SLAC-PUB-11088

CALCULATIONS OF NEUTRON AND PHOTON SOURCE TERMS AND ATTENUATION PROFILES FOR THE GENERIC DESIGN OF THE SPEAR3 STORAGE RING SHIELD

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The FLUKA Monte Carlo particle generation and transport code was used to calculate shielding requirements for the 3 GeV, 500 mA SPEAR3 storage ring at the Stanford Synchrotron Radiation Laboratory. The photon and neutron dose equivalent source term data were simulated for a 3 GeV electron beam interacting with two typical target/shielding geometries in the ring. The targets simulated are a rectangular block of 0.7 cm thick copper and a 5 cm thick iron block, both tilted at 1° relative to the beam direction. Attenuation profiles for neutrons and photons in concrete and lead as a function of angle at different shield thicknesses were calculated. The first, second and equilibrium attenuation lengths of photons and neutrons in the shield materials are derived from the attenuation profiles. The source term data and the attenuation lengths were then used to evaluate the shielding requirements for the ratchet walls of all front-ends of the SPEAR3 storage ring.

INTRODUCTION

The SPEAR storage ring at the Stanford Synchrotron Radiation Laboratory (SSRL) has been upgraded to a third generation storage ring, SPEAR3[1–3]. The average current of the stored electrons in the ring will increase from 100 to 500 mA. The dipole critical energy has increased from 4.8 to 7.6 keV. The existing SSRL injector system consisting of a 150 MeV Linac and the 3 GeV Booster ring[4] will inject the electron beam from the Booster into the ring at an energy of 3 GeV with an average beam power of 4 W.

The existing SPEAR ring shielding is composed of 61 cm thick concrete lateral walls, 30 cm thick concrete roof and 61 or 91 cm thick concrete ratchet walls. In the injection section, the outer lateral wall is 122 cm thick and the roof is 61 cm thick[5]. The minimum distance from ring chamber to the outer lateral wall is 1.2 m, 1.8 m to the inner lateral wall and 1 m to the roof. In the upgrade of the SPEAR ring, the bulk concrete structure (lateral and ratchet walls and roof) did not change. Therefore, the shielding analysis was focused on a detailed review of the use of local shield to supplement the existing bulk shielding of the SPEAR ring.

Typical beam–target–shielding geometries were simulated to calculate the radiation levels outside the shielding walls. Simulations were performed by using the FLUKA Monte Carlo particle generation and transport code[6,7]. These simulations represent the SPEAR3 beam striking either a thin target such as the wall of the vacuum chamber or a thick target such as a mask or a collimator. The radiation source terms (normalised photon and neutron dose equivalent rates in Sv h^{-1} W^{-1} at 1 m), as well as the associated attenuation lengths for the shielding materials of concrete and lead as a function of angle relative to the beam direction, were calculated. These results were then used generically to calculate the dose rates outside the ring shielding. The calculated dose rates outside the concrete wall, when properly adjusted for attenuation in the shield materials and the distance between beam loss and dose points, were compared with SPEAR3 design limits[5]. This paper presents the FLUKA calculations and the resulting data for the generic shielding design of the SPEAR3 ring.

FLUKA CALCULATIONS

The antechamber wall of the SPEAR3 vacuum chamber where the beam can strike is made of 0.7 cm thick copper and is considered a thin target. Most analytical codes (e.g. SHIELD11[8]) cannot be used for this thin target situation. Instead, the FLUKA Monte Carlo code is used to generate the photon and neutron source terms and their attenuation lengths in concrete and lead.

The FLUKA simulations were based on generic target–shield conditions consisting of a beam striking representative targets in the centre of a cylindrical shield, as shown in Figure 1. The following three beam–target geometries were considered:

(1) 5 GeV electron incident on a 2° tilted, 0.2 cm thick iron plate. This geometry was used to validate the FLUKA calculations by comparing

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Submitted to Radiation Protection and Dosimetry

Work supported by Department of Energy contract DE-AC02-76SF00515

their results with the Dinter and Tesch thin target dose measurements [9].

(2) 3 GeV electron incident on 1° tilted, 0.7 cm thick copper. This is to simulate the SPEAR3 beam hitting the thin ring antechamber wall in the C-shaped dipole under the maximum incident angle condition.

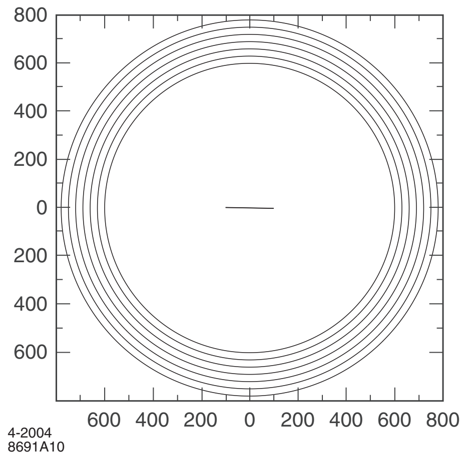

Figure 1. FLUKA cylindrical shield geometry for the generic calculation of SPEAR3 ring shielding design[10]. The 180 cm thick concrete shield starts at the radius of 600 cm. Electron beam (3 or 5 GeV) direction is along the horizontal axis and hits the target plate at (0,0,0) with the target plate tilted at 1°. The dose is scored as a function of angle and shield depth at the median plane ($z = 0$ cm).

(3) 3 GeV electron incident on a 1° tilted, 5 cm thick iron plate. This geometry simulates the SPEAR3 beam incident on thick targets such as masks and magnets in the ring. Its results can also be compared with the SHIELD11 results.

Source terms

Figure 2 shows that the FLUKA dose results for the first case above. Results that were obtained with the energy deposition option and normalised to 10^{11} electrons at 1 m agree with the Dinter measurements within a factor of 2. This agreement shows that the FLUKA calculations can be used for thin target shielding situations.

Figures 3 and 4 summarise the source terms for the second and third cases between 0° and +100° only (i.e. opposite to the beam side) for photons and neutrons, respectively. These results can be used as the source terms for the ring shielding calculations.

As shown in Figures 2–4, the 0.7 cm copper target produces neutrons comparable to those from a 5 cm iron target, whereas a 0.2 cm iron target produces neutrons that are ~10 times smaller. It is important to note that photon dose rates from the thin target (0.7 cm copper) are much higher than the corresponding dose rates for the thick target (5 cm iron), particularly at forward angles. The contribution of the electrons exiting from thin targets to the dose equivalent is rather large, but it is reduced readily in a thin shield layer (as the electrons have very low energies) and will not play a role in determining the required shield thickness.

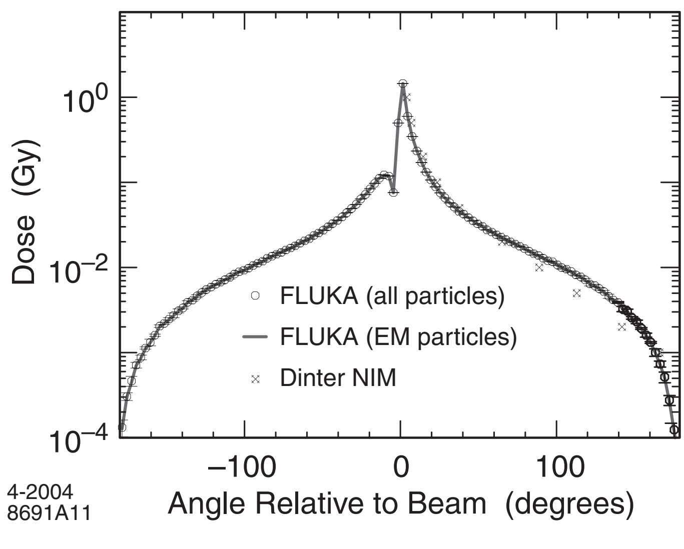

Figure 2. FLUKA dose results (calculated with energy deposition) agree with the Dinter measurements for the case of 10^{11} 5 GeV electrons hitting a 2° tilted, 0.2 cm thick Fe plate. The dose is over a 0.1 cm layer of water cylinder (simulating LiF TLD) behind a 0.1 cm water surface layer. FLUKA shows the dose is contributed from EM (electron and photon) particles.

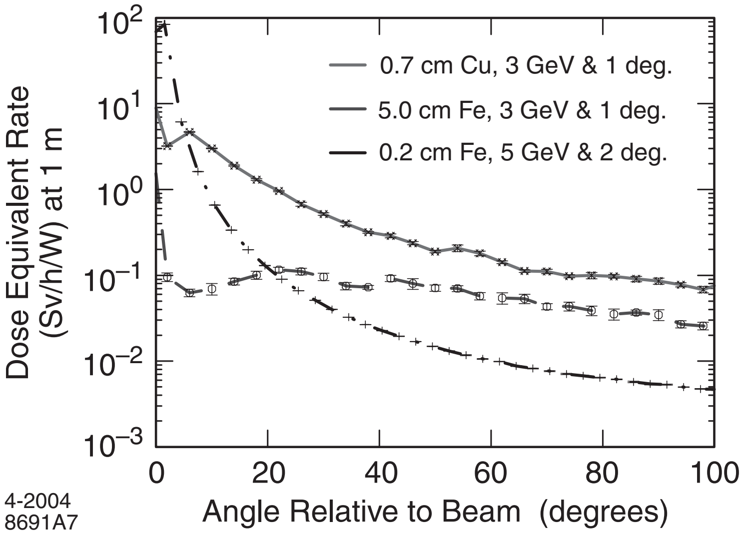

Figure 3. Photon dose source term profiles at 1 m between 0° and 100° for three beam–target conditions with concrete shield. These are used for generic shielding design for the ratchet and lateral walls.

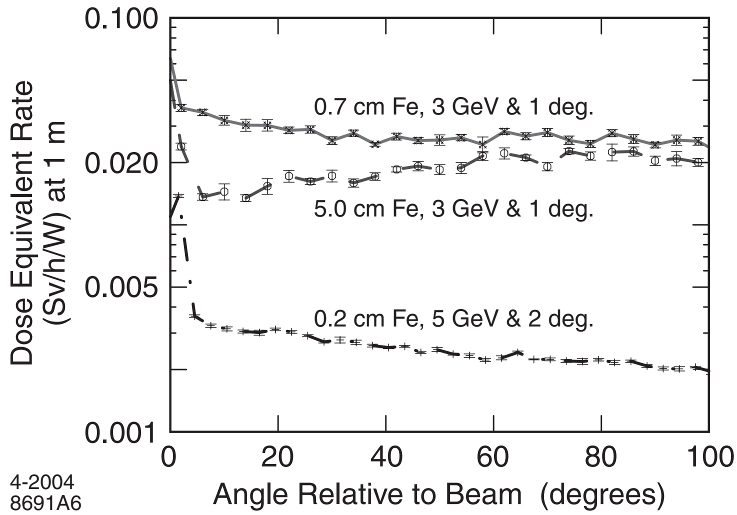

Figure 4. Neutron dose source term profiles at 1 m between 0° and 100° for three beam–target conditions with concrete shield.

Dose profiles in the shield

The photon and neutron depth dose profiles in the 180 cm thick concrete shield were also calculated with FLUKA. In order to obtain results that could be applied generically, the electron beam was simulated to strike the centre of the target, which is surrounded by six layers of cylinders. Each layer is 30 cm thick concrete or 5 cm thick lead. In addition, as shown in Figure 1, the first layer (innermost) was assumed to start at a radial distance of 600 cm from the centre of the target. The roof and the floor (30 cm thick concrete each) are at a distance of 100 cm from the target. A concrete density of 2.35 g cm^{-3} and lead density of 11.35 g cm^{-3} were used in the analysis. Figure 5 shows the photon dose equivalent attenuation profiles in concrete for a 3 GeV electron beam striking the 0.7 cm copper target at 1°. Results were normalised to a distance of 1 m for 12 different angles ranging from 2° to 90°. The attenuation

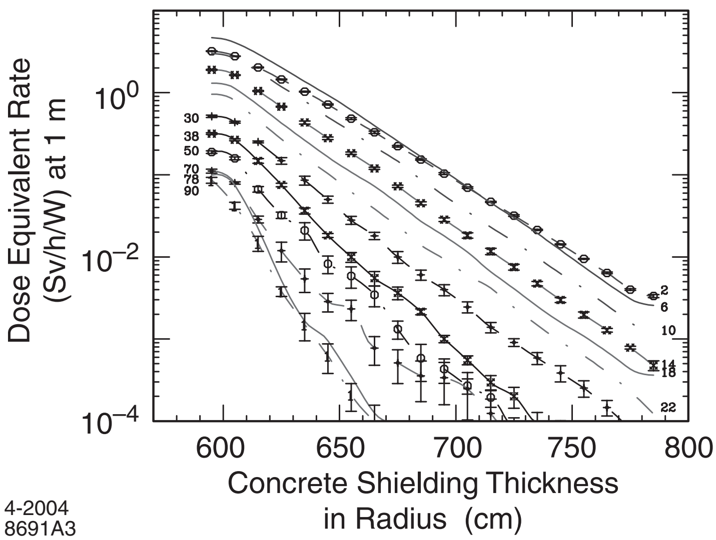

Figure 5. Photon dose attenuation profiles in concrete at various angles from a 3 GeV beam hitting the thin Cu plate. The 180 cm thick cylindrical concrete shield starts at the radius of 600 cm.

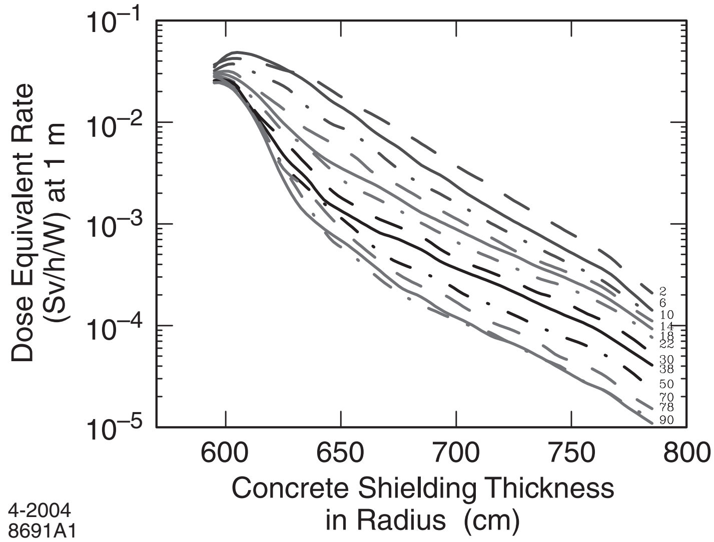

Figure 6. Neutron dose attenuation profiles in concrete shield at various angles from a 3 GeV beam hitting the thin Cu plate. The 180 cm thick concrete shield starts at the radius of 600 cm.

length (λ) can be derived from the slopes of the curves at arbitrary thicknesses. For example, 0–30 cm and 30–120 cm shield depths were used to obtain the 'first' and 'second' attenuation lengths, λ_1 and λ_2, respectively. Note that the slope at the shallow depth is larger than that for the thick shield. This is due to the fact that the secondary radiation exiting from the thin 0.7 cm copper target, particularly at forward angles $<20°$, is still of high energy and can induce a shower at inner layers of the shield. Thus, radiation does not become attenuated as fast as it does in the outer layers. The slope becomes constant at thick depths (called equilibrium attenuation length). Note that the attenuation length is also dependent on the angle.

The photon λ in concrete derived from an equilibrium slope (e.g. 10° curve) is 52 g cm^{-2}. The analytic SHIELD11 code has a photon λ of 42 g cm^{-2} in concrete. Figure 6 shows the corresponding dose equivalent attenuation profiles in concrete for neutrons. The equilibrium λ of neutrons in concrete is 72 g cm^{-2}, which is close to the 'mean' value of the three attenuation lengths for high-energy (120 g cm^{-2}), mid-energy (55 g cm^{-2}) and low-energy (30 g cm^{-2}) neutrons used in SHIELD11.

The attenuation profiles of photons and neutrons in lead from thin and thick targets are also similarly generated and shown in Figures 7 and 8. An equilibrium neutron attenuation length in lead could not be established from the lead thickness studied here owing to the paucity of the statistics. Table 1 summarises the dose equivalent rate source terms and the equilibrium attenuation lengths for thin copper and thick iron targets. A detailed description of the calculations and results for different shield materials is given in Liu *et al.*[10].

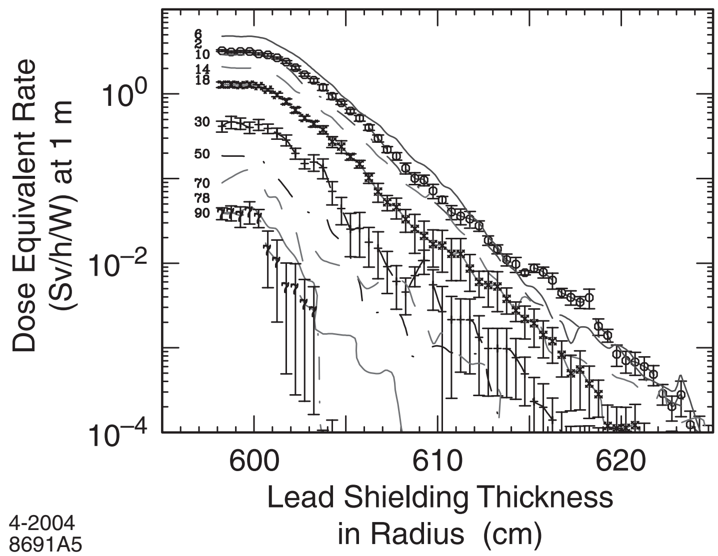

Figure 7. Photon dose attenuation profiles in a lead shield at various angles from a 3 GeV beam hitting the thin Cu plate. The 30 cm thick lead shield starts at the radius of 600 cm.

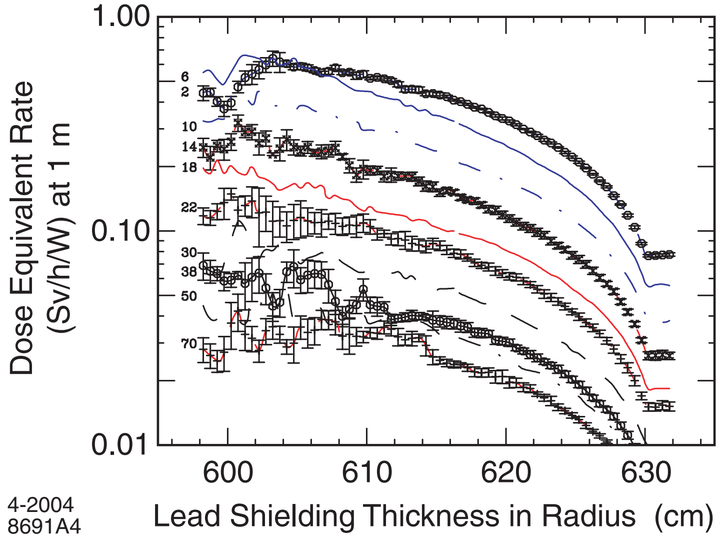

Figure 8. Neutron dose attenuation profiles in a lead shield at various angles from a 3 GeV beam hitting the thin Cu plate. The 30 cm thick lead shield starts at the radius of 600 cm.

Table 1. Summary of source term dose rates and the 'equilibrium' attenuation lengths for photons and neutrons[10].

Target	0.7 cm Cu		5 cm Fe	
Source terms under concrete shield, H (Sv h^{-1} W^{-1} at 1 m)				
Photons	5 at 4° to 0.1 at 90°		0.1 at 4° to 0.03 at 90°	
Neutrons	0.04 at 4° to 0.03 at 90°		0.02 between 4° and 90°	
Shield	Concrete	Lead	Concrete	Lead
'Equilibrium' attenuation length, λ (g cm^{-2})				
Photons	52	27	52	27

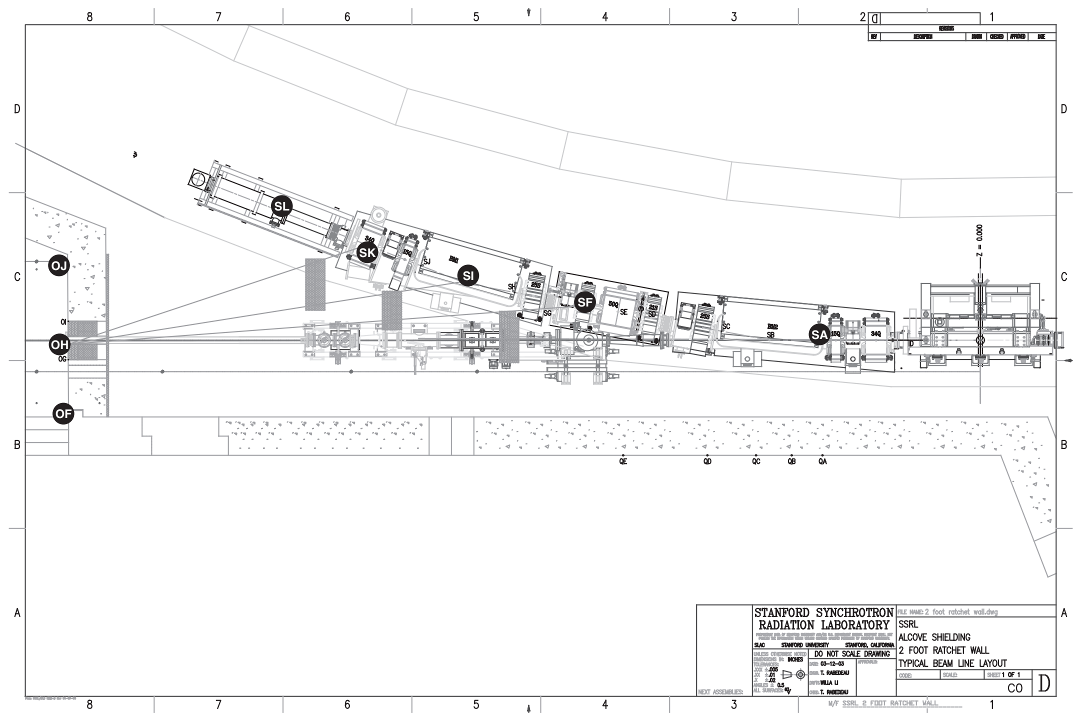

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Figure 9. Typical SPEAR3 alcove geometry featuring a 91 cm thick ratchet wall. The source points are SA to SK. The dose points outside the ratchet wall are OF to OJ[11].

Local shielding

The effect of a local shield to augment the existing concrete shielding walls was also studied with FLUKA. The study considered extending the effect of additional lead or iron sheets (5 or 7.5 cm thick) to augment the existing shielding for the ratchet walls. Note that penetrations through the ratchet walls for the beam pipes are already protected against radiation generated in the ring with local shadow walls. These walls are 30 cm thick (15 cm of lead followed by 15 cm of polyethylene), 30 cm tall and have varying widths. The extra lead sheets can be placed between the ring and the concrete walls, where the existing concrete walls are found to be inadequate, to intercept the secondary radiation generated from beam losses in the ring components.

Results of FLUKA simulation[10] show that with the addition of a 5 cm lead sheet, the neutron and photon depth dose in the concrete shield (60–90 cm) is reduced by a factor of 10 compared with the case with no additional lead shield wall.

Ratchet wall shielding

With the source terms and the derived attenuation lengths, the dose equivalent rate at any angle and shield thickness can be calculated. Figure 9 shows a typical SPEAR3 alcove geometry featuring a 91 cm thick ratchet wall. Dose rates resulting from different source points in the beamline were calculated at specific points outside ratchet walls by using results from ray trace studies performed by SSRL designers(11). For each ray, the angle, distance, shield material and shield thickness is identified. Spread sheets that incorporate the source terms and attenuation lengths were then developed(11) to calculate the corresponding dose rates. Two heights at each dose point were studied: the ray at median plane to examine the thickness and width of shadow walls, and the ray that just passes over the 30 cm tall shadow wall, to examine the need to extend the lead shield above and below the shadow wall. The calculated results for each case were compared with the shield design limits(5).

The study of the maximum dose results for every dose point from various source points shows that in all limit-exceeding cases, the rays have angles $<10^\circ$ and rays just pass over the shadow wall. In addition, $>90\%$ of the doses are from photon radiation. Since an additional 2.5 cm of lead can provide a factor of 3 reduction in dose outside the ratchet wall, the shielding design recommendation(12) is to augment each of the 91 cm thick ratchet walls with 2.5 cm of lead to meet the most stringent shield design criteria(5) at SLAC. The 61 cm thick ratchet walls should be supplemented by a 5 cm lead shield. However, based on the seismic safety consideration, and with credit given for use of active devices, the thickness of the additional lead shield was reduced to 2.5 cm for the 61 cm ratchet walls only. No lead shield will be added to the 91 cm thick ratchet walls.

SUMMARY

In SPEAR3, the ring concrete walls and local lead shield walls form an integral part of shielding to attenuate the radiation from beam losses in the ring. For generic shielding design of the SPEAR3 ring (in particularly the ratchet wall) calculations using FLUKA were performed and photon and neutron source terms and their attenuation profiles in concrete and lead shields were obtained. The accuracy of FLUKA calculations was verified from a comparison with the Dinter and Tesch measurements. This information was used in evaluating the shielding needs by considering the actual geometry for different source and dose points by performing ray trace studies. The estimated dose equivalent rates outside the shield walls, when properly adjusted for the effects of attenuation in the concrete wall and shadow wall, as well as distance, were compared with the applicable dose limits. An extra 2.5 cm of lead shield was added to supplement each of the existing 61 cm thick concrete ratchet walls.

ACKNOWLEDGEMENTS

The authors acknowledge and thank SSRL staff for many stimulating discussions. This work was supported by Department of Energy contract DE-AC03-76SF00515.

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