

# LOCATING RADIATION HAZARDS AND SOURCES WITHIN CONTAMINATED AREAS BY IMPLEMENTING A REVERSE RAY TRACING TECHNIQUE IN THE RADBALL™ TECHNOLOGY

Eduardo B. Farfán,\* Steven Stanley,† Christopher Holmes,† Kathryn Lennox,† Mark Oldham,‡ Corey Clift,‡§ Andrew Thomas,‡ and John Adamovics\*\*

---

**Abstract**—RadBall™ is a novel technology that can locate unknown radioactive hazards within contaminated areas, hot cells, and gloveboxes. The device consists of a colander-like outer tungsten collimator that houses a radiation-sensitive polymer hemisphere. The collimator has a number of small holes; as a result, specific areas of the polymer are exposed to radiation, becoming increasingly more opaque in proportion to the absorbed dose. The polymer hemisphere is imaged in an optical computed tomography scanner that produces a high resolution three-dimensional map of optical attenuation coefficients. A subsequent analysis of the optical attenuation data, using a reverse ray tracing technique, provides information on the spatial distribution of gamma-ray sources in a given area, forming a three-dimensional characterization of the area of interest. The RadBall™ technology and its reverse ray tracing technique were investigated using known radiation sources at the Savannah River Site's Health Physics Instrument Calibration Laboratory and unknown sources at the Savannah River National Laboratory's Shielded Cells facility. *Health Phys.* 102(2):196–207; 2012

**Key words:** contamination; detector, radiation; gamma radiation; radiation dose

---

## INTRODUCTION

THE CONSEQUENCES of radiological operations at various U.S. Department of Energy (DOE) sites have resulted in substantially contaminated facilities (e.g., reactors, fuel

and isotope processing facilities, laboratories, hot cells, gloveboxes, etc.). These facilities are usually associated with extremely high dose rates, and therefore it is imperative to use remote technologies for characterization and decommissioning to keep worker exposures as low as reasonably achievable in these highly contaminated environments. Although technologies might exist in other industry applications that could be tested, modified, and deployed for characterization and decommissioning efforts throughout the DOE complex, development of new and innovative technologies is also needed. In addition, even though it might be possible to complete these tasks without remote/robotic systems, the benefits of remote systems to safety/ALARA and cost/schedule are expected to be substantial. A critical initial step in planning and implementing decontamination and decommissioning of contaminated facilities involves the development of an accurate assessment of the radiological, chemical, and structural conditions inside the facilities. These conditions are often unknown for many of these facilities. Radiological and chemical contamination, as well as structural deterioration of such facilities that presents risks to workers, must be mitigated. To the extent that information can be collected to describe facility conditions using remote technologies, the conservatism associated with planning initial worker entry (and associated cost) can be reduced. For facilities confirmed to be high hazard, remote and robotic technologies for characterization, decontamination, and decommissioning can further reduce the costs to mitigate worker risks.

Various national and international organizations (e.g., the U.S. DOE, Department of Defense, Department of Homeland Security, Nuclear Regulatory Commission, Environmental Protection Agency, and the International Atomic Energy Agency) deal with radioactive contamination on a regular basis. These organizations have expressed the need for better radiation detector systems

---

\* Savannah River National Laboratory, Aiken, SC 29808; † National Nuclear Laboratory, Warrington, WA3 6AE, United Kingdom; ‡ Duke University Medical Center, Durham, NC 27710; § Montefiore Medical Center, Bronx, NY 10467; \*\* Heuris Pharma LLC, Skillman, NJ 08558.

The authors declare no conflict of interest.

For correspondence contact: Eduardo B. Farfán, Environmental Science and Biotechnology, Environmental Analysis Section, Savannah River National Laboratory, Savannah River Nuclear Solutions, LLC, 773-42A, Room 236, Aiken, SC 29808, or email at Eduardo.Farfán@srnl.doe.gov.

(Manuscript accepted 25 August 2011)

0017-9078/12/0

Copyright © 2012 Health Physics Society

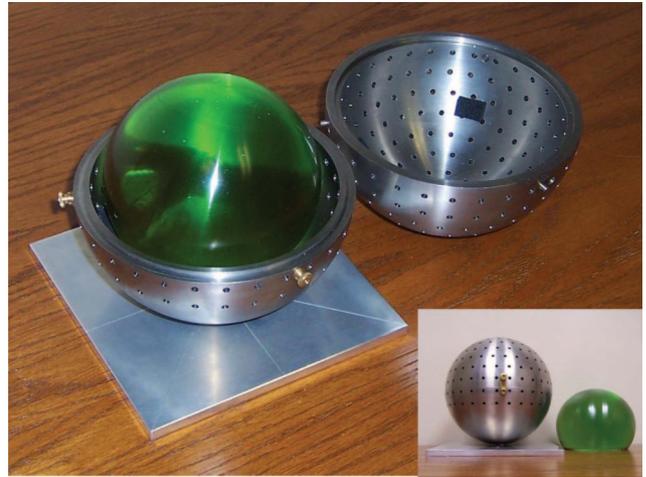
DOI: 10.1097/HP.0b013e3182348c0a

to characterize and locate unidentified sources of radiation such as hot spots within glove boxes, hot cells, and other confined spaces where elevated radiation levels exist. These systems should provide three-dimensional (3D) characterizations of the affected areas while having valuable properties that include low cost, robustness, and stability against falls, impacts, and extreme temperatures. In addition, the systems should be remotely deployable during the measurement/characterization process (no connecting power, communication cords or electronics) to ensure a high degree of deployability that may open up new possibilities for radiation measurement and mapping in areas of a facility that were previously considered physically inaccessible with traditional electrical-based radiation detection systems. A suitable technology should also offer an inexpensive and safer means to perform initial radiological characterizations, in-process surveys, and final status surveys to enable effective decontamination while minimizing exposure to workers.

This study completed at Savannah River National Laboratory (SRNL) addressed key aspects of the testing and further development of an innovative technology, RadBall™, originally developed by the National Nuclear Laboratory (NNL) in the United Kingdom (Stanley 2008; Holmes et al. 2010; Farfán et al. 2010a, 2010b, 2010c; Oldham et al. 2010). RadBall™ technology presents a significant opportunity to expedite initial characterization of radiologically contaminated facilities with respect to ALARA concerns, initial decontamination strategies, and costs associated with the decontamination efforts. RadBall™ will make radiation mapping safer and potentially more accurate and convenient than conventional detection devices, which are often much bigger and more cumbersome due to their electrical components and accessories. A single RadBall™ can be positioned in a highly contaminated area, glove box, or hot cell and left alone to collect data instead of personnel spending valuable time carrying out manual scanning and surveying.

## MATERIALS AND METHODS

The RadBall™ device consists of a colander-like outer shell that houses a radiation-sensitive PRESAGE™ polymer semisphere (Fig. 1) (Adamovics and Maryanski 2006; Doran et al. 2008; Guo et al. 2006a, 2006b, 2006c; Sakhalkar et al. 2009). The outer shell works to collimate radiation sources, and those areas of the polymer semisphere that are exposed react, becoming increasingly less transparent in proportion to the absorbed dose. The RadBall™ prototypes involved three 216-hole tungsten collimators (5.0-, 7.5-, and 10.0-mm-thick). The 5.0-mm-thick tungsten collimator has 2.25-mm holes and one



**Fig. 1.** Two components of a RadBall™ device: the outer tungsten collimator and inner radiosensitive PRESAGE™ polymer core.

single 4-mm hole. The 7.5-mm-thick collimator has 3-mm holes and one single 4-mm hole. The 10.0-mm-thick collimator has 4-mm holes. The collimators (e.g., number of holes and hole diameter) were designed with as few holes as possible to minimize the overlap of the field of view of adjacent holes.

The polymer semisphere is imaged in an optical-CT scanner developed at Duke University (Fig. 2) (Oldham 2006; Oldham et al. 2010), which produces a high resolution 3D map of optical attenuation coefficients. The orientation of the opacity track provides the positional information regarding the source, which is achieved by using a reverse ray tracing technique. The activity of the detected source is assessed by quantifying the magnitude of the opacity change that follows a linear relationship with respect to absorbed dose. There is the potential to characterize radiation sources by studying the depth of the opacity track (the measured opacity in the track over the depth of the track will follow a function that can be interpreted to estimate the characteristic energy or energies of the incident radiation source).

The experiments were completed at the Savannah River Site (SRS) Health Physics Instrument Calibration Laboratory (HPICL) using various gamma-ray sources and an x-ray machine with known radiological characteristics. The objective of these tests was to verify the validity of the reverse ray tracing technique to determine the location of radiation sources within a contaminated area and identify the optimal dose and collimator thickness of the RadBall™. The second set of tests involved a highly contaminated operational hot cell. The objective of this part of the testing was to characterize a hot cell with unknown sources. RadBall™ devices were deployed in the hot cell to obtain a comprehensive 3D

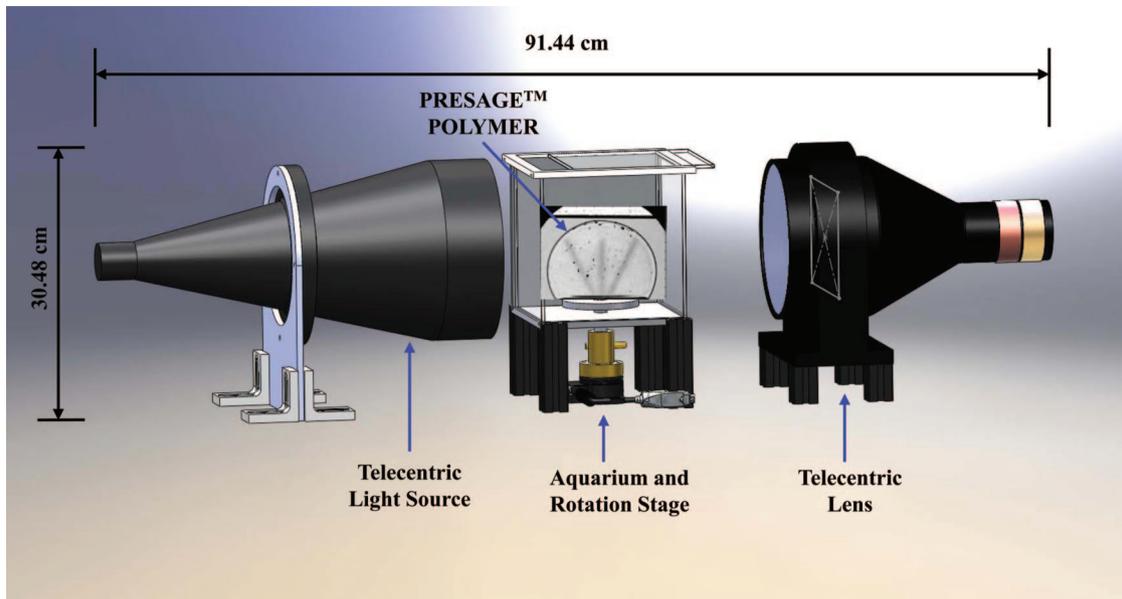


Fig. 2. Schematic representation of the optical computed-tomography scanner developed by Duke University.

characterization (e.g., identify the location of the sources within the hot cell).

### RadBall™ deployment and retrieval

A complete RadBall™ deployment and retrieval process consists of six individual steps illustrated in Fig. 3 (Stanley 2008; Holmes et al. 2010). Step 1 involves placing RadBall™ into a contaminated area such as hot cell, glove box, or contaminated room. Knowing the RadBall™ position and orientation ensures an accurate use of the reverse ray tracing technique. The deployment can be accomplished by using a crane, manipulator, trolley, or robot. The device is triple-bagged to prevent it from becoming contaminated. Step 2 includes knowing the radiation dose rates at the RadBall™ location within the contaminated area. This helps determine the optimal deployment time, during which RadBall™ remains still. Step 3 involves the retrieval of the device from the contaminated area, debugging the device, and checking for contamination. Step 4 includes the removal of the irradiated radiosensitive PRESAGE™ polymer from the RadBall™ collimator. The irradiated polymer contains visible radiation tracks (Fig. 4). Step 5 involves the optical scanning of the polymer using the Duke Mid-sized Optical CT Scanner (DMOS). The scanning produces a matrix of values that indicate the change in optical density (OD) within the irradiated polymer. The OD change can be viewed using a personal computer (PC). DMOS consists of a telecentric light source, a charged couple device (CCD) camera with telecentric lens, a motor-controlled rotation stage for rotating the

polymer sample, an aquarium for holding the sample, an optical refractive index matching fluid, and a PC with associated control and data acquisition software (Fig. 2). The telecentric light source produces a parallel light beam that passes through the aquarium containing the irradiated polymer as well as a fluid with a refractive-index (RI) equivalent to that of the polymer. The resultant image is then collated using the telecentric lens and CCD camera. The aperture on the lens enables a variation in the acceptance angle of light rays that are allowed to form the image of  $\sim 0.2\text{--}10^\circ$ . Light rays that deviate from parallel with the optical axis by greater than the acceptance angle are excluded from the image. The system uses a computed tomography (CT) approach by taking a number of projections from different rotational positions of the polymer and using an image reconstruction algorithm to reconstruct a 3D 16-bit data cube representing the optical density change distribution within the polymer. This data set can then be read using image manipulation software such as the Image Processing and Analysis in Java (ImageJ) software (website: <http://rsbweb.nih.gov/ij/>). The DMOS is able to show radiation tracks within the irradiated polymer when exposed to at least 0.01 Gy. The system has a spatial resolution of about 2 mm. The scanning and data analyses take approximately 30 min. After the radiation-sensitive polymer has been optically scanned, the data is interpreted in Step 6 to produce a final visualization that allows the determination of the source locations within the contaminated area.

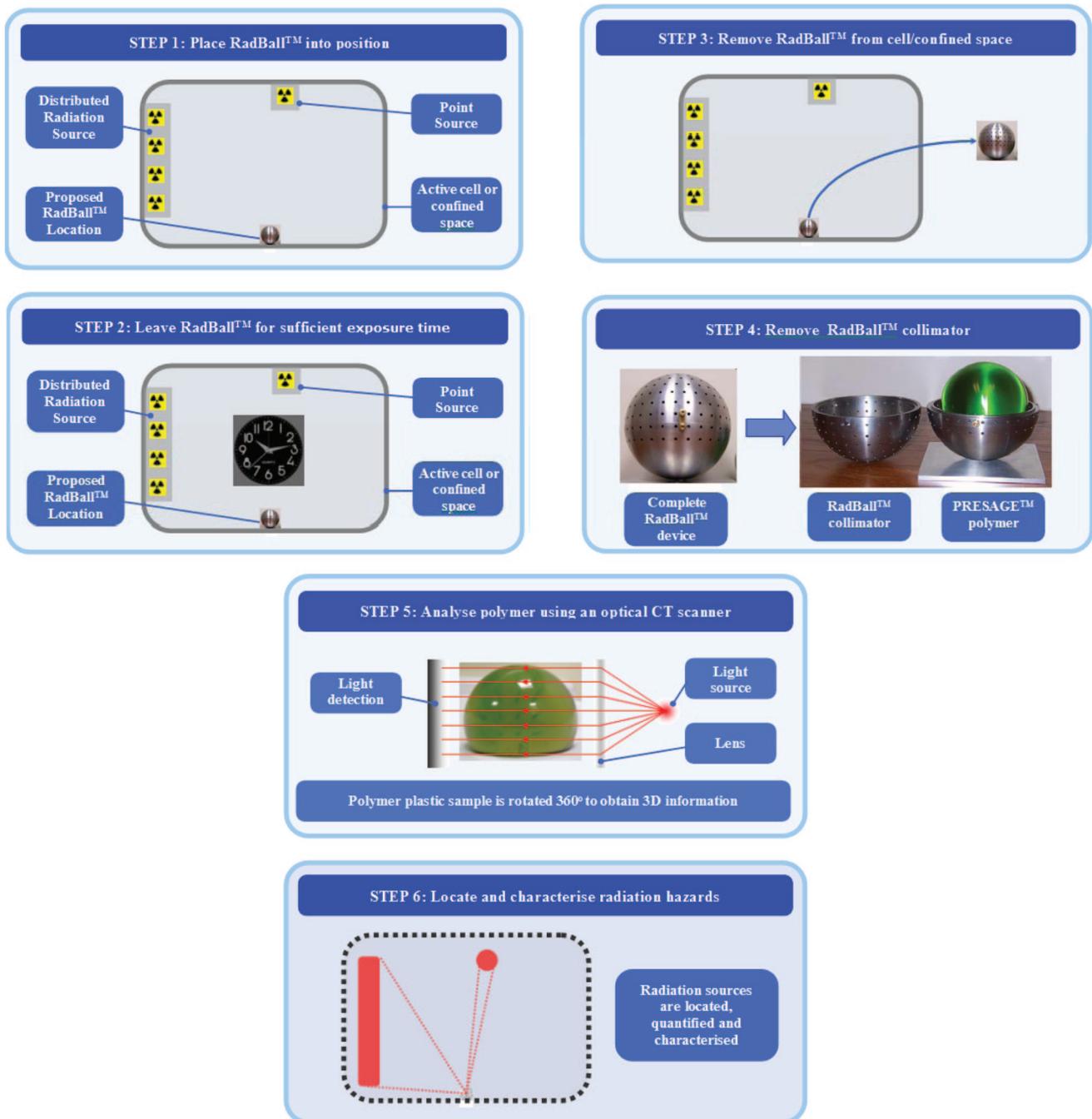
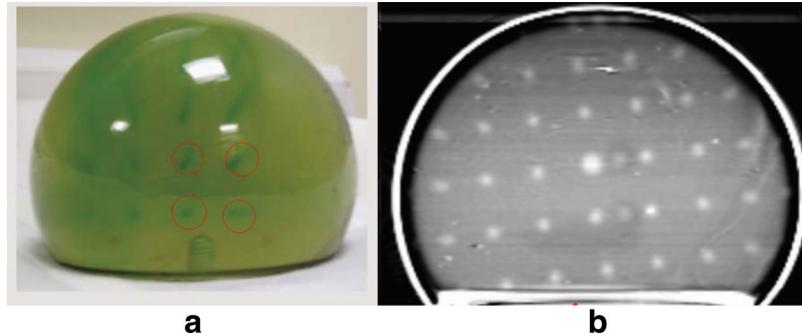


Fig. 3. The six-step process to characterize radiation sources within a contaminated area using RadBall™.

### RadBall™s reverse ray tracing technique

A reverse ray tracing technique is applied to determine the location of radiation sources within a contaminated room. ImageJ is used for the direct visualization of the scan results in the form of a stack of two-dimensional (2D) images. This stack of images can be scrolled through to give the effect of “moving through” the radiation-sensitive polymer. The scan file can be directly imported into ImageJ, and properties

such as the brightness and contrast are adjusted to make the tracks through the RadBall™ easier to identify. Three different views of the image can be used looking down the x, y, and z plane of the image, one of which is shown in Fig. 4b. The data from the areas of interest (radiation tracks) is extracted manually by clicking on several pixels in a track. ImageJ has an “auto next slice” function that moves through the stack after each click of the mouse. This function



**Fig. 4.** a) Visible radiation tracks in the PRESAGE™ polymer. b) ImageJ visualization showing the radiation tracks perpendicular to the plane of the page (looking down the tracks).

allows quick data removal when the image is orientated such that the view is looking down the track.

The exported data is in the form of a list of coordinates and corresponding intensities. By specifying within ImageJ, more information can be extracted about these points if required. These data lists, usually one per track, are then converted into a universal coordinate system for input into the next stage of the analysis in the NNL-developed RadBall™ Tool Software (RTS). To relate the universal set of coordinates into which the data points have been converted to the coordinate system used in the RTS, the radius of the RadBall™ is required (from ImageJ) as well as the width and height of the input image (in pixels).

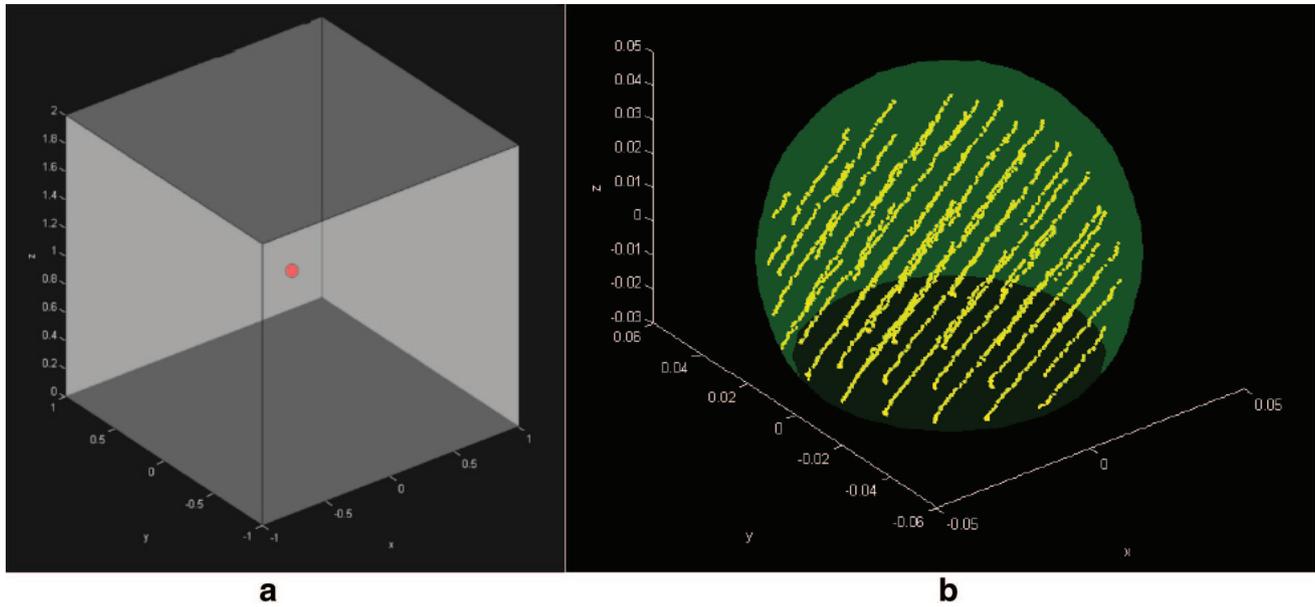
The RadBall™, being a truncated sphere, has the potential to rotate freely about its axis in the direction that the sphere is truncated, which could result in the predicted location of the sources being incorrect. When the RadBall™ is mounted for deployment, a mark is etched onto the polymer. This mark is lined up within the mounting device, which has a mark on the outside, and pointed to a specific place within the deployment area. The mark on the polymer is displayed as a bright mark on the surface area of the polymer in ImageJ. The location of the point needs to be extracted from ImageJ and converted to the global coordinate system in the same way as the data from the radiation tracks, which provides a means to align the radiation sensitive polymer with the overall cell geometry.

Once all data points have been converted to a universal coordinate system, a data file is created in the correct format to be readable by RTS. This consists of several tabs, specifically named, which hold information such as the track data, the mark point, the vector to which the mark is orientated, the size and shape of the deployment volume, and the location and orientation of the RadBall™ within the deployment volume. The first tab is used to view the deployment area and the location of the RadBall™ within the

deployment area, as shown in Fig. 5a. The second tab, as shown in Fig. 5b is used to view the data points of all the tracks within the RadBall™.

For each track within the RadBall™, the RTS creates a line of best fit for the data points provided and chooses the direction of the track by using the intensity values. This line of best fit is extrapolated until it intersects with a wall of the deployment volume. This indicates that the radiation source is on the wall at this location or anywhere along the line of site between the RadBall™ and the point on the wall. If two or more RadBall™ devices are deployed in different locations within the same deployment area, triangulation can be used to predict where along the extrapolated line the radiation source is. The third and final tab within the RTS is used to view the predicted radiation source locations. The RTS also has an image export function that exports each wall of the deployment area as a separate image. Each wall consists of a standard background color and areas of color change, which represent locations of radiation sources. This area of color change is a Gaussian distribution about the extrapolated track intersection point on the wall. Higher intensity tracks within the RadBall™ relate to brighter areas of color change. If more than one Gaussian distribution overlaps, each has a weighted Gaussian distribution calculated (by intensity), and the overlapped area is a summation of the weighted Gaussian distributions.

The final stage of the analysis is creating a file that is a visual representation of the deployment area. This file clearly shows the locations of the radiation sources. Google SketchUp™ (website: <http://sketchup.google.com/>) is a visualization tool that can be used to quickly and easily create rooms and buildings. A room is created with the same dimensions as the deployment volume, and key features such as tables or large objects can be included. Google SketchUp™ has a 2D import function, which allows images or photographs to be placed within the room that has been created. This function is used to paste



**Fig. 5.** Screen shots from the National Nuclear Laboratory's RadBall™ Tool Software Package. a) View of the deployment area and the location of the RadBall™ within the deployment area. b) View of the data points of the tracks within the RadBall™.

each wall that was exported from the RTS into the representation of the deployment area. Images can be layered, so it is very useful to add any photographs from the deployment area to create a more realistic and useful representation of the deployment area and the radiation sources within the deployment area.

## RESULTS AND DISCUSSION

### HPICL controlled experiments

The HPICL at the SRS contains nine Automated Irradiator Systems. All of the irradiators were designed or refurbished by Hopewell Designs Incorporated (website: <http://www.hopewelldesigns.com/>) to provide radiation beams of various types (beta particles, gamma rays, neutrons, and x-rays). The primary purpose of the equipment is to calibrate radiation detection instruments and test and verify personnel dosimeters. The sources and the exposures are therefore known with a high degree of certainty. The higher activity sources were ideal for the RadBall™ experiments since these sources provided shortened periods of exposure time. The highest activity  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  sources were used for the majority of the experiments currently around 45.9 and 178 TBq (1,240 and 4,756 Ci), respectively.

Three experimental phases were completed at the HPICL that included 45 exposures of RadBall™. Table 1 details all of the experiments completed at the HPICL:

- Phase 1 experiments were primarily used to obtain information on the target dose for RadBall™. Experiments were completed with a  $^{137}\text{Cs}$  source with irradiations from 0.5 to 5 Gy and with a  $^{60}\text{Co}$  source also with irradiations over the range of 0.5 to 5 Gy;
- Phase 2 experiments investigated the RadBall™'s performance with different radiation sources and different collimator thicknesses; and
- Phase 3 experiments investigated the ability of the RadBall™ technology to perform with high background levels of radiation. Uncollimated RadBall™ polymers were given a background radiation dose, and then a second irradiation was performed with the collimator fitted.

The  $^{241}\text{Am}$  source was used for one exposure; however, due to its low activity and therefore long exposure times, it was not used in any other test. With the exception of experiment 28 ( $^{241}\text{Am}$  exposed at a distance of 30 cm as shown in Table 1), all experiments were completed with the RadBall™ positioned 1 m away from the radiation source. At a distance of 30 cm and 1 m between the  $^{241}\text{Am}$  source and RadBall™, the source could not be considered a point source. An x-ray source was also used, which generated various photon energies with peaks at 166 keV, 120 keV, and 38 keV. The x-ray source was not ideal since it generated a distribution of photon energies; however, the peaks available were near the 60 keV gamma-ray energy emitted from  $^{241}\text{Am}$ . The

**Table 1.** HPICL experiments.

Test	Total dose (Gy)	Radiation source(s)	RadBall™ polymer	Collimator thickness <sup>a</sup> (mm)
Phase 1				
1	0.5	<sup>137</sup> Cs	N-1-2	5.0
2	1.0	<sup>137</sup> Cs	N-1-3	5.0
3	1.5	<sup>137</sup> Cs	N-1-4	5.0
4	2.0	<sup>137</sup> Cs	N-1-5	5.0
5	3.0	<sup>137</sup> Cs	N-1-6	5.0
6	5.0	<sup>137</sup> Cs	N-2-4	5.0
7	0.5	<sup>60</sup> Co	N-2-1	5.0
8	1.0	<sup>60</sup> Co	N-2-2	5.0
9	1.5	<sup>60</sup> Co	N-2-3	5.0
10	2.0	<sup>60</sup> Co	N-2-5	5.0
11	3.0	<sup>60</sup> Co	N-2-6	5.0
12	5.0	<sup>60</sup> Co	N-1-1	5.0
13	3.0	1.5 Gy <sup>137</sup> Cs + 1.5 Gy <sup>60</sup> Co (collinear)	N-3-2	5.0
14	6.0	3 Gy <sup>60</sup> Co (no collimator) + 3 Gy <sup>60</sup> Co	N-3-3	5.0
15	6.0	3 Gy 120 keV + 3 Gy 38 keV x-ray (rotated 180°)	N-3-1	7.5
Phase 2				
16	2.0	1 Gy <sup>60</sup> Co (no collimator) + 1 Gy <sup>60</sup> Co	N-3-4	5.0
17	4.0	2 Gy <sup>60</sup> Co (no collimator) + 2 Gy <sup>60</sup> Co	N-3-5	5.0
18	8.0	4 Gy <sup>60</sup> Co (no collimator) + 4 Gy <sup>60</sup> Co	N-3-6	5.0
19	3.0	166 keV x-ray	N-5-5	5.0
20	3.0	2 Gy <sup>137</sup> Cs + 1 Gy <sup>60</sup> Co (collinear)	N-4-3	5.0
21	3.0	1 Gy <sup>137</sup> Cs + 2 Gy <sup>60</sup> Co (collinear)	N-5-6	5.0
22	3.0	3 Gy <sup>137</sup> Cs + 1 Gy <sup>60</sup> Co (collinear)	N-4-2	5.0
23	3.0	1 Gy <sup>137</sup> Cs + 3 Gy <sup>60</sup> Co (collinear)	N-4-1	5.0
24	3.0	<sup>60</sup> Co	N-5-1	7.5
25	3.0	<sup>60</sup> Co	N-5-3	10.0
26	3.0	<sup>137</sup> Cs	N-5-2	7.5
27	3.0	<sup>137</sup> Cs	N-5-4	10.0
28	0.5	<sup>241</sup> Am	N-4-4	5.0
29	3.0	1.5 Gy 120 keV x-ray, rotated 90° & 1.5 Gy 38 keV	N-4-5	5.0
Phase 3				
30	3.0	1.5 Gy <sup>137</sup> Cs (no collimator) + 1.5 Gy <sup>137</sup> Cs (with collimator)	N-7-2	7.5
31	3.0	2.0 Gy <sup>137</sup> Cs (no collimator) + 1.0 Gy <sup>137</sup> Cs (with collimator)	N-8-2	7.5
32	3.0	2.5 Gy <sup>137</sup> Cs (no collimator) + 0.5 Gy <sup>137</sup> Cs (with collimator)	N-7-4	7.5
33	3.0	2.75 Gy <sup>137</sup> Cs (no collimator) + 0.25 Gy <sup>137</sup> Cs (with collimator)	N-8-5	7.5
34	3.0	2.85 Gy <sup>137</sup> Cs (no collimator) + 0.15 Gy <sup>137</sup> Cs (with collimator)	N-8-3	7.5
35	3.0	1.5 Gy <sup>137</sup> Cs (no collimator) + 1.5 Gy <sup>137</sup> Cs (with collimator)	N-7-1	10.0
36	3.0	2.0 Gy <sup>137</sup> Cs (no collimator) + 1.0 Gy <sup>137</sup> Cs (with collimator)	N-8-1	10.0
37	3.0	2.5 Gy <sup>137</sup> Cs (no collimator) + 0.5 Gy <sup>137</sup> Cs (with collimator)	N-10-3	10.0
38	3.0	2.75 Gy <sup>60</sup> Co (no collimator) + 0.25 Gy <sup>137</sup> Cs (with collimator)	N-9-1	10.0
39	3.0	2.85 Gy <sup>137</sup> Cs (no collimator) + 0.15 Gy <sup>137</sup> Cs (with collimator)	N-7-3	10.0
40	3.0	<sup>60</sup> Co: Mimic a distributed source by moving the RadBall in a direction perpendicular to the line between the source and the RadBall's initial position; i.e., irradiate using <sup>60</sup> Co to deliver 0.5 Gy. Then, move the RadBall by 0.5 cm and repeat a 0.5 Gy exposure until a total dose of 3.0 Gy is delivered.	N-9-2	7.5
41	3.0	<sup>60</sup> Co: Repeat experiment 40 moving the RadBall by 1.0 cm in each step.	N-9-3	7.5
42	3.0	<sup>60</sup> Co: Mimic multiple sources that are close to each other by rotating the RadBall between each irradiation; i.e., irradiate using <sup>60</sup> Co to deliver 0.5 Gy. Then, rotate the RadBall by 5° and repeat exposure (0.5 Gy). Repeat this sequence until a total dose of 3.0 Gy is delivered.	N-8-6	7.5
43	3.0	<sup>60</sup> Co: Repeat experiment 42 using an angle of rotation of 10°.	N-8-4	7.5
44	6.0	<sup>60</sup> Co: Irradiate RadBall with an initial dose of 1 Gy, then rotate the RadBall by 60° and give another 1 Gy dose. Repeat sequence until six irradiations have been completed and the RadBall has received a total dose of 6.0 Gy.	N-10-2	10.0
45	6.0	<sup>60</sup> Co: Repeat experiment 44 with the RadBall tilted at a 45° angle.	N-10-1	10.0

<sup>a</sup> The 5.0-mm-thick tungsten collimator has 2.25-mm holes and one single 4-mm hole. The 7.5-mm-thick collimator has 3-mm holes and one single 4-mm hole. The 10.0-mm-thick collimator has 4-mm holes.

x-ray machine offered a much higher rate of exposure than the  $^{241}\text{Am}$  source and was therefore much more convenient in terms of exposure times.

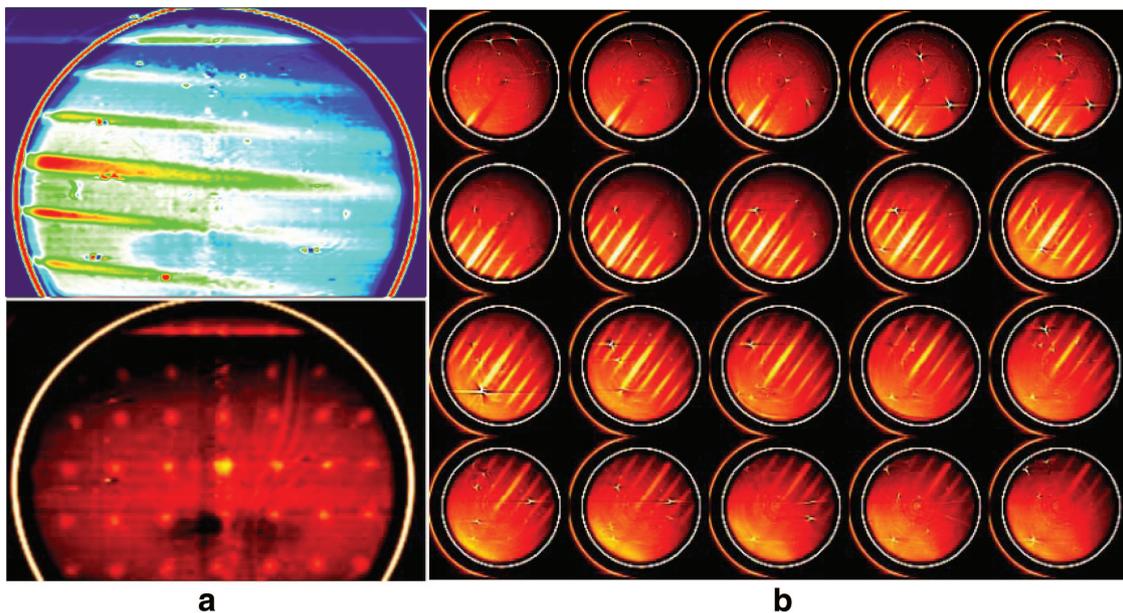
Fig. 6 shows a typical set of radiation tracks through an irradiated RadBall™ as seen from a number of viewing angles: two side view images (Fig. 6a) and a montage of horizontal slices moving through the RadBall™ top to bottom (Fig. 6b) produced in ImageJ from the optical CT scan data for RadBall™ N-2-4, which was irradiated with a  $^{137}\text{Cs}$  source from a distance of 1 m with a collimator thickness of 5.0 mm (Table 1). A dose of 5.0 Gy was delivered to N-2-4. The top left image is a vertical slice taken from the middle of the RadBall™. It shows the radiation tracks entering from the left of the RadBall™ at a slight angle above horizontal. The bottom left image shows the radiation tracks penetrating into the polymer through the holes of the collimation device. The set of montage images shows radiation tracks appearing in the polymer as one moves up through the stack of horizontal slices, with the middle of the RadBall™ showing the largest number and highest intensity radiation tracks. This is consistent with aligning the radiation source to deliver the radiation dose to the middle of the RadBall™.

Phase 1 experiments 1–12 produced results similar to those displayed in Fig. 7, which shows images of a horizontal slice of a RadBall™ (N-2-4) with pre-contrast (Fig. 7a) and post-contrast (Fig. 7b) enhancement applied (a feature within the ImageJ software, which allows the

contrast between the radiation tracks and the background to be enhanced). For both the  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  radiation sources, the experiments demonstrated a linear response between the opacity change of the PRESAGE™ polymer and the radiation dose delivered.

Fig. 7c is a plot profile taken from across the radiation tracks shown in Fig. 7b of RadBall™ N-2-4 (Table 1) and highlights the ability to be able to pick out the radiation tracks from against areas of the unirradiated polymer. Seven tracks are visible in the plot profile with a wider diameter radiation track in the middle of the RadBall™. This is to be as expected as the middle collimation hole was slightly larger than the other holes on the collimation device. The diminishing intensity of the peaks to the left and right of the middle peak is due to the curvature of the collimator geometry. Fig. 8a shows the scan images of RadBall™ N-4-5 (Table 1) irradiated with two sources (1.5 Gy 120 keV x-ray and 1.5 Gy 38 keV at  $90^\circ$  to the first irradiation). The scans show four radiation tracks entering from the top left and three radiation tracks entering from the top right, which cross over in the middle of the RadBall™.

Fig. 8b shows optical scan images for RadBall™ N-8-4 (Table 1). The aim of this experiment was to simulate multiple sources that are close to each other. The RadBall™ was delivered a  $^{137}\text{Cs}$  dose of 0.5 Gy, rotated by 10 degrees, and then delivered another  $^{137}\text{Cs}$  dose of 0.5 Gy. This exercise was repeated until a total dose of 3.0 Gy was delivered. The scan images from



**Fig. 6.** Typical set of radiation tracks through an irradiated RadBall™ as seen from a number of viewing angles. a) Two side view images. b) A montage of horizontal slices moving through the RadBall™ top to bottom produced in ImageJ from the optical CT scan data for RadBall™ N-2-4 irradiated with a 5.0 Gy  $^{137}\text{Cs}$  source from a distance of 1 m with a collimator thickness of 5.0 mm.

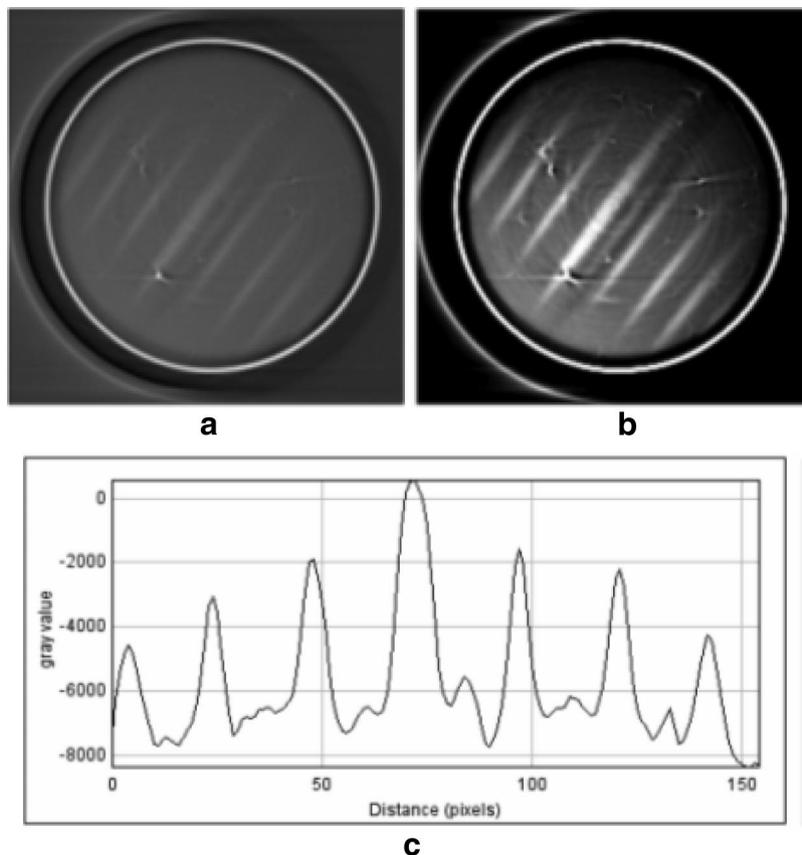


Fig. 7. ImageJ images of a) pre- and b) post-contrast enhanced slices of RadBall™ N-2-4. c) Plot profile of tracks.

RadBall™ N-8-4 highlight an interesting infringement pattern effect, where the radiation tracks are closer together at the bottom left of the image and become more dispersed and spread out toward the top right of the image. Brighter spots appear where radiation tracks are overlaid over one another.

Fig. 8c shows optical scan images for RadBall™ N-10-2 (Table 1). In this experiment, the RadBall™ was given an initial dose of 1 Gy, rotated by 60 degrees, and another 1 Gy dose delivered. This exercise was repeated until six irradiations had been completed. The pattern appearing in the polymer is similar to isometric graph paper. Higher intensity bright spots appear where one or more radiation tracks have been overlaid, increasing the radiation dose delivered to that area.

All 45 RadBall™ irradiations completed at the HPICL resulted in radiation tracks that were visible in the optical CT scans and have demonstrated the effective performance of the RadBall™ against the selected radiation sources and doses. Analysis of the RadBall™ optical CT scans from the HPICL experiments has indicated that for optimum contrast and thus ability to accurately locate radiation tracks in the PRESAGE™ polymer, a target dose of between 3–5 Gy is required. At

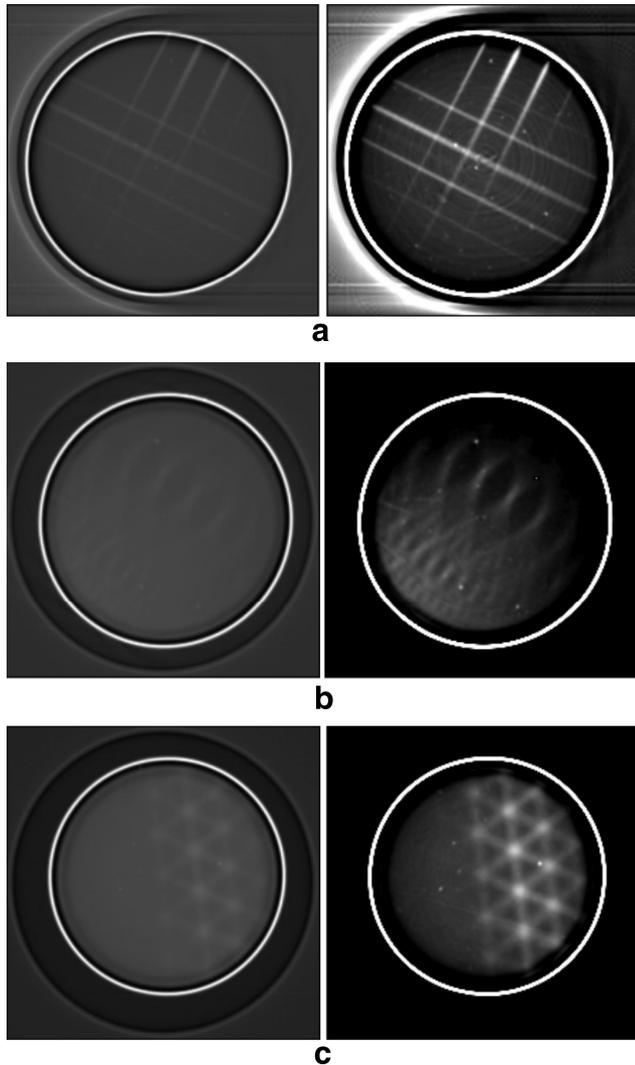
these target doses, the contrast of optical CT scans is improved by increasing the collimator thickness. Experiments completed with the 10 mm collimator provided the optimum contrast for data analysis.

#### SRNL hot cell deployment

The SRNL Shielded Cells Facility (SCF) has been used to work with a wide variety of highly radioactive samples. These cells offered an area to test RadBall™, as over the years their use has resulted in the buildup of contamination on the walls and floor. Another benefit of testing RadBall™ is the existence of the infrastructure to move the RadBall™ around in the cell with the cell's manipulator arms and crane. The shielded cell can also be viewed during exposure, which is beneficial for knowing where the RadBall™ is in the cell and how it is orientated. Fig. 9 shows a photograph of the SCF and the hot cell in which RadBall™ was deployed.

An electronic personal dosimeter (EPD) was placed in various shielded cells to gain an estimate of dose rates. The shielded cell with the highest EPD reading was chosen to minimize the amount of time RadBall™ would need to be exposed in the cell. Fig. 10a shows a top view of the hot cell, and Fig. 10b is a 3D visualization of the

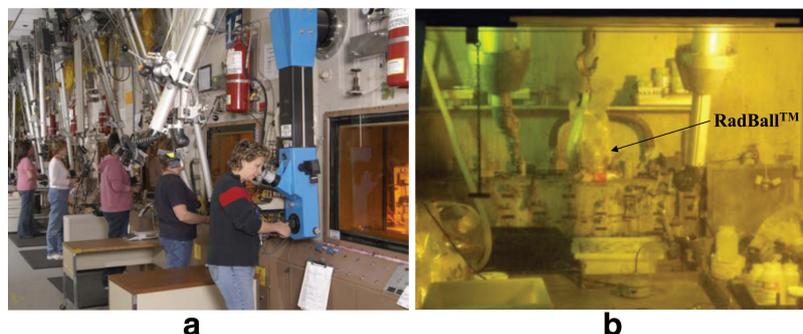
chosen hot cell created in Autodesk Inventor™ (website: <http://usa.autodesk.com>), used in conjunction with the radiation results from the deployed RadBall™ to effectively visualize the origins of the detected radiation.



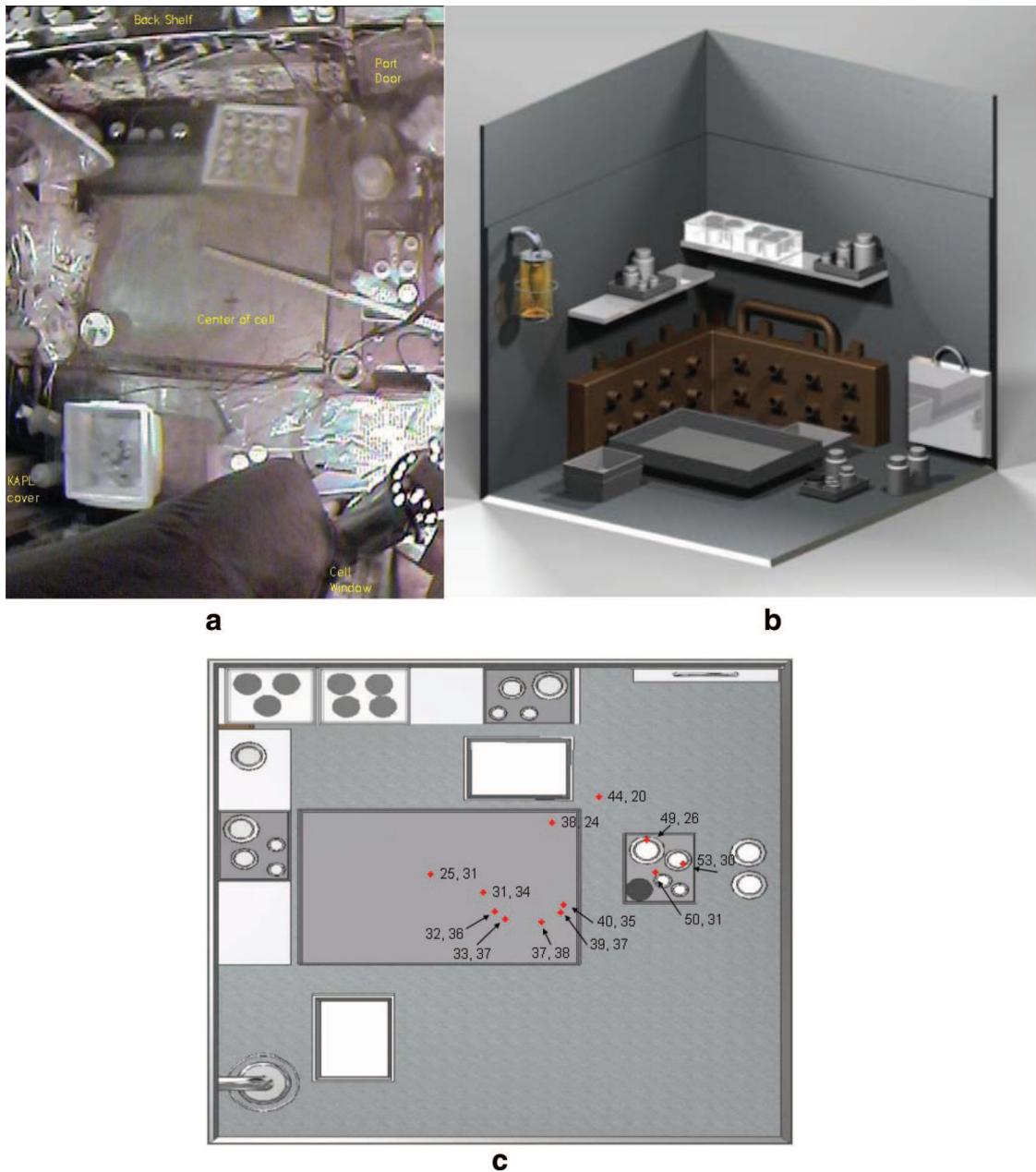
**Fig. 8.** ImageJ pre- and post-contrast images of RadBall™ tests a) N-4-5, b) N-8-4, and c) N-10-2.

Swipes were obtained in the selected hot cell, and  $^{60}\text{Co}$ ,  $^{137}\text{Cs}$ ,  $^{154}\text{Eu}$ , and  $^{241}\text{Am}$  sources were determined to be on the floor and walls. Other isotopes may be present in containers in the cell. The EPD was used to estimate exposure rates at various locations in the selected shielded cell. The center of the floor gave an EPD reading of  $0.18\text{ Gy h}^{-1}$  ( $18\text{ rad h}^{-1}$ ). The EPD read  $0.02\text{ Gy h}^{-1}$  ( $2.0\text{ rad h}^{-1}$ ) at 145 cm and  $0.039\text{ Gy h}^{-1}$  ( $3.9\text{ rad h}^{-1}$ ) at 91.4 cm above the floor. It was estimated that at 107 cm there would be  $0.0326\text{ Gy h}^{-1}$  ( $3.26\text{ rad h}^{-1}$ ).

RadBall™ N-7-5 was deployed in the hot cell at a raised height of 107 cm above the floor and left for a 72 h time period with a 10-mm collimator. The optical CT scans of N-7-5 showed 21 faint radiation tracks in the RadBall™ polymer. The coordinates of these tracks were imported into the NNL's in-house software along with the geometry of the hot cell. These combined data sets predicted the location of the radiation sources in the hot cell. Using the reverse ray tracing technique, the majority of the radiation was determined to be originating from the floor. These predicted radiation location results are overlaid in Fig. 10a on a computer-aided design (CAD) drawing of the floor and in Fig. 10c on a floor view from the 3D visualization of the hot cell. RadBall™ has located 12 closely distributed radiation sources originating from the floor, which are pointed toward the bottom of the equipment tray and the bottles located on the right hand side of the tray shown in Fig. 10a. This analysis is consistent with the RadBall™ pre-deployment EPD investigations that confirmed that the highest radiation doses were on the floor of the hot cell. While not knowing the isotopes in the bottles to the right of the tray, it is reasonable to assume that the tray on the hot cell floor would have the highest radiological contamination in the hot cell from bottle spills, airborne particle settlement due to gravity, etc. This contamination would be concentrated at the lowest point in the cell. This will be more advantageous when differentiating the radiation



**Fig. 9.** a) Photograph of the Savannah River National Laboratory's Shielded Cells Facility. b) Hot cell in which RadBall™ was deployed.



**Fig. 10.** a) Top view of the SRNL SCF hot cell. b) 3D visualization of the chosen hot cell created in Autodesk Inventor™. c) Hot cell floor with located radiation sources.

tracks in the polymer from the different area/volume and weak/strong sources.

### CONCLUSION

The RadBall™ technology has responded well during the HPICL experiments. Radiation tracks were visible in all of the 45 experiments and demonstrated that the RadBall™ technology is sensitive to  $^{60}\text{Co}$ ,  $^{137}\text{Cs}$ , and  $^{241}\text{Am}$  sources over the radiation range of 0.5 to 6 Gy. Larger doses are possible and would make the radiation

tracks more visible and useful when using RadBall™'s reverse ray tracing technique. The thicker the RadBall™ collimator, the better the signal-to-noise ratio would be. However, based on the limitations on the RadBall™ size and weight presented by the tools and instruments (e.g., manipulators and cranes) used to deploy RadBall™ into a hot cell or glovebox, the optimal collimation thickness would be 10 mm. To minimize unnecessary irradiation of the polymer, the collimator should have small collimator holes (e.g., 2.25 mm). Using the reverse ray tracing technique, the HPICL experiments have demonstrated

that RadBall™ has the ability to locate radiation point sources.

Upon completion of the HPICL testing, the RadBall™ technology was deployed in a hot cell in the SRNL SCF. RadBall™ located the strongest radiation sources originating from the floor of the hot cell, and the location of these radiation sources has been displayed on a 3D visualization of the hot cell using the reverse ray tracing technique. This represents the first successful hot cell deployment of the RadBall™ and a further step in demonstrating NNL's unique radiation mapping device with the ability to be remotely deployed with no electrical supplies into difficult-to-access areas and locate and quantify radiation hazards. Further work is ongoing to investigate whether the RadBall™ technology is able to characterize more complex radiation environments.

*Acknowledgments*—The authors would like to thank Andrew P. Szilagy, Director of the Office of Deactivation and Decommissioning (D&D) and Facility Engineering (EM-44), U.S. Department of Energy—Office of Environmental Management, for his support of the project entitled “Hot Cell Characterization” involving the testing, verification, and development of the RadBall™ technology. In addition, the authors would like to express their gratitude to Don Mackenzie for his guidance in the beginning of this project, Rebecca Butler (SRNS General Counsel) and Eric Frickey (SRNL Technology Transfer) for their support on the new technologies developed during this project, Ronald Blessing (SRNL Shielded Cells) for his help with the hot cell deployments at SRNL, and Michelle Holman-Abbott (SRNS Radiological Monitoring) for her help with the RadBall™ testing at the SRS Health Physics Instrument Calibration Laboratory. This project is being completed at Savannah River National Laboratory in collaboration with the United Kingdom's National Nuclear Laboratory, Duke University Medical Center, and Heuris Pharma LLC.

*Disclaimer*—This manuscript has been co-authored by Savannah River Nuclear Solutions, LLC, under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting this article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the authors or their corresponding organizations.

## REFERENCES

- Adamovics J, Maryanski M. Characterization of PRESAGE™: a new 3-D radiochromic solid polymer dosimeter for ionizing radiation. *Radiat Protect Dosim* 120:107–112; 2006.
- Doran SJ, Stanley SJ, Jennesson PM, Prott E, Adamovics J. RadBall™: a new departure for 3D dosimetry, DOSGEL. In: *The 5th International Conference on Radiotherapy Gel Dosimetry*. Crete: University of Heraklion; 2008; 1-5. Available at [http://iopscience.iop.org/1742-6596/164/1/012042/pdf/1742-6596\\_164\\_1\\_012042.pdf](http://iopscience.iop.org/1742-6596/164/1/012042/pdf/1742-6596_164_1_012042.pdf). Accessed on 28 November 2011.
- Guo P, Adamovics J, Oldham M. Simple 3D validation experiments for PRESAGE™/optical-CT dosimetry. *J Phys Conf Ser* 56:187–194; 2006a.
- Guo P, Adamovics J, Oldham M. Quality assurance in 3D dosimetry by optical-CT. *J Phys Conf Ser* 56:191–194; 2006b.
- Guo P, Adamovics J, Oldham M. Investigation of the dosimetric characteristics of PRESAGE™. *J Phys Conf Ser* 56:207–210; 2006c.
- Farfán EB, Foley TQ, Stanley SJ, Holmes CJ, Mills RW, Knight P, Mackenzie D, Jannik GT, Oldham M, Clift CG, Thomas A, Adamovic J, Gladden JB. Control testing of the UK's National Nuclear Laboratory's RadBall™ Technology at Savannah River National Laboratory. In: *Waste management 2010*. Phoenix, AZ: WMS; 2010a; 1-5. Available at <http://www.wmsym.org/app/2010cd/wm2010/pdfs/10080.pdf>. Accessed 29 November 2011.
- Farfán EB, Foley TQ, Jannik GT, Harpring LJ, Gordon JR, Blessing R, Coleman JR, Stanley SJ, Holmes CJ, Oldham M, Adamovics J. RadBall™ technology testing in the Savannah River Site's Health Physics Instrument Calibration Laboratory. In: *The 6th International Conference on 3D Radiation Dosimetry*. *J Phys Conf Ser* 250:012080; 2010b; 1-5. Available at <http://iopscience.iop.org/1742-6596/250/1/012080>. Access 29 November 2011.
- Farfán EB, Foley TQ, Jannik GT, Harpring LJ, Gordon JR, Blessing R, Coleman JR, Holmes CJ, Oldham M, Adamovics J, Stanley SJ. RadBall™ technology testing and modeling of the tungsten collimator. In: *The 6th International Conference on 3D Radiation Dosimetry*. *J Phys Conf Ser* 250:012081; 2010c; 1-5. Available at <http://iopscience.iop.org/1742-6596/250/1/012081>. Access 29 November 2011.
- Holmes CJ, Farfán EB, Oldham M, York T, Green P, Jackson P, Stanley SJ. Some recent technology developments from the UK's National Nuclear Laboratory to enable hazard characterization for nuclear decommissioning applications. In: *Waste Management 2010*. Phoenix, AZ: WMS; 2010; 1-10. Available at <http://www.wmsym.org/app/2010cd/wm2010/pdfs/10317.pdf>. Accessed 29 November 2011.
- Oldham M. 3D Dosimetry by optical-CT scanning. *J Phys Conf Ser* 56:58–71; 2006.
- Oldham M, Clift C, Thomas A, Farfán EB, Foley TQ, Jannik GT, Adamovics J, Holmes CJ, Stanley SJ. Initial experience Optical-CT scanning of RadBall™ dosimeters. In: *The 6th International Conference on 3D Radiation Dosimetry*. *J Phys Conf Ser* 250:012079; 2010; 1-5. Available at <http://iopscience.iop.org/1742-6596/250/1/012079>. Access 29 November 2011.
- Sakhalkar HS, Adamovic J, Ibbot G, Oldham M. A comprehensive evaluation of the PRESAGE™/optical-CT 3D dosimetry system. *Med Phys* 36(1); 71–82; 2009.
- Stanley SJ. RadBall™: a small deployable polymer based radiation mapping device for locating, quantifying and characterizing contamination in a given cell/glovebox/room. *Nucl Future* 4:302–308; 2008.