements to rewrite their report on particle accelerators has prompted us to publish these results. In this paper we describe the experiment and the results with the hope that the findings can be used in the shielding design for medical accelerators. The results of Monte Carlo calculations performed to simulate part of the experiment are published in another paper [2].

2. THEORETICAL BACKGROUND

Fig. 1 shows the schematic of a Varian[1] medical accelerator head. Electrons are emitted from the electron gun and accelerated in a linear accelerator. The electrons are then bent by a magnet and allowed to strike a target, producing a beam of photons. The photons pass through a flattening filter, a pair of transmission ion chambers and two pairs of jaws which collimate the beam. Neutrons are produced whenever electrons or photons with energies greater than a threshold energy strike any component in the head. For most stable nuclei heavier than carbon, this threshold energy lies in the range of 6 to 16 MeV[1]. The thresholds for beryllium and deuterium are 1.67 and 2.22 MeV, respectively.

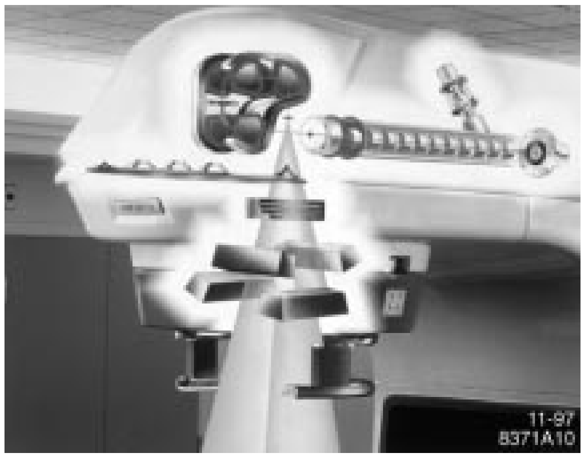

Figure 1: Schematic of a Medical Accelerator Head

The accelerator head is usually shielded for photons with high-Z materials such as lead or tungsten. The shielding is thicker in the forward direction. However, this shielding configuration is not adequate for neutrons which are emitted almost isotropically. Further, the high-Z material does not attenuate the neutron fluence, though it does degrade the energy of the neutrons by inelastic collisions and (n,2n) reactions.

The primary neutron spectrum from the target in the accelerator head resembles a fission spectrum [1]. However, the spectrum emanating from the accelerator head after traversing the head shielding is quite different. This spectrum can be simulated by the spectrum from a fission source moderated by tungsten.

According to NCRP 79 [1], neutron fields in the room consist of 3 components: 1) a direct component from the accelerator head that follows the inverse square law, 2) lower-energy neutrons with uniform spatial distribution of fluence produced by a few scatters in the room, and 3) thermal neutrons with uniform spatial distribution of fluence produced by several scatters in the room.

Fast and intermediate energy-neutrons that traverse the maze are degraded in energy by scattering in the concrete walls, ceiling and floor. Some of the neutrons undergo neutron capture reactions in the walls of the concrete maze and in the door, producing gamma rays. The neutron capture gamma rays are quite energetic. For example about 2 gamma rays are produced per capture in concrete with energies extending up to 10 MeV [1]. Capture in hydrogen results in a 2.2 MeV gamma ray. The average gamma ray energies from capture in polyethylene and concrete are 2 and 3 MeV, respectively. In addition to capture gamma rays, photons from the accelerator head will also contribute to the radiation fields in the maze. However, these photons must scatter at least once in order to reach the inner door. The highest energy that a 90^0 Compton scattered photon can have is 0.511 MeV. The tenth value layer (TVL) for 0.511 MeV is 2.3 cm. These photons can be shielded easily compared to the more energetic capture gamma rays. Massive outer doors would be required to attenuate the capture gamma rays with TVLs of up to 6.1 cm of lead. A proper maze design would eliminate the need for heavy outer doors.

The addition of boron to hydrogenous materials such as polyethylene enhances the thermal neutron capture because of its high neutron capture cross-section (3840 barns/atom). Boron produces one 0.478 MeV gamma per capture. Because of this lower gamma ray energy the use of an inner borated polyethylene (BPE) door should

---

[1] Varian Associates, Palo Alto , California.

reduce the capture gamma dose rates at the maze entrance. The efficacy of such an inner door may depend on its location along the maze. Therefore it would be important to determine its optimum location.

3. EXPERIMENTAL PROCEDURE

A concrete room with a single-legged maze was constructed as shown in Fig. 2. The thickness of the maze walls and roof was 122 cm. The height and width of the maze were 244 cm and 122 cm, respectively. The distance along the maze as measured from point A is hereafter referred to as "distance along the maze". The entrance to the maze is at 0 cm (Fig. 2) and is located at a distance of 6.405 m from point A. A Cf source (yield = 8.1×10^{8} n/s) was placed inside the room to simulate the primary neutron spectrum from the target in the accelerator head. Radiation measurements were made at various locations along the length of the maze and outside the maze under the conditions described later. The distance from the maze entrance to the various locations are shown in Fig. 2. All measurements were made at the center of the maze and at a height of 123 cm above the floor.

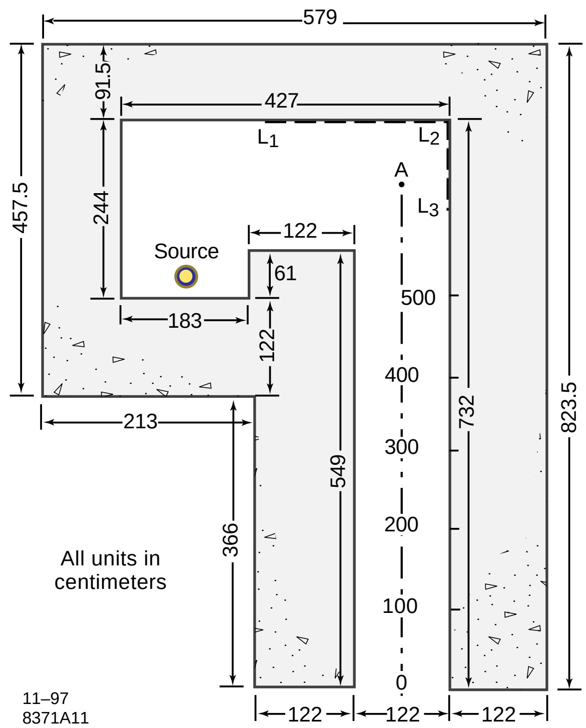

Figure 2: Schematic Of Maze

Photon dose equivalent rates were made with a Bicron micro remmeter[2] placed with its axis parallel to the maze centerline. Neutron dose equivalent and fluence rates were measured with an Andersson Braun (AB) rem meter and a moderated BF_3 proportional counter [3]. Thermal neutron fluence rates were measured with a bare BF_3 counter. The instruments were placed horizontally with their axes perpendicular to the maze centerline.

Photon and neutron measurements were made at various locations along and outside the maze. The measurements were repeated after placing a BPE (5% boron by weight, ρ= 1.02 g/cm^3) door of varying thickness (2.54 - 10.16 cm) at a) 3.5 m and b) 5.35 m from the maze entrance. The BPE was manufactured in 1 inch - (2.54 cm) thick sheets with an accuracy of about 1/16 inch. In one case, measurements were also made with a door consisting of 1 inch of polyethylene and 1 inch of borated polyethylene.

Next, a tungsten shell of thickness 5.08 cm (2 inches) was placed around the neutron source to simulate the spectrum emanating from a shielded accelerator head. Further measurements were performed both without and with a BPE door of varying thickness (2.54 cm - 10.16 cm thick) located at c) 2.0 m and d) 3.5 m from the maze entrance.

---

[2] Harshaw/Bicron, Solon, Ohio.

The effect on dose equivalent rates at the entrance to the maze by lining portions of the maze wall with neutron moderating materials (instead of using an inner BPE door) were also studied. Measurements were made at the entrance to the maze with W- moderated Cf after lining the maze wall with 2.54 cm of a)BPE and b) fire retarded plywood door[3] (ρ= 0.51 g/cm^3) from floor to ceiling along the walls (L1-L2-L3) as shown in Fig. 2. This plywood had been treated with an unknown boron compound (of unknown concentration) to resist fire.

Measurements were also made along the maze with a ^{137}Cs gamma ray source placed inside the room to understand how primary photons from the accelerator attenuate with distance along the maze. Results of other measurements that were made during the same experiment can be found in Ref.4.

4. SOURCES OF ERROR

The energy response of the AB remmeter is tailored to approximate the fluence-to-dose-equivalent conversion curve. The detector overresponds to intermediate energy neutrons and underresponds to thermal neutrons, and its response drops sharply at neutron energies greater than 10 MeV. The detector has similar energy response to neutrons incident from the side and from the end. However, the response of the detector for neutrons incident from the head (i.e. from the side on which the electronics is) can be lower (20-50%) depending on the source energy. Thus, the instrument suffers from directional dependence. One would expect the measured dose rates to be less than the true values when the thermal neutron fluence is high. The addition of BPE would reduce thermal neutrons and increase the relative contribution of intermediate-energy neutrons. Therefore, after some optimum thickness, the measured dose equivalent rates will be higher than the true neutron dose equivalent rates.

The moderated BF_3 counter consists of a 5 cm-diameter, 33 cm-long probe with an attached preamplifier. The probe is inserted into a cadmium covered cylindrical polyethylene moderator (radial thickness of polyethylene = 6 cm). The counter is designed to have an energy-independent fluence response over a wide range of energy. The counter has a strong directional dependence. For neutrons incident on the side, the response is flat from 10 eV to 10 keV and increases to a maximum at 1 MeV. The response falls sharply at energies greater than 10 MeV. For neutrons incident from the end the response though similar in shape to the side-on response, is only 10% of the latter. The directional dependence of the moderated and bare BF_3 will have an impact on neutron fluence. Neutrons coming down the maze will be detected more efficiently than neutrons scattering from the maze wall. The Bicron detector will detect both capture gamma rays as well as Compton scattered gamma rays from the Cf source. The primary photons from the Cf source must scatter by about 110^0 in order to reach the inner door located at 5.35 m from the entrance. The scattered photon spectrum is therefore probably not very different from a 350 keV x-ray spectrum whose Tenth Value Layer (TVL) is about 1 cm of BPE. Hence as the thickness of the BPE increases, the scattered photons from the Cf source will be sufficiently reduced so that measured gamma dose equivalent rates will be dominated by the capture gamma rays.

5. RESULTS AND DISCUSSION

Figures 3 and 4 show the dose equivalent as a function of distance along the maze (as measured from point A) for the bare Cf source and the W-moderated Cf source. Measurements made at distances of 1.0, 3.0 and 8.0 m (7.405, 9.405 and 14.405 m from point A) from the maze entrance are also shown. The curves have been drawn only to aid the eye.

[3] Baxter, Eugene, Oregon

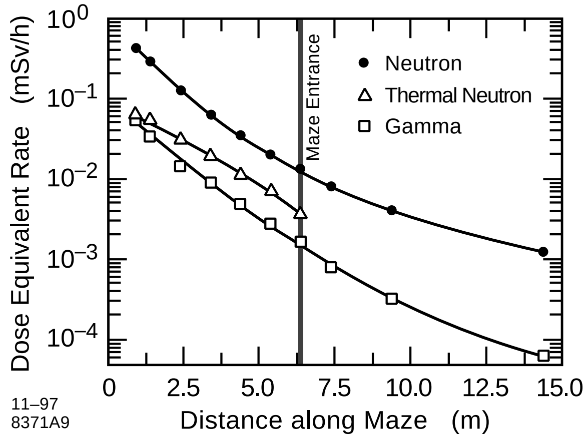

Figure 3: Dose Equivalent as a Function of Distance along Maze for ^{252}Cf

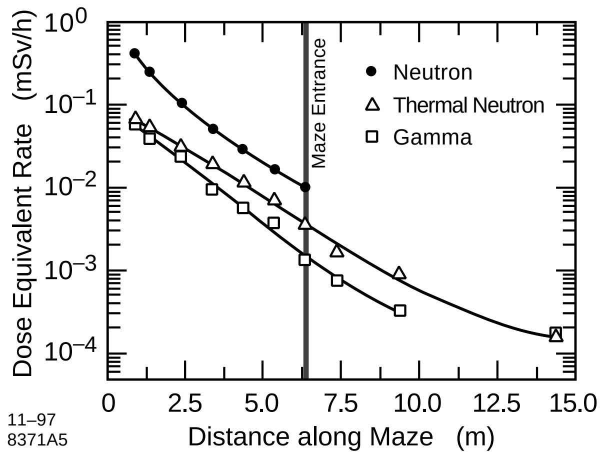

Figure 4: Dose Equivalent as a Function of Distance along Maze for W- Moderated ^{252}Cf

The measured first and second tenth value distances (TVD) for fast neutron dose equivalent are 3.35 and 6.15 m, respectively for the bare Cf source. Since the data used for the second TVD extend past the maze entrance, the second TVD of 6.15 m may be conservative. The first TVD for the moderated Cf is 3.3 m. The results are reasonably consistent with empirical values of 3 and 5 m, derived by McCall and Kersey (1).

The first TVD for thermal neutron dose equivalent is 4.7 m for the bare Cf source. The first and second TVDs for the moderated Cf source are 4.35 m and 4.65 m, respectively. For capture gamma rays, the first and second TVDs for Cf and moderated Cf are 3.4 m, 4.15 m; and 3.45 m, 3.8 m; respectively.

In general, the TVDs for Cf and W-moderated Cf are reasonabley close in value to each other. The neutron dose equivalents for the bare source are only slightly higher than those for the W-moderated source. However, the thermal neutron dose equivalents are slightly higher for the moderated source.

Figure 5 shows the gamma dose equivalent as a function of distance along the maze for the ^{137}Cs source. The first and second TVDs are 2.9 and 5.35 m, respectively. Comparing these values with the TVDs obtained for gamma rays with the bare (3.4 and 4.15 m) and W-moderated (3.45 and 3.8 m) Cf source, one finds that initially the gamma rays from the source fall off more rapidly with distance than the capture gamma rays. This is to be expected as capture gamma rays are continuously generated in the walls, floor and ceiling of the maze.

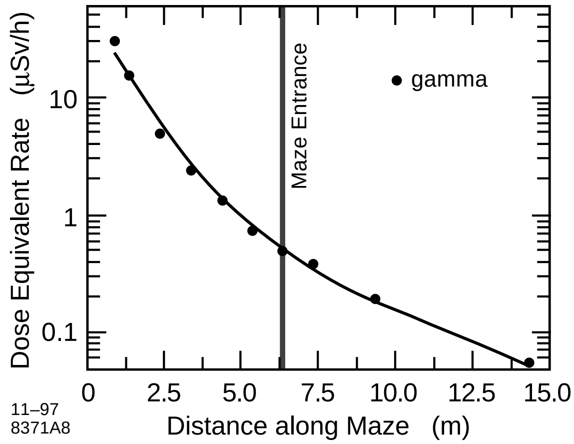

Figure 5: Dose Equivalent as a Function of Distance along Maze for ^{137}Cs

Tables 1 and 2 show the contributions of gamma and neutron components to the total dose equivalent rate at the maze entrance, as a function of BPE thickness for Cf and W-moderated Cf, respectively. The gamma, total neutron and thermal neutron dose equivalent rates are the measured values. The total dose equivalent rate is obtained by the sum of the gamma and total neutron dose equivalent rates. The neutron dose equivalent (> 0.4 eV) is obtained by the difference between the total and thermal neutron dose equivalents. The relative contributions of gamma rays, neutrons and thermal neutrons to the total dose equivalent at the entrance of the maze without the inner door are about 0.11 (0.12), 0.89 (0.88) and 0.25 (0.32) for the Cf (W-moderated Cf) source, respectively. There is no significant difference in the relative contributions of the various components of dose equivalent at the entrance to the maze for bare and the W-moderated Cf without the inner door. Overall there is no significant difference in total dose equivalent rate attenuation at the maze entrance between the 2 door locations for both Cf and W-moderated Cf.

Door Location	3.5 m					5.35 m				
Dose Equiv. Rate (µSv/h) BPE → Thickness (cm)	**Total**	Gamma	Total Neutron	Thermal Neutron	Neutron (>0.4 eV)	**Total**	Gamma	Total Neutron	Thermal Neutron	Neutron (>0.4 eV)
0	15.85	1.75	14.10	3.90	10.20	15.85	1.75	14.10	3.90	10.20
2.54	6.03	0.65	5.38	0.35	5.03	7.85	0.85	7.0	0.57	6.43
5.08	3.75	0.55	3.2	0.15	3.05	3.3	0.70	2.6	0.24	2.36
7.62	1.98	0.55	1.43	0.07	1.36	2.15	0.45	2.2	0.13	2.07
10.16	1.26	0.43	0.83	0.04	0.79	1.76	0.45	1.31	0.07	1.24

Table 1: Gamma and Neutron Contributions to Dose Equivalent Rate at Maze Entrance vs. BPE thickness for ^{252}Cf

Door Location	2.0 m					3.5 m				
Dose Equiv. Rate (µSv/h) BPE → Thickness (cm)	**Total**	Gamma	Total Neutron	Thermal Neutron	Neutron (>0.4 eV)	**Total**	Gamma	Total Neutron	Thermal Neutron	Neutron (>0.4 eV)
0	11.89	1.40	10.49	3.78	6.71	11.89	1.40	10.49	3.78	6.71
2.54	4.25	0.70	3.55	0.26	3.29	3.88	0.55	3.33	0.35	2.98
5.08	2.19	0.65	1.54	0.10	1.44	2.29	0.45	1.84	0.13	1.71
7.62	1.35	0.55	0.80	0.04	0.76	1.38	0.45	0.93	0.06	0.99
10.16	0.94	0.50	0.44	0.02	0.42	0.87	0.40	0.47	0.03	0.44

Table 2: Gamma and Neutron Contributions to Dose Equivalent Rate at Maze Entrance vs. BPE thickness for W-Moderated ^{252}Cf.

Tables 3-6 show the fast neutron dose equivalent , fast neutron fluence, thermal neutron fluence and gamma dose attenuation for each inch (2.54 cm) of BPE for the bare and moderated ^{252}Cf sources with BPE doors at various locations.

Distance from Maze Entrance (m) \ Door Location (m)	**3.5 m** BPE Thickness (cm)				**5.35 m** BPE Thickness (cm)			
	2.54	5.08	7.62	10.16	2.54	5.08	7.62	10.16
0	0.381	0.228	0.101	0.059	0.496	0.184	0.156	0.093
1	0.449	0.243	0.120	0.074	0.451	0.211	0.164	0.084
2	0.463	0.219	0.120	0.063	0.513	0.199	0.140	0.079
3	0.460	0.273	0.119	0.065	0.494	0.219	0.133	0.074
4					0.429	0.218	0.128	0.073
5					0.464	0.203	0.116	0.062

Table 3a: Neutron Dose Equivalent Attenuation Factor of BPE for ^{252}Cf

Distance from Maze Entrance (m) \ Door Location (m)	**3.5 m** BPE Thickness (cm)				**2.0 m** BPE Thickness (cm)			
	2.54	5.08	7.62	10.16	2.54	5.08	7.62	10.16
0	0.318	0.176	0.088	0.040	0.338	0.147	0.076	0.042
1	0.295	0.152	0.090	0.047	0.358	0.188	0.101	0.0470
2	0.323	0.156	0.0831	0.0419				
3	0.352	0.165	0.086	0.046				

Table 3b: Neutron Dose Equivalent Attenuation Factor of BPE for W-Moderated ^{252}Cf

Distance from Maze Entrance (m) \ Door Location (m)	**3.5 m** BPE Thickness (cm)					**5.35 m** BPE Thickness (cm)			
	2.54	5.08	7.62	10.16	5.08*	2.54	5.08	7.06	10.16
0	0.347	0.145	0.074	0.020	0.133	0.405	0.220	0.110	0.037
1	0.364	0.147	0.072	0.022	0.133	0.440	0.210	0.103	0.038
2	0.382	0.162	0.082	0.021	0.144	0.440	0.202	0.101	0.038
3	0.415	0.173	0.081	0.016	0.154	0.437	0.198	0.098	0.033
4						0.419	0.195	0.095	0.025
5						0.399	0.179	0.083	0.016

(*)1st layer PE, second layer BPE

Table 4a: Fast Neutron Fluence Attenuation Factor of BPE for ^{252}Cf

Door Location (m) / Distance from Maze Entrance (m)	3.5 m BPE Thickness (cm)				2.0 m BPE Thickness (cm)			
	2.54	5.08	7.62	10.16	2.54	5.08	7.62	10.16
0	0.312	0.115	0.050	0.025	0.308	0.115	0.050	0.024
1	0.308	0.118	0.050	0.024	0.348	0.132	0.056	0.028
2	0.340	0.128	0.056	0.026				
3	0.368	0.141	0.058	0.028				

Table 4b: Fast Neutron Fluence Attenuation Factor of BPE for W-Moderated ^{252}Cf

Door Location (m) / Distance from Maze Entrance (m)	3.5 m BPE Thickness (Cm)					5.35 m BPE Thickness (Cm)			
	2.54	5.08	7.62	10.16	5.08*	2.54	5.08	7.62	10.16
0	0.091	0.037	0.017	0.010	0.038	0.147	0.062	0.034	0.010
1	0.095	0.038	0.018	0.009	0.037	0.154	0.065	0.033	0.011
2	0.092	0.037	0.017	0.009	0.037	0.154	0.067	0.031	0.010
3	0.073	0.030	0.013	0.007	0.031	0.140	0.061	0.029	0.011
4						0.125	0.054	0.026	0.013
5						0.088	0.040	0.020	0.010

(*) 1st layer PE, second layer BPE

Table 5a: Thermal Neutron Fluence Attenuation Factor of BPE for ^{252}Cf

Door Location (m) / Distance from Maze Entrance (m)	3.5 m BPE Thickness (cm)				2.0 m BPE Thickness (cm)			
	2.54	5.08	7.62	10.15	2.54	5.08	7.62	10.16
0	0.093	0.034	0.015	0.008	0.069	0.025	0.011	0.006
1	0.095	0.035	0.014	0.007	0.070	0.025	0.011	0.005
2	0.089	0.033	0.014	0.007				
3	0.073	0.027	0.012	0.006				

Table 5b: Thermal Neutron Fluence Attenuation Factor of BPE for W-Moderated ^{252}Cf

Distance from Maze Entrance (m) \ Door Location (m)	**3.5 m** BPE Thickness (cm)					**5.35 m** BPE Thickness (cm)			
	2.54	5.08	7.62	10.16	0.508*	2.54	5.08	7.06	10.16
0	0.371	0.314	0.314	0.246	0.314	0.486	0.40	0.26	0.26
1	0.458	0.322	0.271	0.254	0.322	0.458	0.32	0.254	0.237
2	0.495	0.340	0.330	0.262	0.359	0.573	0.282	0.262	0.223
3	0.682	0.524	0.471	0.418	0.577	0.524	0.365	0.270	0.227
4						0.500	0.43	0.364	0.331
5						0.542	0.542	0.471	0.399

Table 6a: Gamma Dose Equivalent Reduction Factor of BPE for ^{252}Cf

Distance from Maze Entrance (m) \ Door Location (m)	**3.5 m** BPE Thickness (cm)				**2.0 m** BPE Thickness (cm)			
	2.54	5.08	7.62	10.16	2.54	5.08	7.62	10.16
0	0.357	0.321	0.321	0.286	0.500	0.464	0.393	0.357
1	0.291	0.253	0.215	0.190	0.405	0.354	0.304	0.266
2	0.412	0.260	0.260	0.235				
3	0.598	0.548	0.447	0.397				

Table 6b: Gamma Dose Equivalent Reduction Factor of BPE for W-Moderated ^{252}Cf

In all cases the BPE is most effective in the attenuation of the thermal neutrons and least effective in the reduction of the gamma rays as expected. The first inch (2.54 cm) of BPE in general reduces the fast neutron dose equivalent (Table 1) at all locations by a factor that is slightly greater than 2 for bare ^{252}Cf and almost a factor of 3 for the W-moderated ^{252}Cf with the door located at 3.5 m. In both cases each subsequent inch of BPE provides a reduction by a factor that is slightly less than 2. There were no significant differences in neutron dose equivalent attenuation between the door located 3.5 m and 5.35 m for the bare ^{252}Cf source; and for the moderated ^{252}Cf source between the door located at 3.5 m and 2.0 m, at all locations.

For the bare ^{252}Cf with the door located at 3.5 m and 5.35 m, the first inch of BPE reduces the fast neutron fluence by average factors of about 2.7 and 2.3, while subsequent inches provide reduction of about a factor of 2 (except for the door at 3.5 m)(Table 2). The combination of 1 inch of polyethylene (PE) and 1 inch of BPE is slightly more effective than using 2 inches of BPE as expected. Pure PE contains 7.7 x 10^{22} atoms/cc of hydrogen while BPE (5% boron) contains 6.9 x 10^{22} atoms/cc of hydrogen[4].

Tables 4a and b show that the first inch of BPE is slightly more effective for the moderated ^{252}Cf source, providing a neutron fluence reduction by about a factor of 3. Even subsequent inches appear more effective than for the bare source.

The thermal neutron fluence is reduced by about a factor of 11 with the first inch of BPE for both the bare and moderated source with the door located at 3.5 m . Each subsequent inch of BPE results in fluence reduction by a factor of 2 or more.

The first inch of BPE reduces the capture gamma dose rates in general by about a factor of 2 while each subsequent thickness provides very little attenuation.

[4] Catalog, Reactor Experiments, 1275 Hammerwood Ave, Sunnyvale, CA 94089

Lining the inner corner wall of the maze from floor to ceiling extending from L1 to L2 and L2 to L3 (as shown in Fig. 2) with 2.54 cm of BPE provides an attenuation at the maze entrance in fast neutron dose equivalent, fast neutron fluence and thermal neutron fluence (or dose equivalent) and gamma dose equivalent of 0.62, 0.65, 0.49 and 0.68, respectively for the W moderated source. Fire retarded plywood of the same thickness at the same location provides corresponding attenuation factors of 0.85 and 0.87 for neutron dose equivalent and fluence, respectively, without any effect on thermal neutron and gamma dose equivalent.

6. CONCLUSIONS

The variation and contributions of individual components of the radiation fields as a function of distance along the maze have been studied for both bare and W-moderated Cf sources. Tenth value distances for neutrons, thermal neutrons and gamma rays that have been obtained can be used directly in shield design.

The relative contributions of gamma rays, neutrons and thermal neutrons to the total dose equivalent at the entrance of the maze without the inner door are about 0.11 (0.12), 0.89 (0.88) and 0.25 (0.32) for the Cf (W-moderated Cf) source, respectively. Capture gamma rays are not a dominant component. There is no significant difference in the relative contributions of the various components of dose equivalent at the entrance to the maze for bare and the W-moderated Cf without the inner door. Overall there is no significant difference in total dose equivalent rate attenuation at the maze entrance between the 2 door locations for both Cf and W-moderated Cf.

In general the first inch of BPE reduces the fast neutron dose equivalent (Table 1) at all locations by a factor that is slightly greater than 2 for bare ^{252}Cf and almost a factor of 3 for the W-moderated ^{252}Cf with the door located at 3.5 m. In both cases each subsequent inch of BPE provides a reduction by a factor that is slightly less than 2.

The thermal neutron fluence is reduced by about a factor of 11 with the first inch of BPE for both the bare and moderated source with the door located at 3.5 m. Each subsequent inch of BPE results in fluence reduction by a factor of 2 or more. The first inch of BPE reduces the capture gamma dose rates in general by about a factor of 2 while each subsequent inch provides very little attenuation.

Lining a portion of the maze walls with BPE is more effective than lining with fire retarded-plywood. Using a BPE inner door is more effective in dose equivalent reduction than lining the maze walls with BPE.

ACKNOWLEDGEMENTS

Gratitude is expressed to Sherry Oppenheim, Sandra Bickford, Ruth McDunn and the SLAC Publications Department for their help in the preparation of this manuscript and to Alberto Fasso for useful discussions.

REFERENCES

1. Neutron Contamination from Medical Electron Accelerators, NCRP Report 79 (Bethesda, MD:NCRP), 1984.
2. A. Fasso', N. E. Ipe, R. C. McCall and A. Reyna, "Shielding Of Radiation Fields Generated by ^{252}Cf in a Concrete Maze, Part I – Simulation''(to be published in the Proceedings of the Topical Meeting of the American Nuclear Society).
3. J.C. Liu, T. M. Jenkins, R. C. McCall, and N.E. Ipe, "Neutron Dosimetry at SLAC: Neutron Sources and Instrumentation", SLAC TN-91-3, October 1991.
4. N. E. Ipe, R. C. McCall, T. M. Jenkins and E. Benson, "Shielding Of Radiation Fields Generated by ^{252}Cf in a Concrete Maze, Part I - Experiment", SLAC PUB 7695 Extended Version, November 1997.