Evaluation of Scattered Radiation in a Calibration Range Using Exposure Rate Energy Spectra

THESIS

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By

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Abstract

ISO standard 4037 specifies that for calibrating protection level dosimeters, scattered radiation should contribute less than 5 percent of the exposure. In previous work, we reported the results of an MCNP analysis of the shadow shield technique that was performed for a calibration range with a Cs-137 irradiator. This thesis examines the energy distribution of the photons contributing to the exposure percent scatter ($S_{\%}$) and the detailed origin of the scatter that originates in the irradiator. In summary, it reports that: 1) the majority of $S_{\%}$ is due to photons with energies that are significantly below the source energy, 2) a significant percentage of $S_{\%}$ is due to photons that scatter within the source and source capsule walls, and 3) $S_{\%}$ due to scatter within the irradiator is even more significant than we previously reported.

Dedication

This document is dedicated to my family and friends.

Acknowledgments

I would first like to thank my family and friends for their support and encouragement. Without them I would never be where I am today.

I would especially like to thank my advisor, Dr. Thomas Blue, for his dedication and his patience working with me for the past two years. I would like to thank Kevin Herminghuysen for reviewing my thesis and Dr. Richard Denning for serving on my thesis committee. Finally I would like to thank the Department of Energy Nuclear Energy University Program for supporting me during my graduate studies.

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Introduction

The Ohio Emergency Management Agency (OEMA) Radiological Instrument Maintenance & Calibration (RIM&C) facility maintains a gamma calibration range, which is 10 meters in length. An International Organization for Standardization (ISO) requirement limits the percentage of scattered exposure ($S_{\%}$), *extraneous to that from the source capsule*, [ISO] to less than 5%. The results of measurements using the shadow shield technique (Minniti and Seltzer 2007) showed that, in order to satisfy the ISO requirements, use of the range should be restricted to source to ion chamber (IC) distances (R) less than 7 meters. An MCNP model was constructed to identify the origins of the scattered component of the exposure (Steele et al. 2011) in the hope that this component can be reduced, if its origins are known. The results of this thesis have been published in a paper titled “Evaluation of Scattered Radiation in a Calibration Range Using Exposure Rate Energy Spectra” in the Health Physics journal (Petrie et al. To be published). The body of this thesis is in large part identical to the paper.

This thesis reviews:

1. The development of an MCNP model that accurately simulates the OEMA Irradiator Calibration Range;

2. The origins of scattered radiation contributing to $S_{\%}$ as calculated using the MCNP model, by alternately setting the importances of the lead in the irradiator, the walls, and the floor to zero.

This thesis presents as new material:

1. Exposure rate differential photon energy distributions for various R, as calculated using the MCNP model of the OEMA Calibration Range.
2. The origins of the radiation comprising $S_{\%}$ for various R, as determined by integrating over energy the exposure differential photon energy distributions which have been determined using the MCNP model of the OEMA Calibration Range.

Background

OEMA Calibration Lab

The OEMA performs calibrations of devices which are used for gamma radiation detection. The calibration facility is located on the west campus of The Ohio State University (OSU), and is similar to many instrument calibration facilities. The OEMA's facility includes a gamma irradiator and a track which allow the user to select a source-to-IC distance between 46 cm and 997 cm in 1 mm increments. The gamma irradiator is a JL Shepherd 81-14T which utilizes, at the user's discretion, any of three ^{137}Cs sources with nominal activities at manufacture of 0.04, 4, and 400 Ci. The room in which this system lies has length, height, and width dimensions of 11.7 x 3.20 x 5.48 m³, respectively.

JL Shepherd Range Irradiator

The source sits with its center 126.36 cm above the floor. The source capsule is comprised of the source material itself, which is cesium chloride, encapsulated by two stainless steel shells. The inner shell has a thickness of 0.0635 cm, and the outer shell has a thickness of 0.127 cm. The source material is cylindrical in shape with a radius of

0.635 cm and a height of 5.08 cm. The encapsulated source is held in an aluminum cup with thickness 0.0813 cm. Two stainless steel tubes, each of thickness 0.12446 cm, surround the aluminum cup. A drawing of the source, as generated by the MCNP visualization utility VISED, is shown in lateral and transverse cross-sectional views in Figure 1 and Figure 2, respectively. The X-dimension represents the distance downrange (north) from the source and the Z-dimension is positive in the vertical direction.

Figure 1. Cross Sectional View of the ^{137}Cs Source in the X-Z Plane at Y=0

Figure 2. Cross Sectional View of the ^{137}Cs Source on the X-Y Plane at Z=0

The irradiator is 182.42 cm tall with a radius of 18.41 cm. It is constructed of lead with a 0.635 cm thick layer of steel on its exterior surfaces and a 0.3175 cm thick steel lining inside the beam port. The beam port is a truncated rectangular pyramid with angles for each side of the port of 7.5 degrees with respect to the horizontal and vertical and an area of $(5.45 \times 2.15) \text{ cm}^2$ at the inner radius of the irradiator.

Range Irradiator Room Specifications

The irradiator is centered between the east and west side walls of the irradiator room, with 168.9 cm on either side of the irradiator centerline. The walls upbeam (south)

and downbeam (north) from the irradiator are at respective distances of 76.8 cm and 1097.3 cm from the center of the source. The ceiling in the facility is a dropped panel ceiling. The structural ceiling is 503 cm in height. Neither the dropped panel ceiling, nor the structural ceiling were included in the model, since photons that suffer collisions in these ceilings have been shown in MCNP calculations that are not included in this text, to make insignificant contributions to the exposure rate. The walls to the east, west, and south of the irradiator are constructed of concrete block that is filled with mortar. The north wall and the floor are both poured Portland concrete with a density of $2.3 \frac{g}{cm^3}$ and a thickness of 91.4 cm. There are also 0.28 cm thick lead sheets on the north wall.

ISO Standard 4037-1:1996

The ISO published a standard (ISO 4037-1:1996) which gives a general outline for gamma-ray calibration requirements. The scope of the standard is quoted as, “specification of the characteristics and production methods of X and gamma reference radiation for calibrating protection level dosimeters and rate dosimeters at air kerma rates from $10 \mu Gy \cdot h^{-1}$ to $10 Gy \cdot h^{-1}$ and for determining their response as a function of photon energy.” Section 6.3 of the standard outlines the requirement for scattered radiation as follows: “The air-kerma rate due to radiation scattered by the environment shall not exceed 5% of that due to direct radiation.”

We have chosen to calculate $S_{\%}$ as a ratio of exposure rates, instead of as a ratio of air kerma rates, because the exposure rate is a measured quantity. The air kerma rate in Gy/s is related to the exposure rate in Roentgens/s by the expression

$$\dot{K}(\text{Gy/s}) = 5.450 * 10^{-3} \left[\frac{\mu_{tr}}{\mu_{en}} \right]_{air} \dot{X}(R/s) \quad (1)$$

where μ_{tr} is the linear energy transfer coefficient and μ_{en} is the linear energy absorption coefficient. The ratio $\frac{\mu_{tr}}{\mu_{en}} = 1.0017$ for a photon energy of 0.6 MeV and decreases to unity for photon energies below 0.0015 MeV. In summary, since $S_{\%}$ is a ratio of scattered and total rates (either exposure or air kerma) and $\frac{\mu_{tr}}{\mu_{en}}$ is a monotonic function that decreases with decreasing photon energy from a ratio that differs from unity by closer than 0.2% at 0.6 MeV, $S_{\%}$ is equal for exposure rate and air kerma rate to less than 0.2%.

Section 6.4 of the standard clarifies the meaning of the words “radiation scattered by the environment” with the phrase "scattered radiation extraneous to the source" and further states that “at the various experimental distances, the contribution due to scattered radiation extraneous to that from the source capsule does not exceed 5% of the total air-kerma rate.” Clearly, there is inconsistency within the standard regarding the denominator in the calculation of $S_{\%}$. In our analysis, we have chosen to calculate $S_{\%}$ with the denominator defined as the total exposure rate, as opposed to the exposure rate due to direct radiation. The relationship between $S_{\%}$ calculated with the total exposure

rate in the denominator ($S_{\%Total}$) and $S_{\%}$ calculated with the exposure rate due to direct radiation in the denominator ($S_{\%Direct}$) is given by the expression

$$S_{\%Direct} = \frac{S_{\%Total}}{1 - \frac{S_{\%Total}}{100}} \quad (2)$$

In the remainder of this thesis, when $S_{\%}$ is written, it should be interpreted as $S_{\%Total}$. The subscript “Total” is not written so as to minimize the notational complexity.

Previous Work

Previous work performed by (Steele et al. 2011) and (Steele 2009) developed a MCNP model of the OEMA calibration range for the purposes of assessing the applicability of the shadow shield technique for determining the scattered contribution to the total exposure rate. The shadow shield technique involves taking measurements of the exposure rate using an IC placed at various positions along the centerline of the direct beam. Those measurements are then repeated with a 10 cm thick lead brick large enough to obscure the entire IC placed in front of the IC. The idea is that the lead brick, or shadow shield, will block the direct beam while still allowing scattered radiation to reach the IC. The scatter percentage is then calculated by determining the ratio of the shielded measurement to the unshielded measurement and multiplying by 100. The conclusions from (Steele et al. 2011) and (Steele 2009) were that the shadow shield method is

accurate in determining the scatter percentage due to scatter from the room walls and floor for source to IC distances less than 6 m. When the source to detector distance is increased beyond 6 m the shadow shield begins to block photons that are scattered from the room walls and floor causing the scatter percentage as predicted using the shadow shield method to be too small. The shadow shield also blocks photons that have scattered from the lead irradiator and the steel lining of the beam port. This effect is observed over all source to IC distances and results in a scatter percentage that is as much as 10% lower than the true scatter percentage. Therefore, the shadow shield method was determined to be unsuitable for predicting the scatter percentage for the modeled calibration range.

The results of (Steele et al. 2011) are summarized in the paper titled “Evaluation of Scattered Radiation in a Calibration Range Using Exposure Rate Energy Spectra” that is to be published in the Health Physics journal (Petrie et al. To be published). Since (Petrie et al. To be published) is a continuation of the work presented in (Steele et al. 2011), some of the phrases in this thesis and in (Petrie et al. To be published) are taken from (Steele et al. 2011) and (Steele 2009).

Scope of Master’s Research

This research was performed in order to properly characterize the scatter percentage and specific origin for the radiation field at the OEMA calibration range and to provide a general methodology for determining the scatter percentage for gamma calibration facilities. The MCNP model that was used for calculations that were

performed as a part of this thesis is an improvement on the model that was used in (Steele et al. 2011). In particular, the source and irradiator are now modeled with more detail concerning the source capsule and the materials within which the source is transported from its shielded non-operational position to its operational position. This detail was necessary in order to properly quantify the amount of radiation that is scattered from the source and capsule before reaching the IC. The MCNP model that was used in (Steele et al. 2011) did not include either the structural ceiling or the dropped panel ceiling that are a part of the range irradiator room. This thesis shows the intersections of the direct beam with the various ceilings, the room walls, and the floor in order to justify not including the ceilings in the model. Additional MCNP calculations were performed, with the ceilings included in the model, to show that the contributions to the exposure rate due to scatter from the various ceilings are insignificant. Scatter origin calculations that were performed in (Steele et al. 2011) were repeated in this thesis with the updated model using the method of zeroing importances that is described later in this thesis. This thesis also gives a methodology for calculating the contributions to the scatter percentage due to certain materials whose contributions to the scatter percentage could otherwise not be calculated using the method of zeroing importances that was developed by (Steele et. al 2011). This methodology allows one to calculate a scatter percentage that is consistent with the ISO standard, so that scatter from the OEMA calibration range can be evaluated with respect to the ISO limit on scattered radiation. The methodology used to determine the ISO scatter percentage is described later in this thesis.

Methods - MCNP5 Model Calculations

MCNP Code Package

The Monte Carlo N-Particle (MCNP) code package is a radiation transport code package that was developed at Los Alamos National Lab. The code uses Monte Carlo methods to simulate the history of individual particles. The user must provide the geometry and material data for a particular simulation in addition to specifying statistical distributions for the particle source. MCNP has continuous energy cross section libraries for determining the probability of a particular interaction between a particle and its surrounding material. The user can also specify tallies of a particular quantity such as fluence or energy deposition. In this thesis, the code is used to track individual photons from their origin in the source material until they eventually are absorbed or leave the volume of interest. The photon fluence is tallied using a F4 tally which tallies the photon fluence averaged over a particular cell. The contributions to the F4 tally are calculated by determining the track length of a particular photon as it passes through the cell of interest and dividing by the volume of the cell of interest. The sum of the contributions to the F4 tally from all source photons is divided by the total number of particle histories to give an output of fluence per source particle. Statistical uncertainty is quantified using counting statistics. In addition to providing a statistical uncertainty for each tally, MCNP also

performs 10 statistical checks to ensure that the tally values are statistically well behaved and that the estimated uncertainty in the result reflects the true confidence interval of the result. The 10 statistical checks that are performed involve the statistical behavior of the mean, the relative error, the variance of the variance, a figure of merit (a function of the square of the relative error and the computation time), and a history score probability density function. Additional information regarding MCNP and its treatment of statistical uncertainties can be found in the MCNP5 manual (X-5 MC Team 2008).

MCNP5 Model

The OEMA Irradiator and calibration range were modeled using the MCNP5 and MCNPX codes (X-5 MC Team 2008; Pelowitz 2008). The room was modeled to be the same dimensions and material as described in the subsection that is entitled Range Irradiator Room Specifications. In order to simplify the model, the concrete block and mortar walls were modeled as Portland concrete with the density of the concrete reduced to $2.0231 \frac{g}{cm^3}$. The material data for the concrete walls was found using the Compendium of Material Composition Data for Radiation Transport Modeling from Pacific Northwest National Laboratory (PNNL) (Williams III et al. 2006). A three dimensional VISED representation of the room is shown in Figure 3, where the irradiator is depicted as the cylinder and the spheres on the centerline are the ion chambers (ICs). The coordinate system for the model is shown in the figure. It is consistent with the coordinate system in Figure 1 and Figure 2 which is namely: the positive x axis is co-

linear with the centerline of the irradiator beam, the z-axis is perpendicular to the floor and directed upward, and the y-axis lies perpendicular to the left and right walls and is directed to the left, when viewed from the perspective of beam photons.

Figure 3. VISED 3D Model of Irradiator Room

The Cs-137 source and irradiator were modeled as they are described in the subsection that is entitled JL Shepherd Range Irradiator. VISED drawings of the irradiator as it is modeled in MCNP are presented with varying levels of detail in Figure 1, Figure 2, and Figure 3 above and in Figure 4 and Figure 5 below, which are VISED representations of the MCNP model as seen from lateral and transverse cross-sectional perspectives, respectively. In Figure 4, A indicates the line formed by the intersection of the direct

beam from the top of the source with the floor and B indicates the line formed by the intersection of the direct beam from the bottom of the source with the floor. The AB segment defines an area with only partial view of the source (increasing as one approaches B). Similarly, C and E indicate the lines formed by the intersection of the direct beam from the bottom of the source with the dropped panel ceiling and the structural ceiling, respectively. The points D and F indicate the lines formed by the intersection of the direct beam from the top of the source with the dropped panel ceiling and the structural ceiling, respectively. The points D and F are not shown in Figure 4 because the intersection of the direct beam from the top of the source with both the dropped panel ceiling and the structural ceiling would be at a distance beyond the back wall of the room. In Figure 5, the meanings of G and H are analogous to the meanings of A and B, but with the floor replaced by the walls. The coordinates of the points A through H are presented in Table 1.

Figure 4. Cross-Sectional View of the ^{137}C Irradiator and Irradiator Room in the $Y=0$ plane with IC

Figure 5. Cross-Sectional View of the ^{137}Cs Irradiator and Irradiator Room in the $Z=0$ Plane with IC

Table 1. Coordinates of points A through H shown in Figure 4 and Figure 5

Point	X (cm)	Y (cm)	Z (cm)
A	299.9	0	-126.4
B	914.8	0	-126.4
C	456.2	0	193.7
D	1412.4	0	193.7
E	880.8	0	376.6
F	2764.5	0	376.6
G	772.4	168.9	0
H	1129.3	168.9	0

Tallies and Spectra Formation

The exposure per source particle (X_{sp}) was determined using F4 tallies for spherical tally volumes (1000 cm^3), that are identical to the volume of the ICs that have been used to measure the exposure rate in the calibration range. X_{sp} was determined by modifying an F4 tally of the photon fluence per MCNP source particle using de and df flux modifier cards. The de card stores values for the photon energy, while the df card stores the corresponding values of the response function. The response function (Equation 5.30, Shultis and Faw 2000) that was implemented is given by the expression

$$\Re_x(E) = 1.835 * 10^{-8} E \left(\frac{\mu_{en}}{\rho} \right)_{air} \quad (3)$$

where E is the photon energy in MeV, and $\frac{\mu_{en}}{\rho}$ is given in Table C.5 of the same text (Shultis and Faw 2000). Using this response function in MCNP produces an F4 tally output in units of $\frac{\text{Roentgens}}{\text{source photon}}$. The exposure rate was calculated from X_{sp} , which is output from MCNP, using Equation 4

$$\dot{X} = \frac{\text{Exposure (Roentgens)}}{\text{MCNP source particle}} * \text{Total Photon Yield} \left(\frac{\text{MCNP source particle}}{\text{decay}} \right) * \text{Activity} \left(\frac{\text{decays}}{\text{s}} \right) \quad (4)$$

In addition to being combined, on a photon-by-photon basis, to form X_{sp} , the contributions to X_{sp} were also binned, on a photon-by-photon basis, into histograms with N=15 bins. The contributions to X_{sp} were binned according to the energy of the photon contributing to the tally, thus allowing us to form histograms of exposure rate versus photon energy. Next the histograms of exposure rate versus photon energy were converted into differential exposure rate energy spectra by dividing the group values of the exposure rate ($\dot{X}_g$) in the histograms of exposure rate versus photon energy by the width of the photon energy group (ΔE_g); i.e. $\dot{X}(E_g) = \dot{X}_g / \Delta E_g$.

S_% Calculations

S_%^m Calculations – Scatter Origin Determinations by Zeroing Importances

The scatter percentage $S_{\%}^m$ was previously calculated (Steele et al. 2011) for scatter from a variety of constituents (m) (such as the irradiator (I), walls (W), and floor (F)) using Equation 5 below

$$S_{\%}^m = \frac{(\dot{X}^{All} - \dot{X}_{m=0})}{\dot{X}^{All}} * 100 \quad (5)$$

where $\dot{X}^{All}$ is the exposure rate for the base model accounting for all scattering, and $\dot{X}_{m=0}$ is the exposure rate calculated with a modified configuration of the base model, with the modification being that the components indicated by the subscript m were given zero

importance (as indicated by the subscript $m=0$). For example, $S_{\%}^{W,F}$ was calculated with the walls and floor importances set to zero (i.e. $I_W=I_F=0$). In this case any particle which entered a wall or floor cell was killed and hence could not scatter back into the IC. Scatter that was calculated with m denoting the wall and floor is denoted as a percentage by the symbol $S_{\%}^{W,F}$. Similarly, in order to find the scatter due to the irradiator, walls, and floor, the importance of the irradiator, walls, and floor were set to zero (i.e. $I_I=I_W=I_F=0$), so that any particle that came in contact with those structures would be killed. The irradiator was considered to be the lead shielding of which the irradiator is mainly composed, as well as the steel that covers its outer surface, including the steel lining of the beam port (but excluding the steel tubes within the beam port within which the source is transported from its non-operational to its operational position).

$S_{\%}^m$ Calculations – Scatter Origin Determinations Using Exposure Rate Tally

Histograms

$S_{\%}^I$ is comprised of contributions to scatter from scatter events occurring in the lead shielding of the irradiator as well as the steel lining the beam port of the irradiator. Scatter within the aluminum cup or the stainless steel tubes surrounding the source and the source capsule walls does not contribute to $S_{\%}^I$. Furthermore, photons can also be scattered within the source and the source capsule walls. The contribution to scatter from scatter events occurring in any of these materials cannot be calculated using the methods described in the above subsection, because if the importance of either the aluminum cup,

the stainless steel tubes, the source, or the source capsule walls were set equal to zero, the calculated response would be zero. We calculated the contributions to $S_{\%}$ from scattering events in the source and capsule walls using exposure rate tally histograms. Specifically, we used the following methods. We calculated the fraction of the exposure rate resulting from photons with energies less than the source energy ($E_0 = 0.6612$ MeV). For this calculation, $I_I = I_W = I_F = 0$. The aluminum cup and the stainless steel tubes were modeled as void, as was the room air, so that scattering events in the source and capsule walls could be distinguished from scattering events in the total irradiator (which includes the aluminum cup and stainless steel tubes and is denoted as I_{Total}), room air, walls, and floor. These tally values are hereafter referred to as $\dot{X}_g^{mod}$. Tallied photons were considered to be at the source energy, and therefore uncollided, if the energy of the tallied photon was in the uppermost energy group ($g=N$), which contains all tallied photons with energy greater than or equal to 0.6612 MeV. The percent contribution to the exposure rate due to photons that are scattered only in the source (S) or source capsule (C), hereafter denoted as $S_{\%}^{S,C}$, was determined from Equation 6. The quantity $S_{\%}^{S,C}$ is equivalent to the area under the curve shown in Figure 7, expressed as a percent.

$$S_{\%}^{S,C} = \frac{\dot{X}_{Collided}^{mod}}{\dot{X}_{Total}^{All}} * 100 \quad (6)$$

where

$$\dot{X}_{Collided}^{mod} = \sum_{g=1}^{N-1} \dot{X}_g^{mod} \quad (7)$$

and

$$\dot{X}_{Total}^{All} = \sum_{g=1}^N \dot{X}_g^{All} \quad (8)$$

The reader should note that the definition of $S_{\%}^{S,C}$ as given by Equation 6 slightly overestimates $S_{\%}^{S,C}$ in that it includes in the numerator of $S_{\%}^{S,C}$ the low energy photons (4.5 to 36.4 keV) that are emitted in the decay, but which may not have scattered. These low energy photons are low yield and subject to attenuation within the source and source capsule, thus reducing their contribution to the lowest energy interval for the differential exposure rate energy spectra shown in Figure 7.

The percent of exposure resulting from photons that have suffered a collision within I_{Total} , and/or air, and/or the walls, and/or the floor, but excluding the source and capsule, was calculated using Equation 9. It is denoted as $S_{\%}^{ISO}$.

$$S_{\%}^{ISO} = \frac{(\dot{X}_{Collided}^{All} - \dot{X}_{Collided}^{mod})}{\dot{X}_{Total}} * 100 \quad (9)$$

where

$$\dot{X}_{Collided}^{All} = \sum_{g=1}^{N-1} \dot{X}_g^{All} \quad (10)$$

The superscript ISO has been assigned to this $S_{\%}$ because the calculation of $S_{\%}^{ISO}$ is consistent with the definition of the percentage of the scattered exposure that is limited by the ISO standard to being less than 5%.

Results

Validation

In order to ensure that the model reflected the actual characteristics of the room, two checks were conducted. These checks were: 1) comparing the specific gamma constant (Γ) for the source calculated with MCNP with accepted values, and 2) comparing the exposure rates calculated with MCNP with measurements of the exposure rate for points on the centerline of the beam. The specific gamma constant relates the exposure rate to the source activity for a specific radionuclide at a specified distance. The results of the validation calculations are presented in (Steele et al. 2011).

$S_{\%}$ and $S_{\%}^m$ Calculation Results

The ICs in the MCNP model were placed at 1 meter intervals for source to IC distances (R) from 1 m to 10 m. We determined $S_{\%}^m$ using Equation 5 for m corresponding to I (not I_{Total}), W, and F; W and F, and I. All calculations were performed with air included in the model. The results of the calculations are shown in Figure 6 and are summarized below:

- o Generally speaking, calculated values of $S_{\%}^{I,W,F}$ and $S_{\%}^{W,F}$ increase with increasing R. $S_{\%}^{I,W,F}$ may be interpreted as the $S_{\%}$ due to any scatter that is external to the source capsule, and external to the aluminum cup and stainless steel tubes of the irradiator that surround the source capsule. Its value is much larger than the ISO value of <5%. $S_{\%}^{W,F}$ is the contribution to $S_{\%}$ that is due to scatter from the walls and floor.
- o $S_{\%}^I$ is the contribution to $S_{\%}$ that is due to scatter from the lead in the irradiator as well as the stainless steel that lines the beam port and covers the outer surface of the irradiator. These materials contribute substantially to the scattered component of the exposure. $S_{\%}^I$ decreases slightly with increasing R from about 12.2% to 11.4% as R ranges from 1 to 10 m. Also, $S_{\%}^I/S_{\%}^{I,W,F} \sim 1$ for R=1 m while $S_{\%}^I/S_{\%}^{I,W,F} \sim 0.6$ for R=10 m.

Figure 6. $S_{\%}^{I,W,F}$, $S_{\%}^{W,F}$, and $S_{\%}^I$ Calculated Using Equation 5 and the sum of $(S_{\%}^I + S_{\%}^{W,F} - S_{\%}^{I,W,F})$ vs Distance Down Range

The sum $S_{\%}^I + S_{\%}^{W,F}$ exceeds $S_{\%}^{I,W,F}$ as a consequence of photons that scatter in both the irradiator and in the walls and/or floor before reaching the detector. The difference $(S_{\%}^I + S_{\%}^{W,F} - S_{\%}^{I,W,F})$ is presented in Figure 6 to emphasize that the sum of $S_{\%}^I$ and $S_{\%}^{W,F}$ exceeds $S_{\%}^{I,W,F}$ and to provide insight regarding the importance of multiple scatter contributions to $\dot{X}^{All}$.

Exposure Rate Energy Spectra

Normalized (by the total exposure rate, including all sources of scatter) exposure rate energy spectra, resulting from photons that have been scattered only within the source and capsule walls, $\left(\frac{\dot{X}_{Collided}^{S,C}(E)}{\dot{X}_{Total}^{All}}\right)$ are shown in Figure 7. The differences among the spectra are not significant, especially when normalized exposure rate energy spectra that include all mechanisms for scatter are compared. Note that room air is model as void in the calculation of $\dot{X}_{Collided}^{S,C}(E)$. Analogous calculations for $S_{\%}^{S,C}$ were performed with the room air included in the model. The scatter percent in this case is denoted as $S_{\% with air}^{S,C}$. Results of these calculations are presented later in this thesis.

Figure 7. Normalized Differential Exposure Rate from Photons Reaching the Detector Having Scattered Only in the Source and Capsule Walls $\left(\frac{\dot{x}_{Collided}^{S,C}(E)}{\dot{x}_{Total}^{All}}\right)$

Normalized (by the total exposure rate, including all sources of scatter) exposure rate energy spectra resulting from photons that have been scattered within any material

$\left(\frac{\dot{x}_{Collided}^{All}(E)}{\dot{x}_{Total}^{All}}\right)$ are shown in Figure 8. These spectra show a peak just below the source energy, at about 0.6 MeV, and as R increases, this peaks starts to disappear and a second peak starts to form at lower energies, centered around 0.2 MeV. Small angle scattering within the source, source capsule, aluminum cup, and the stainless steel tubes that surround the aluminum cup and small angle scattering from the beam port materials are

the likely origin for the peak around 0.6 MeV, since this peak is more pronounced for smaller R. Large angle scatter likely accounts for the peak around 0.2 MeV, which one would expect to be most evident at the 10 m distance, since the back wall is close to the IC for this R. The energy of a 662 keV photon that suffers scattering through 180° is 184 keV. Photons with energies below 184 keV have necessarily suffered multiple scatters.

Figure 8. Normalized Differential Exposure Rate from Photons Reaching the Detector Including All Sources of Scatter $\left(\frac{\dot{X}_{Collided}^{All}(E)}{\dot{X}_{Total}^{All}} \right)$

Figure 9 shows normalized (by the total exposure rate, including all sources of scatter) exposure rate energy spectra resulting from all (both collided and uncollided) photons $\left(\frac{\dot{X}_{Total}^{All}(E)}{\dot{X}_{Total}^{All}}\right)$. The spectra in Figure 7, Figure 8, and Figure 9 are normalized to the same quantity (namely the total exposure rate, including all sources of scatter), so that these spectra can be compared.

Figure 9. Normalized Differential Exposure Rate from All Photons Reaching the Detector $\left(\frac{\dot{X}_{Total}^{All}(E)}{\dot{X}_{Total}^{All}}\right)$

$$S_{\%}^{All}, S_{\%}^{ISO}, S_{\% with air}^{S,C}, S_{\%}^{S,C}, \text{ and } S_{\%}^{I,W,F}$$

Figure 10 shows the percent contribution to the total exposure due to photons scattering from various materials. $S_{\%}^{All}$ was calculated using Equation 6 with $\dot{X}_g^{mod}$ replaced by $\dot{X}_g^{All}$; $S_{\%}^{ISO}$ was calculated using Equation 9; $S_{\% with air}^{S,C}$ was calculated using Equation 6 with room air replacing void; $S_{\%}^{S,C}$ was calculated using Equation 6; $S_{\%}^{I,W,F}$ was calculated using Equation 5.

Figure 10. $S_{\%}^{All}$, $S_{\%}^{ISO}$, $S_{\%}^{S,C}$, $S_{\%}^{S,C,air}$, and $S_{\%}^{I,W,F}$ vs. Distance Down Range

Figure 10 shows that $S_{\%}^{ISO}$ is significantly greater than the ISO limit of 5% over the entire range. One can also see that $S_{\%}^{ISO}$ is much greater than $S_{\%}^{I,W,F}$ over the entire range. This shows that scatter from the aluminum cup and the stainless steel tubes that are a part of the irradiator add significantly to the total scatter percentage. $S_{\%}^{S,C}$ is significant over the entire range and is almost equal to $S_{\%}^{ISO}$ for $R=3$ m. Finally, by comparison of results for

$S_{\%}^{S,C}$ and $S_{\% \text{ with air}}^{S,C}$, one can see that the percent scatter due to air is relatively small and contributes less than one percentage unit for all R.

Conclusions

ISO standard 4037 specifies that for calibrating protection level dosimeters, scattered radiation should contribute less than 5 percent of the exposure. In previous work, we reported the results of an MCNP analysis of the shadow shield technique that was performed for a calibration range with a Cs-137 irradiator. This thesis examines the energy distribution of the photons contributing to the exposure percent scatter ($S_{\%}$) and the detailed origin of the scatter that originates in the irradiator. Using exposure rate energy spectra, it was found that the majority of the scattered exposure is due to photons with energy significantly below the source energy. Scatter from the aluminum cup and stainless steel tubes that are a part of the irradiator contribute as much as 4.5 percentage units to the total scatter percentage. Because the shadow shield method blocks photons that scatter from the irradiator, these findings further support the previous conclusion that the shadow shield method is unsuitable for determining the total scatter percentage. The exposure rate energy spectra also show that scatter from the source and capsule walls is significant and can contribute as much as 15 percentage units to the total exposure. We suggest a more fundamental (although admittedly less operational) limit for the scattered exposure. Namely we suggest that instead of specifying that the scattered radiation should contribute less than 5 percent of the total exposure, it may be better to specify that

the scattered (as defined by the ISO standard) exposure be less than some fraction of the scattered exposure that originates in the source and the source capsule.

References

- Attix FH, Introduction to radiological physics and radiation dosimetry. New York: Wiley & Sons; 1986.
- Grove Software, Inc. Microshield® User's Manual. 1992-2008.
- International Organization for Standardization. X and gamma reference radiation for calibrating dosimeters and doserate meters and for determining their response as a function of photon energy. ISO 4037-1, Part 1; 1996.
- Minniti R, Seltzer SM. Calibration of a ^{137}Cs gamma-ray beam irradiator using large size chambers. Appl Radiat Isot 65: 401-406; 2007.
- Pelowitz DB ed. MCNPXTM User's Manual. Version 2.6.0. Los Alamos National Lab; LA-CP-07-1473; 2008.
- Shultis JK and Faw RE, Radiation shielding. The American Nuclear Society; 2000.
- Steele DR. Evaluation of ISO 4037-1:1996 and the Shadow Shield Technique for the Measurement of Scattered Radiation. MS Thesis. Ohio State University, Columbus, OH, 2009
- Steele DR, Petrie CM, Herminghuysen K, Blue TE. Evaluation of the Shadow Shield Technique for the Measurement of Scattered Radiation. Health Physics 101.1: 59-66; 2011.

Williams III RG, Gesh CJ, Pagh RT. Compendium of material composition data for radiation transport modeling. Pacific Northwest National Lab; PNNL-15870; 2006.

X-5 Monte Carlo Team. MCNP-a general Monte Carlo particle transport code. Version 5. Los Alamos National Lab; LA-UR-03-1987; 2003; revised 2008.

Petrie CM., Herminghuysen K, Blue TE. Evaluation of Scattered Radiation in a Calibration Range Using Exposure Rate Energy Spectra. Health Physics, to be published.

Appendix A: MCNP Input Deck

```
JL Shepherd Irradiator - with energy bins
c 2/16/11
c
c ***** ROOM/IRRADIATOR CELLS *****
c
c Concrete floor
1 1 -2.3 -1 2 -4 -7 8 10 imp:p=1
c Right concrete wall
2 1 -2.0 1 -9 5 -7 10 -3 imp:p=1
c Left concrete wall
3 1 -2.0 1 -9 -6 8 10 -3 imp:p=1
c Far concrete wall
4 1 -2.3 1 -9 -4 3 -7 8 imp:p=1
c Back concrete wall
5 1 -2.0 2 -9 -7 8 -10 11 imp:p=1
c Air filled room
6 0      -70 #1 #2 #3 #4 #14 #15
          #5 #9 #10 #11 #12 #13
          #30 #31 #32 #33 #34 #35 #36 #37
          #38 #39 #40 #41 #42 #43 #44 #45
          #46 #47 #48 #49 #50 imp:p=1
c Do not track outside of sphere
7 0 70 imp:p=0
c Lead irradiator
9 3 -11.35 -20 21 -22 1 #12 #13 imp:p=1
c Far left lead shield
10 3 -11.35 -50 52      imp:p=1
c Far right lead shield
11 3 -11.35 -50 -51      imp:p=1
c Beam port
12 0      60 -61 -62 63 64 -65 21 -20 imp:p=1
c SS shields in beam port
13 2 -7.92 80 -81 -82 83 21 -20 64 #12 #41 #42 #43 #44
          #45 #46 #47 #48 #49 #50 imp:p=1
c Lead below the source
14 3 -11.35 -21 -117 1 imp:p=1
c Lead above the source
```



```

15 3 -11.35 -21 118 -22 imp:p=1
c Lead shadow shield (made air for these runs)
c Copy the following material and density to make air: 4 -0.0012041
c Copy the following material and density to make lead: 3 -11.35
c 21 4 -0.0012041 -91 imp:p=1
c Source volume
30 5 -3.99 -100 111 -110      imp:p=1
c First SS capsule
31 2 -7.92 -101 100 -112 113      imp:p=1 $ Annular Region
32 2 -7.92 -100 113 -111      imp:p=1 $ Bottom
33 2 -7.92 -100 110 -112      imp:p=1 $ Top
c Air Gap
c Second SS capsule
34 2 -7.92 -103 102 -114 115      imp:p=1 $ Annular Region
35 2 -7.92 -102 115 -113      imp:p=1 $ Bottom
36 2 -7.92 -102 112 -114      imp:p=1 $ Top
c Air Gap
c Aluminum cup
37 6 -2.6989 104 -105 -114 116      imp:p=1 $ Annular Region
38 6 -2.6989 -104 116 -115      imp:p=1 $ Bottom
c Air gap
c SS tube
39 2 -7.92 106 -107 117 -118      imp:p=1
c Air gap
c SS tube welded to SS in beam port
40 2 -7.92 108 -109 117 -118      imp:p=1
c Air gap
c Target spheres
41 4 -0.0012041 -201 imp:p=1
42 4 -0.0012041 -202 imp:p=1
43 4 -0.0012041 -203 imp:p=1
44 4 -0.0012041 -204 imp:p=1
45 4 -0.0012041 -205 imp:p=1
46 4 -0.0012041 -206 imp:p=1
47 4 -0.0012041 -207 imp:p=1
48 4 -0.0012041 -208 imp:p=1
49 4 -0.0012041 -209 imp:p=1
50 4 -0.0012041 -210 imp:p=1
c
c

c ***** SURFACES *****
c
1 pz -126.36      $ Floor surface

```

2 pz -217.80	\$ Floor bottom
3 px 1097.28	\$ Far concrete wall inner
4 px 1188.72	\$ Far concrete wall outer
5 py 168.9	\$ Left wall inner
6 py -168.9	\$ Right wall inner
7 py 199.38	\$ Left wall outer
8 py -199.38	\$ Right wall outer
9 pz 193.68	\$ Top of concrete walls
10 px -76.83	\$ Back concrete wall inner
11 px -107.31	\$ Back concrete wall outer
20 cz 18.41	\$ Irradiator cylinder outer
21 cz 1.42875	\$ Irradiator cylinder inner
22 pz 56.06	\$ Top of irradiator
50 RPP 1097 1097.28 -120 120 -126.36 150	\$ Lead shield at far wall
51 py -20	\$ Left side of right lead sheet
52 py 20	\$ Right side of left lead sheet
60 P 0.2633 0 -2 -5.3848	\$ Angled SS in beam port (inner)
61 P -0.2633 0 -2 5.3848	\$ " "
62 P -0.2633 2 0 1.905	\$ " "
63 P 0.2633 2 0 -1.905	\$ " "
64 px 0	\$ Origin of beam port
65 px 25	\$ End of beam port
70 sx 500 1000	\$ Outside universe
80 p 0.2633 0 -2 -6.0198	\$ Angled SS in beam port (outer)
81 p -0.2633 0 -2 6.0198	\$ " "
82 p -0.2633 2 0 2.54546	\$ " "
83 p 0.2633 2 0 -2.54546	\$ " "
91 RPP 981.2765 991.4365 -10.16 10.16 -10.16 10.16	\$ Shadow shield
c Source capsule	
100 cz 0.635	\$ CsCl outer radius
101 cz 0.6985	\$ SS inner capsule outer radius
102 cz 0.73152	\$ SS outer capsule inner radius
103 cz 0.85852	\$ SS outer capsule outer radius
104 cz 0.889	\$ Al source holder cup inner radius
105 cz 0.97028	\$ Al source holder cup outer radius
106 cz 1.14554	\$ SS tube inner radius
107 cz 1.27	\$ SS tube outer radius
108 cz 1.30429	\$ Inner radius of SS tube welded to SS in beam port
109 cz 1.42875	\$ Outer radius of SS tube welded to SS in beam port
110 pz 2.54	\$ Top of source
111 pz -2.54	\$ Bottom of source
112 pz 2.6035	\$ Top of first SS capsule wall
113 pz -2.6035	\$ Bottom of first SS capsule wall
114 pz 2.7305	\$ Top of second SS capsule wall

```

115 pz -2.7305 $ Bottom of second SS capsule wall
116 pz -2.81178 $ Bottom of bottom layer of Al cup
117 pz -3.5052 $ Bottom of SS tubes
118 pz 3.5052 $ Top of SS tubes
201 sx 100 6.2035 $ Target at 1 m
202 sx 200 6.2035 $ Target at 2 m
203 sx 300 6.2035 $ Target at 3 m
204 sx 400 6.2035 $ Target at 4 m
205 sx 500 6.2035 $ Target at 5 m
206 sx 600 6.2035 $ Target at 6 m
207 sx 700 6.2035 $ Target at 7 m
208 sx 800 6.2035 $ Target at 8 m
209 sx 900 6.2035 $ Target at 9 m
210 sx 1000 6.2035 $ Target at 10 m
c
c

c ***** MODE AND TERMINATION *****
mode p
c ctme 720
nps 9000000000
c
c
c ***** SOURCE *****
c
sdef ERG=d1 POS= 0 0 -2.54 AXS=0 0 1 RAD=d2 EXT= d3 PAR=2
c Photon energies
si1 L 0.0045 0.0318 0.0322 0.0364 0.6616
c Photon probabilities
sp1 0.01056 0.02106 0.038858 0.01414 0.9153795
si2 0 0.635
sp2 -21 1
si3 0 5.08
sp3 0 1
c
c
c ***** TALLIES *****
c
fc04 Fluence Tally
f04:p 41 42 43 44 45 46 47 48 49 50
e04 0.1 0.15 0.2 0.25 0.3 0.35
0.4 0.45 0.5 0.55 0.6 0.63
0.65 0.6612 0.67
c

```

fc14 Fluence Tally Multiplied by Dose Function

f14:p 41 42 43 44 45 46 47 48 49 50

e14 0.1 0.15 0.2 0.25 0.3 0.35

0.4 0.45 0.5 0.55 0.6 0.63

0.65 0.6612 0.67

de14 0.0010 0.0015 0.0020 0.0030 0.0032

0.0040 0.0050 0.0060 0.0080 0.0100

0.0150 0.0200 0.0300 0.0400 0.0500

0.0600 0.0800 0.1000 0.1500 0.2000

0.3000 0.4000 0.5000 0.6000 0.8000

1.0000

df14 6.60417e-008 3.26997e-008 1.93115e-008 8.88507e-009 7.80976e-009

5.60482e-009 3.60669e-009 2.49927e-009 1.38667e-009 8.70157e-010

3.67183e-010 1.97776e-010 8.46118e-011 5.01542e-011 3.75991e-011

3.34814e-011 3.53348e-011 4.26637e-011 6.87024e-011 9.80624e-011

1.58104e-010 2.16457e-010 2.72130e-010 3.25125e-010 4.23078e-010

5.11782e-010

c

c

c ***** Materials *****

c

m1 1000 -0.010000 \$ Averaged Portland Concrete

6000 -0.001000

8000 -0.529107

11000 -0.016000

12000 -0.002000

13000 -0.033872

14000 -0.337021

19000 -0.013000

20000 -0.044000

26000 -0.014000

c

m2 14000 -0.010 \$ Si Stainless Steel

24000 -0.170 \$ Cr

25000 -0.020 \$ Mn

26000 -0.655 \$ Fe

28000 -0.120 \$ Ni

42000 -0.025 \$ Mo

c

m3 82000 -1.0 \$ Pb

c

m4 7000 0.78439 \$ Air

8000 0.21074

18000 0.00469

```

        6000    0.00016
        10000   0.00002
c
m5  55000    0.5      $ Cesium Chloride
    17000    0.5
c
m6  13000   -1.0      $ Al
c
c
c ***** Print Cards *****
c
print -85
prtmp 2j 1 4
c
c

```