Contract No. and Disclaimer:

RadBall^{TM} Technology Testing and MCNP Modeling of the Tungsten Collimator

Eduardo B. Farfán[1], Trevor Q. Foley[1], J. Rusty Coleman [1], G. Timothy Jannik[1], Christopher J. Holmes[2], Mark Oldham[3], John Adamovics[4], and Steven J. Stanley[2]

[1] Savannah River National Laboratory, SRS, Aiken, SC 29808, USA.
[2] National Nuclear Laboratory, Risley, Warrington, United Kingdom.
[3] Duke University Medical Center, Durham, NC 27710, USA.
[4] Heuris Pharma LLC, Lawrenceville, NJ 08648, USA.

Email: Eduardo.Farfan@srnl.doe.gov

Abstract. The United Kingdom's National Nuclear Laboratory (NNL) has developed a remote, non-electrical, radiation-mapping device known as RadBall^{TM}, which can locate and quantify radioactive hazards within contaminated areas of the nuclear industry. RadBall^{TM} consists of a colander-like outer shell that houses a radiation-sensitive polymer sphere. The outer shell works to collimate radiation sources and those areas of the polymer sphere that are exposed react, becoming increasingly more opaque, in proportion to the absorbed dose. The polymer sphere is imaged in an optical-CT scanner, which produces a high resolution 3D map of optical attenuation coefficients. Subsequent analysis of the optical attenuation matrix provides information on the spatial distribution of sources in a given area forming a 3D characterization of the area of interest. RadBall^{TM} has no power requirements and can be positioned in tight or hard-to reach locations. The RadBall^{TM} technology has been deployed in a number of technology trials in nuclear waste reprocessing plants at Sellafield in the United Kingdom and facilities of the Savannah River National Laboratory (SRNL). This study focuses on the RadBall^{TM} testing and modeling accomplished at SRNL.

1. Introduction

The RadBall^{TM} technology was initially developed by the United Kingdom's National Nuclear Laboratory (NNL). The U.S. Department of Energy (DOE) and Savannah River National Laboratory (SRNL) have initiated a collaborative development initiative with the NNL, to test and further develop the technology. RadBall^{TM} was developed to provide surveys of high radiation environments such as reactor spaces or hot cells. It has the advantage of being relatively inexpensive, having no electronic parts subject to radiation damage, and requiring no power. The product of a RadBall^{TM} deployment is a three dimensional projection of gamma radiation sources for the space into which it is deployed. Certain elements of the overall technology and deployment system are still under development and other components will need refinement and modification to optimize performance as additional demonstration projects are conducted. The optimized technology is expected to provide high quality survey results at modest cost and reduce worker exposure relative to existing approaches related to radiation surveys of highly contaminated facilities. This study involved the testing of the RadBall^{TM}

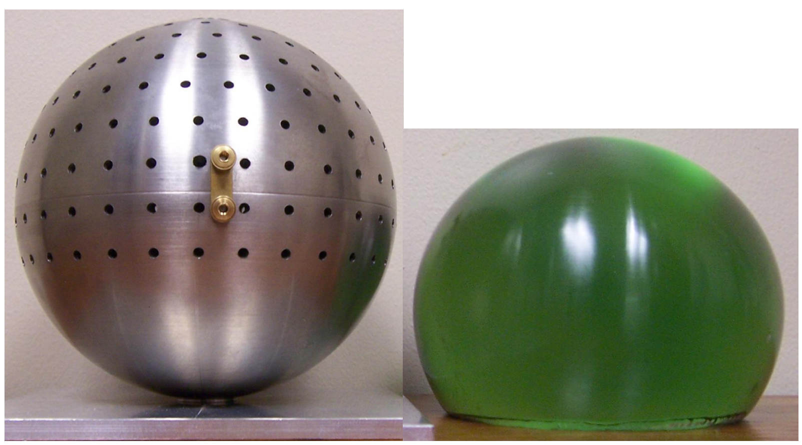
technology under controlled radiation exposures at the Savannah River Site (SRS) and modeling of the tungsten collimator using a Monte Carlo computer code.

2. RadBall^{TM} Testing

RadBall^{TM} (a novel, non-electrical, remote radiation mapping device) offers a means to collect 3-D information regarding the intensity and distribution of radiation in a given hot cell, glovebox, or room [1, 2]. The device consists of two constituent parts shown in Figure 1: an inner core and an outer collimation shell. The inner core is made from a radiation sensitive polymer material: PRESAGE^{TM}. On manufacture, the inner core is semi-transparent; however, on exposure to radiation the material exhibits an increase in opacity. The outer collimation shell is cast from a tungsten alloy and contains over 200 individual collimation holes.

2.1. The principle of RadBall^{TM}

Once the device is deployed in a radioactive area, the collimation shell partially attenuates the incident radiation while preferentially allowing radiation to pass through the collimation holes. This radiation then creates opacity tracks within the inner core which provides information required to locate and quantify the radiation sources. The orientation of the opacity track provides the positional information regarding the source, achieved by using a reverse ray tracing technique. The activity of the detected source is assessed by quantifying the magnitude of the opacity change, which follows a linear relationship with respect to absorbed dose.



A B

Figure 1. Two components of a RadBall^{TM} device: A) the outer collimation shell and B) inner polymer core.

2.2. RadBall^{TM} testing at the HPICL

The RadBall^{TM} technology was tested at the SRS Health Physics Instrument Calibration Laboratory (HPICL) in three phases involving various controlled exposure scenarios [2]. After irradiation, the RadBall^{TM} PRESAGE^{TM} polymers were sent to Duke University Medical Center (DUMC) for optical CT scanning. The scanning process produces a digital representation of the exposed polymer. Three experimental phases were completed at the HPICL, which included the exposure of 45 RadBall^{TM} PRESAGE^{TM} polymers.

2.3. Experimental phases

All experiments were completed with the RadBall^{TM} positioned 100 cm away from the radiation source in the HPICL. The center of the RadBall^{TM} collimator was placed at the same height as the source. An x-ray source was used to test photons with significantly less energy than photons generated from ^{60}Co and ^{137}Cs sources. The x-ray machine generated an energy spectrum with peaks at 38 keV, 120 keV, and 166 keV.

Three RadBall™ tungsten collimators were used at the HPICL, a 5.0, 7.5, and 10.0 mm thick collimator with 2.25, 3.0, and 4.0 mm hole diameters, respectively. The 5.0 and 7.5 mm thick collimators also had a single larger hole with a diameter of 4.0 mm. All the other collimator holes were uniform in size. All of the collimator holes were drilled with the drill bit perpendicular to the RadBall™ surface and positioned towards the center of the collimator.

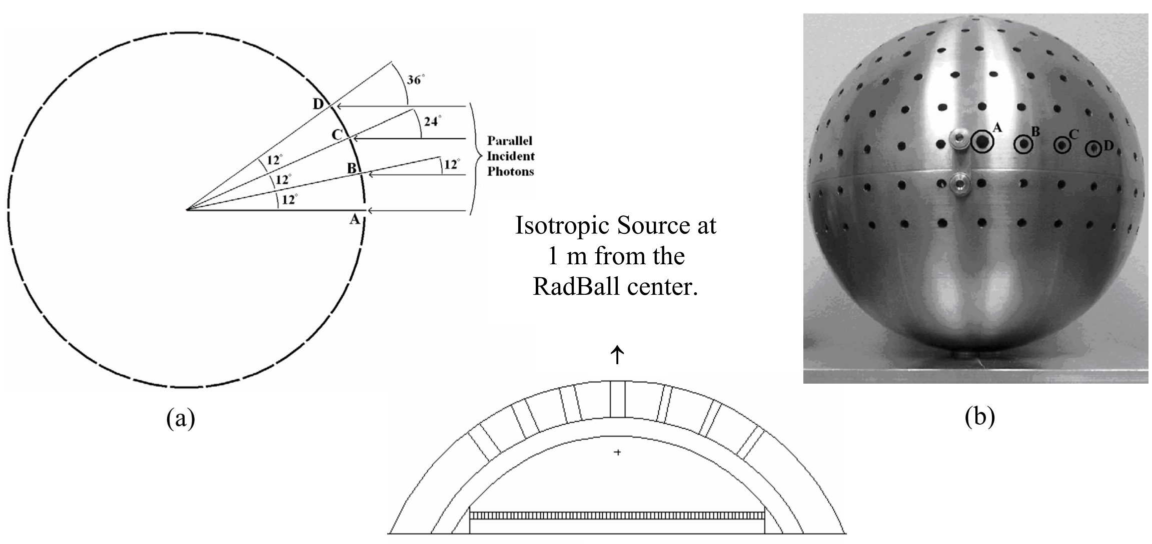
Table 1 details three selected experiments completed at the HPICL (using x-ray, ^{60}Co, and ^{137}Cs sources respectively). In each of these experiments the RadBall received a total dose of 3.0 Gy.

Table 1. Selected HPICL tests.

Test	Radiation Source	RadBall	Collimator Thickness (mm)
19	166 keV x-ray	N-5-5	5.0
25	^{60}Co	N-5-3	10.0
27	^{137}Cs	N-5-4	10.0

3. RadBall™ Modeling

An isotropic point source emitting photons with a single energy was modeled in a General Monte Carlo N-Particle Transport Code (MCNP) – Version 5[1]. Multiple MCNP runs were completed varying the energy, collimator thickness, and collimator hole diameter. The center of the collimator was placed one meter from the point source. Seven of the collimator holes were included in the model. These seven holes create a section of a single row containing collimator holes spaced at 12 degree increments, as shown in Figure 2. A hole pointed directly at the source and three holes on each side were modeled. Tungsten with a density of 19.25 g cm^{-3} was entered into MCNP. Eighty cells were placed behind the collimator holes (Figure 2). Photons that entered these cells were counted to determine what effect the tungsten had on the incident photons.



(c)

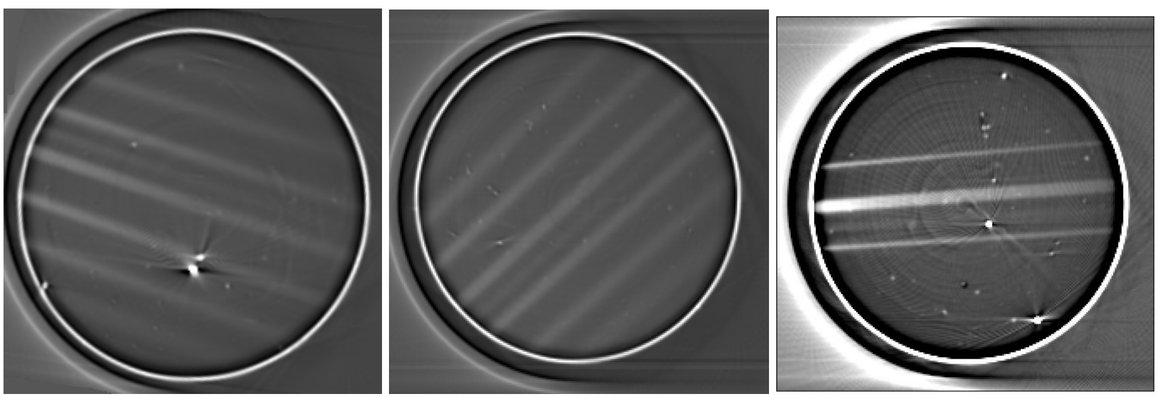
Figure 2. (a) Cross-section of the collimator with four holes labeled A,B,C, and D (b) photo of collimator showing labeled holes A,B,C, and D (c) computer model cross-section showing that only seven holes were considered and also showing the 80 MCNP tally cells.

[1] MCNP is described in great detail at http://mcnp-green.lanl.gov/index.html and is available at http://www-rsicc.ornl.gov/

The 10 mm, 7.5 mm, and 5.0 mm thick collimators were modeled in MCNP. In the MCNP runs the actual hole diameter was used for the center and left side holes, different size holes were used on the right side. The three holes on the right side were all uniform in diameter size. This allowed for comparison between what was actually used in the HPICL exposures and alternative hole diameter sizes. It was hypothesized that smaller hole diameter sizes would improve the collimation effect on incoming photons. The collimation effect could not be easily shown in the experimental tests completed at HPICL as the collimators differed in thickness and hole diameter.

4. Results and conclusion

The Image Processing and Analysis in Java software (ImageJ website: http://rsbweb.nih.gov/ij/) representations for the tests in Table 1 are shown in Figure 3. These cross section images show the tracks created along a row of collimator holes. There are some high illumination points that appear in the images; these are unwanted artifacts. All the collimators provided enough shielding that tracks were visible in all 45 exposures. The dose range of 0.5 to 5.0 Gy created visible tracks with both the ^{60}Co and ^{137}Cs sources.



RadBall^{TM} ID: N-5-4
Source: ^{137}Cs (662 keV)
Total Absorbed Dose: 3.0 Gy
Collimator Thickness: 10 mm
Hole Diameter: 4.0 mm
Point Source

RadBall^{TM} ID: N-5-3
Source: ^{60}Co (1.17 & 1.33 MeV)
Total Absorbed Dose: 3.0 Gy
Collimator Thickness: 10 mm
Hole Diameter: 4.0 mm
Point Source

RadBall^{TM} ID: N-5-5
Source: 166 keV x-ray
Total Absorbed Dose: 3.0 Gy
Collimator Thickness: 5.0 mm
Hole Diameter: 2.25 mm
Point Source

Figure 3. ImageJ representations of RadBall^{TM} exposures at HPICL.

The collimator holes are designed to collimate the incident photons and prevent exposure to the RadBall^{TM} dosimeter if the incident photons are not aligned with the collimation holes. The exposures with the ^{60}Co and ^{137}Cs sources demonstrate that the collimator holes allowed an angle of approximately 36 degrees into the dosimeter at higher photon energies above 600 keV. If it is deemed necessary to lower this 36 degree angle of view, it is recommended that the thickness of the collimator be increased or the diameter of the hole decreased.

As expected, the MCNP modeling represented in Figure 4 has indicated that higher energy photons are not fully shielded by the RadBall^{TM} collimator. MCNP modeling demonstrates that higher energy photons (above 200 keV) penetrate the solid section of the collimator; thus uniformly irradiating the RadBall^{TM}. This is shown by the minimum values on the Figure 4 plots of the lines pertaining to energies above 200 keV; minimums above zero indicate photons penetrating the tungsten shield. This has to be accounted for in the analysis of the RadBall^{TM} scan and could be used for isotopic differentiation between isotopes that emit significantly different photon energies.

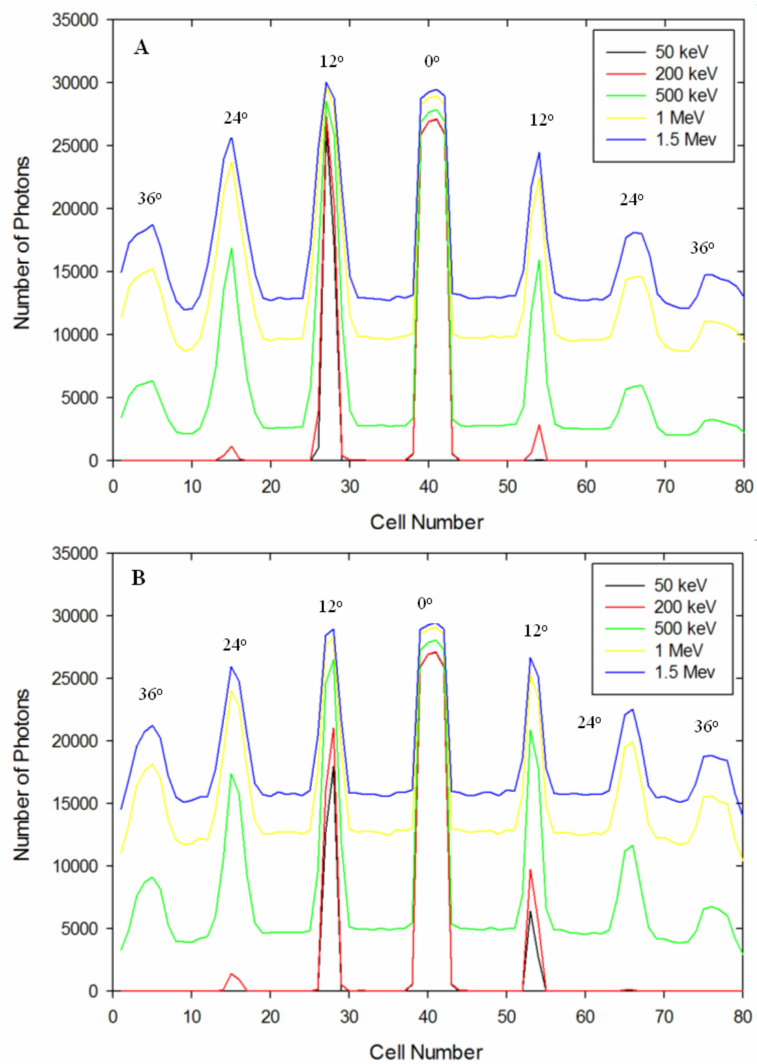


Figure 4. Number of particles crossing the cells. A) 10 mm thick tungsten collimator with 4.0 mm holes left (0 to 45 cell numbers) and 2.25 mm holes right (46 to 80 cell numbers). B) 7.5 mm thick tungsten collimator with 3.0 mm holes left (0 to 45 cell numbers) and 2.25 mm holes right (46 to 80 cell numbers).

5. References

[1] S.J. Stanley, RadBall: A Small Deployable Polymer Based Radiation Mapping Device for Locating, Quantifying and Characterizing Contamination in a Given Cell/Glovebox/Room, Nuclear Future, **4**(6), pp 302-308 (2008).

[2] E.B. Farfán, T. Q. Foley, G.T. Jannik, J. R. Gordon, L.J. Harpring, R. Blessing, S.J. Stanley, C.J. Holmes, M. Oldham, and J. Adamovics, *Testing of the RadBall Technology at Savannah River National Laboratory*. Savannah River National Laboratory, Aiken, SC 2009 (SRNL-2009-00808).