Characterizing Inorganic Scintillation Detectors for Determining Radiation Exposure - 11358

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ABSTRACT

A number of buildings at Oak Ridge National Lab (ORNL) and Y-12 National Security Complex have been slated for deactivation and decommissioning (D&D) under the Integrated Facility Disposition Project (IFDP). Virtually all of these buildings were used for developing nuclear and radiochemical technologies. The buildings slated for D&D may be contaminated with unknown quantities of radioactive materials. A survey to determine the location of radioactive material and the extent of contamination needs to be performed in each building before personnel can safely enter the buildings and begin D&D.

This paper describes the method and equipment used to correlate gamma ray spectra to dosimetric data and methods employed in identifying the gamma detectors that are most effective for dosimetric conversion. The absolute efficiency of several NaI(Tl) and $LaBr_3$(Ce) detectors have been measured as a function of distance from several high-activity radioactive isotopes. Systematic surveys of contaminated sites can locate and identify contaminating isotopes. If the source is identified and the position is known, an absolute efficiency value can be matched to the source, allowing for the activity to be easily calculated. If the activity of the source has been determined, using methods described by the National Council on Radiation Protection and Measurements, the dose to personnel as a function of distance from a source can be determined.

INTRODUCTION

Buildings at ORNL scheduled for D&D need to be radiologically surveyed prior to personnel entering the building to avoid exposing them to hazardous levels of radiation. Detailed historical records of the materials used/stored within the buildings are either not available or are not sufficient enough to determine which materials might be present. Surveys of the buildings need to be performed so contaminants can be identified and located. Exposure rates from identified contaminants need to be determined. To perform the survey, robotic systems will be mounted with ultrawideband (UWB) location sensors. The transmission from the UWB sensor is picked up by a network of sensors within the building and be can used to pinpoint the location of the robot within the building. When the location data are coupled with the scintillation detector data, maps of the radiation field can be constructed.

Spectral data are collected using inorganic scintillation detectors (NaI(Tl) and $LaBr_3$(Ce)) and ORTEC® hardware/software. Data collected from the scintillation detectors can be used to measure the intensity of the radiation field and identify contaminants. These data will then be used to calculate the activity of the contaminants, which can then be used to calculate exposure

rates. The decision to use gamma-ray spectroscopy over traditional measurements (dosimeter data, Geiger counters, etc) to do the survey is because gamma-ray spectroscopy is quicker and can be used for isotope identification.

Before calculations can be made, detector performance must be characterized in order to convert spectral data to exposure values. Understanding how the detector performs under a variety of circumstances is required to perform accurate calculations such as the activity of the contaminating isotopes and exposures rates from said isotopes. This experiment identifies detector performance, methods used to determine source activity and methods used to calculate exposure rates. This experiment also contains an example of a survey of a simulated contamination site.

EXPERIMENT

For this experiment, all measurements were performed on a test bed developed at the Institute for Clean Energy Technology (ICET) for creating characterized radiation fields [1]. At the center of the test bed (the origin), sources can be placed at a variety of heights above the test bed. Radiating from the origin, holes were drilled and tapped which allows for the mounting of detectors and badge supports to the test bed. The holes are separated in 15° increments from each other to form rays emanating from the origin. The holes are positioned to allow for measurements to be made at repeatable positions every two inches along each ray. For mounting locations beyond the test bed, a differential GPS can be used to determine the location of the detectors of relative to the source.

For this experiment, a Cs-137 source was supported one meter above the test bed. The source was mounted at this height to keep backscattering off the test stand at a minimum and so measurements could be made above and below the source. A special detector mount was constructed for this experiment. The constructed mount allows for multiple detectors to be placed above the same position of the test bed at varying heights. The mount also allows for the adjustment of the vertical and horizontal angle of the detectors relative to the source. Figures 1 and 2 shows the general layout of the test stand.

Detectors used for spectroscopy measurements include 3x3 cerium-activated lanthanum bromide ($LaBr_3(Ce)$) and 3x3 thallium-activated sodium iodide (NaI(Tl)). $LaBr_3(Ce)$ detectors have exceptional resolution and efficiency compared to the standard 3x3 NaI(Tl) detector. The major benefit of using NaI(Tl) is that the detectors cost 3% - 4% of that of a similar $LaBr_3(Ce)$ detector. Table 1 contains data on the properties of each detector type [2].

Table 1. Detector Properties

Detector	Y ph/MeV	τ (ns)	λ (nm)	ρ (cm/g^3)
NaI(Tl)	43,000	230	415	3.67
$LaBr_3(Ce)$	61,000	17-35	-	5.29

Fig. 1. Test stand used to create characterized radiation fields with a Cs-137 source placed 1 cm above the test stand. $LaBr_3(Ce)$ detectors are located in the horizontal plane of the source and 1 m above and below the source.

Fig. 2. A view from above the test stand.

The detectors are mounted by an ORTEC® digiBASE™. The digiBASE™ controls the photomultiplier tube of the detector and is a multichannel analyzer. ORTEC®'s Scintivision™ software was used to collect, calibrate, and save spectra from the detectors. A $LaBr_3$(Ce) detector mounted with an ORTEC® digiBASE™ can be seen in Figure 3.

Fig. 3. $LaBr_3$(Ce) detector mounted with an ORTEC® digiBASE™.

To calculate exposure rates to personnel from gamma spectra, the location of contaminants must be known. To determine the position of the contaminants, a survey with scintillation detectors must be done. Detectors can be attached to automated or robotic systems to perform surveys. A sample of a survey done with scintillation detectors can be seen in Figure 4. Using Geosoft® Oasis montaj software, the location of the contaminants can be determined. By analyzing the spectra collected during the survey, identification of the contaminating isotope can be determined.

Determination of the source activity is more difficult than identifying the isotopes or their locations. The activity of a source can be calculated using Equation 1 [3]. Table 2 contains a description of each variable in Equation 1. All of the variables in Equation 1 are known except the absolute efficiency. This equation describes the activity of a source based on the number of gamma-ray photons detected at the photopeak of the isotope and the absolute efficiency for the detector-source geometry.

The absolute efficiency describes how well the detector collects gamma-ray photons at the photopeak. The absolute efficiency is the number of photons detected by the scintillation detector at the photopeak of the isotope divided by the total number of gamma-rays emitted from the source during the duration of the measurement. This absolute efficiency is a function of the energy of the incident gamma-rays and, and more importantly, the detector-source geometry.

The absolute efficiency must be determined prior to using Equation 1 and can be easily measured on the test bed designed to create characterized radiation fields.

$$\text{Activity (Bq)} = \frac{Counts\ (E)}{t_L \varepsilon_{abs} I_\gamma(E)} \frac{\lambda t_r}{1 - e^{-\lambda t_r}} \quad \text{(eq. 1)}$$

$$\lambda = \frac{\ln(2)}{t_{1/2}} \quad \text{(eq. 2)}$$

$$\frac{\lambda}{1 - e^{-\lambda t_r}} \approx 1 \text{ ; for Long half-lifes} \quad \text{(eq. 3)}$$

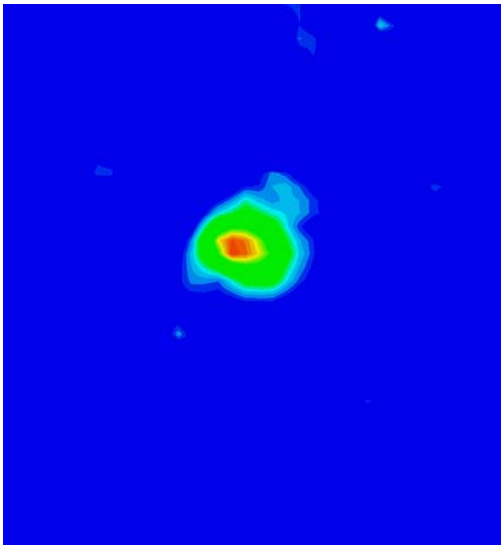

Fig. 4. Survey map constructed from data collected from an array of scintillation detectors from the depleted uranium project at ICET.

Table 2. Description of the variables in Equations 1 and 2.

Variable	Description
$Counts\ (E)$	Number of photos detected at the photo peak of the identified isotope.
t_r	Total amount of time to collect spectra.
t_L	Total amount of time the scintillation detector is collecting data. Specified by user.
ε_{abs}	Absolute efficiency
$I_\gamma(E)$	Number of particles emitted from isotope divided by the total number of particles emitted.
$t_{1/2}$	Half-Life of the isotope

To ensure spectra were collected with the appropriate geometries, a test matrix was constructed. This text matrix contains a large variety of source-detector geometries. Each source-detector geometry included a range of distances from the origin. The distances from the origin range from 0.5 m to 2.9 m in increments of 0.15 m. Each distance was combined with a detector height. The detector heights were 0.1 m, 0.5 m, 1.0 m, 1.5 m, and 2.0 m above the floor of the test stand. This text matrix also includes source heights of 0.1 m, 1.0 m, and 2.0 m above the floor of the

test stand. Each detector distance from the origin, detector height, and source height combination was evaluated to determine the absolute efficiency for that particular geometry. The absolute efficiency for a 3x3 $LaBr_3$(Ce) detectors as a function of distance and vertical height above the floor can be found in Figures 5 and 6. For these figures, a 10 mCi Cs-137 source was located 1.0 m above the floor of the test stand. Figure 5 shows that it is critical to locate the source to ensure the correct absolute efficiency is used in calculating the activity of the contaminants.

The absolute efficiency is also a function of the energy of the incident gamma-rays. Therefore the absolute efficiency is dependent on the isotope in question. Since the contaminants in question are unknown, a library of absolute efficiencies needs to be constructed for a variety of isotopes.

After a survey is performed the location of a source can be determined. Then a random spectrum near the source can be evaluated to identify the source. With the identification and location of the source known and the location of where the random spectrum was collected, the distance between the two can be calculated. With this information, an absolute efficiency for this source-detector geometry can be looked up in the absolute efficiency database and the activity calculated using Equation 1.

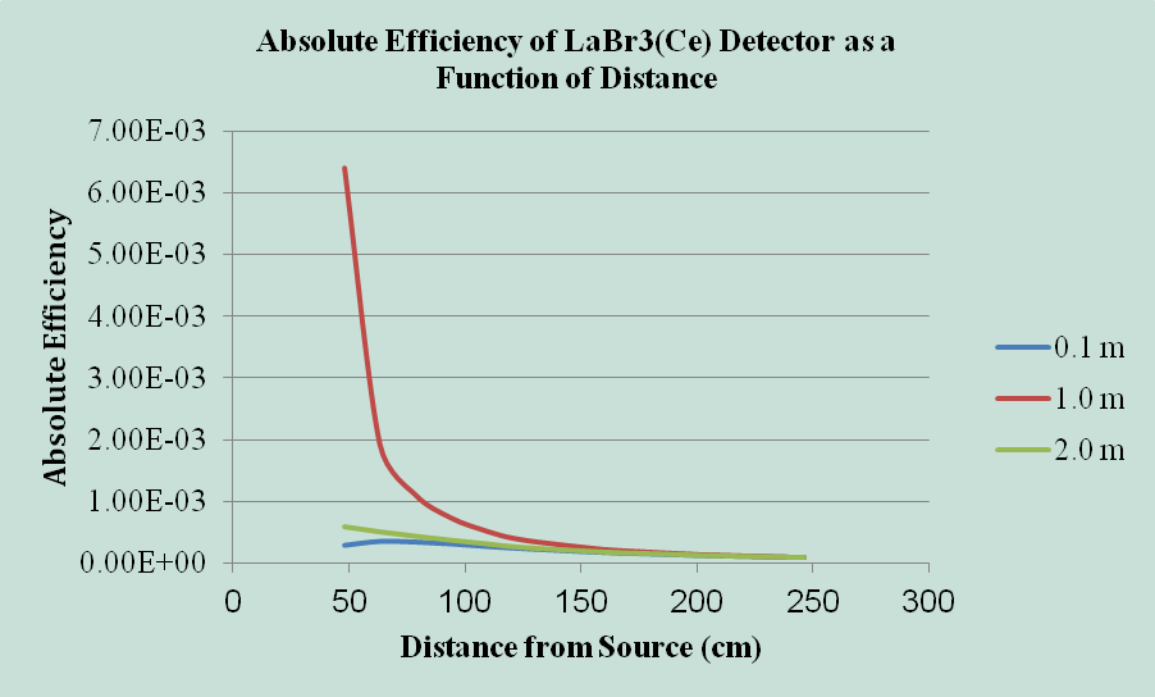

Fig. 5. Absolute efficiency of a 3x3 $LaBr_3$(Ce) as a function of distance from center of test stand and distance above the floor of the test stand. Source used was a sealed 10 mCi Cs-137 source placed at the center of the test stand, one meter above the floor of the test stand.

PROOF OF CONCEPT

As a proof of concept, 3x3 NaI(Tl) and 3x3 $LaBr_3$(Ce) detectors were placed at distances where the absolute efficiencies were already determined for a Cs-137 source located 1.0 m above the floor of the test stand. Absolute efficiencies for these measurements were for detectors that were also placed 1.0 m above the floor of the test stand. This experiment was undertaken to prove that

it is feasible to measure the activity of a source from gamma-ray spectroscopy data and compare the performance differences between NaI(Tl) and $LaBr_3$(Ce) detectors. Figure 6 shows a comparison between the absolute efficiency of NaI(Tl) and $LaBr_3$(Ce).

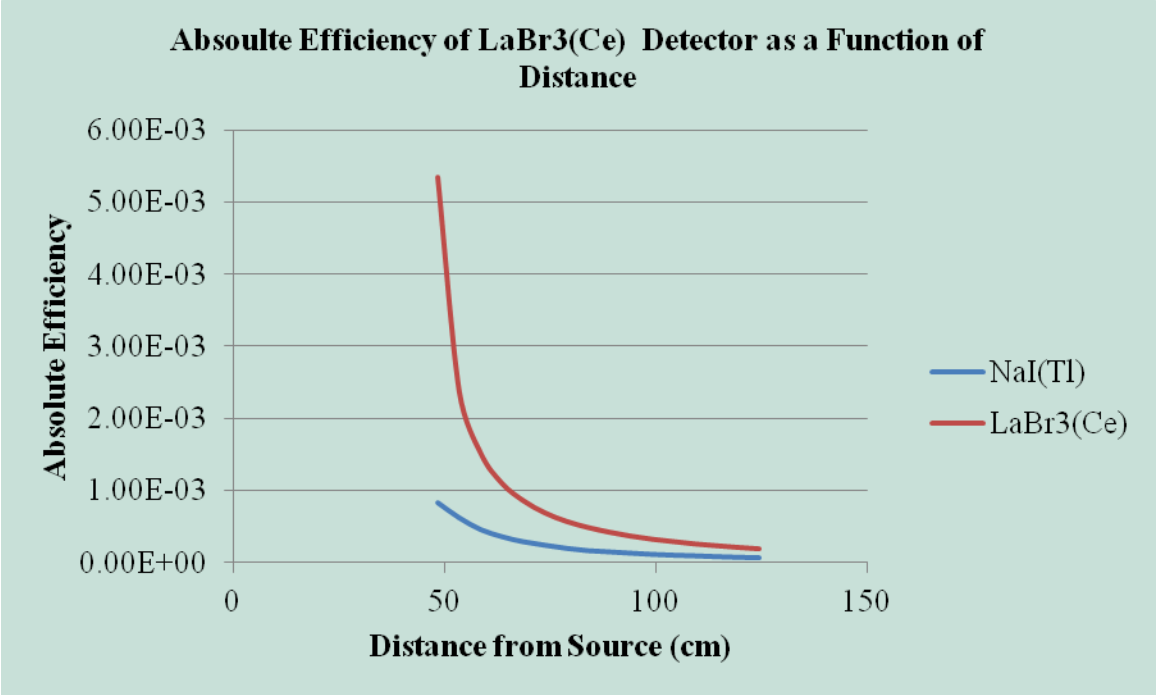

Fig. 6. Efficiency comparison between NaI(Tl) and $LaBr_3$(Ce).

A second set of Cs-137 spectra was collected, processed, and the activity of the source was determined for each distance using the measured efficiencies in Figure 6. Figure 7 shows the calculated activity of the Cs-137 source at each location spectra were collected. The true activity of this source is 10 mCi. From the data in Figures 6 and 7, it is clearly shown that $LaBr_3$(Ce) detectors are superior to NaI(Tl) detectors in performance. The $LaBr_3$(Ce) detector has better absolute efficiencies, which lead to better counting statistics for calculating more accurate activities. Even though NaI(Tl) detectors are inferior to $LaBr_3$(Ce), they can still be used in determining the activity of contaminants.

Once the activity of the source is known, using methods described by the National Council of Radiation Protection, the dose rate coming form contaminants can be calculated as a function of distance. To determine the dose rate, Equation 4 can be used [4][5][6]. “A” is the activity of the source, “r” is the distance from the source, and Γ is the specific gamma ray constant and is used for the conversion of activity to dose. Gamma values for several common isotopes can be found in Table 3. Using Equation 4 with the gamma value for Cs-137, a plot of the exposure rates as a function of distance can be constructed (Figure 9).

$$\text{Dose} = \frac{34.6 A t_{1/2} \Gamma (1 - e^{\frac{-0.693 t_r}{t_{1/2}}})}{r^2} \qquad \text{(eq. 4)}$$

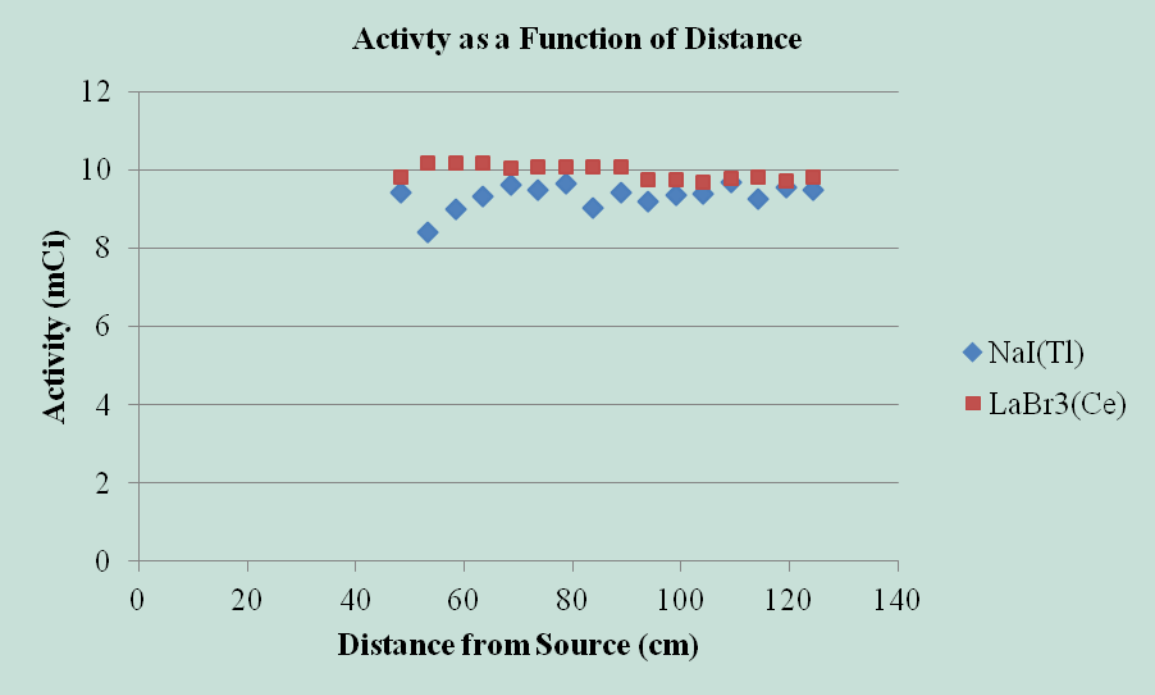

Fig. 8. Calculated activity from gamma-spectra of a 10 mCi Cs-137 source.

Table 3. Gamma values for several isotopes.

Isotope	Γ (R-cm^2/mCi-h)
F-18	5.73
I-131	2.20
Tc-99m	0.78
Ga-67	0.79
Cs-137	3.30
Co-60	13.2
Ir-192	4.80
Sr-89	0.00046

LARGE-SCALE PROOF OF CONCEPT

To prove this method can be used for surveys on a large scale, a Cs-137 source will be placed randomly in a vacant parking lot that has been gridded off so it can be surveyed. The survey area is 10.0 m by 10.0 m. The area has been marked off in 0.5 m increments for a total of 400 locations to collect spectra. Spectra will be collected at each location for 30 seconds. Each spectrum will be combined with its positional data for processing.

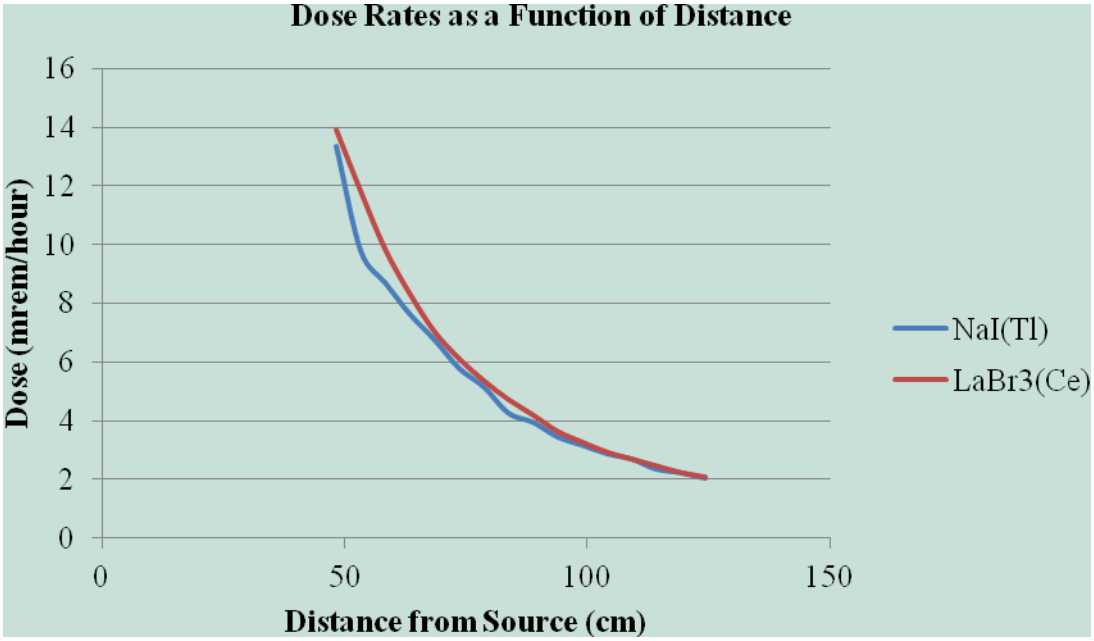

Fig. 9. Calculated dose rates using the activities calculated in Figure 8.

The spectra collected at each location will be processed in Geosoft® Oasis montaj software to determine the location of contaminant. After the location of the source is determined, one of the spectra files near the source can be used to identify that the source is a Cs-137 source. With the location and the identification of the contaminant known, absolute efficiencies can be matched to collected spectra to verify the activity. With the position and activity of the contaminant known, using equation 4, we can construct a 3-dimensional map of the surveyed area of the exposure rates.

Figure 10 is an image of the surveying system used in this large-scale proof of concept. The detectors are placed at 0.1 m, 1.0 m and 2.0 m above the ground because the absolute efficiencies for these detector positions relative to the ground have already been determined. A platform behind the 1.0 m detector has been added as a support stand for a laptop and other electronic hardware required for the survey.

RESULTS OF LARGE-SCALE PROOF OF CONCEPT

For this sample survey, a 10 mCi Cs-137 source was placed within the surveying area. Oasis Montaj was successful in locating the position of the source by using a built in peak detection algorithm. With the position of the source known, all of the spectra files within 2.5 m of the source were used in combination of the predetermined absolute efficiencies to calculate the activity of the source. It was calculated that the source had an activity of 10.5 mCi, slightly higher than the actual value of the source. Figure 11 is the Oasis Montaj data used to determine the location of the source. Figure 12 is the dose rates within the survey area. Equation 4 was used to calculate the dose rates.

Fig. 10. Surveying system.

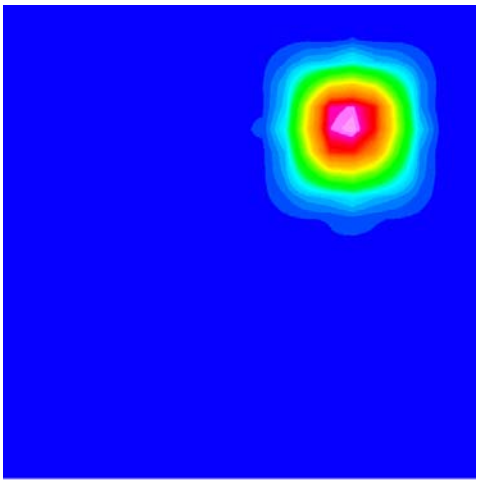

Fig. 11. Survey of the 10 m by 10 m predetermined survey area with the randomly placed source.

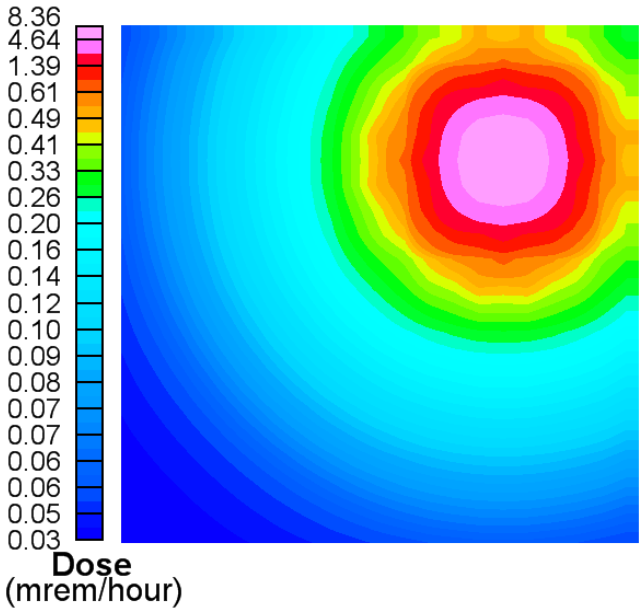

Fig. 12. Exposure rates from the Cs-137 source.

SUMMARY AND CONCLUSION

In this experiment, methods to calculate dose rates from gamma ray spectrometer data were explored. To calculate the exposure rate from a source, the source activity must be known. The activity of the source can be calculated using photopeak counts from the spectral data. If the detector/source geometry is known then a direct conversion to the activity can be calculated. The important factor in the conversion is calculating the absolute efficiency of the detector at the energy of the photopeak. Software was written that calculates the absolute efficiency of detectors and enters the data into a database containing information on the geometry used. Additional spectra were collected at known geometries and analyzed to ensure efficiency calculations worked properly in calculating the activity of the source. With the source identity and activity known, exposure rates as a function of distance were calculated. It was also determined that $LaBr_3$(Ce) performs better in this application than the standard 3x3 NaI(Tl) detector. However, the use of NaI(Tl) could still be used with acceptable accuracy.

It was also demonstrated that using the described methods, it is possible determine exposure rates from spectra collected during surveys. Using spectral data from a mock survey, Oasis Montaj software, and absolute efficiency data, it was possible to determine the position and activity of a source within a survey area. With the position and activity of the source known, it was then possible to calculate exposure rates within the survey area.

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