

Testing and Performance Validation of a Sensitive Gamma Ray Camera Designed for Radiation Detection and Decommissioning Measurements in Nuclear Facilities-13044

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ABSTRACT

This paper describes the measurements, testing and performance validation of a sensitive gamma ray camera designed for radiation detection and quantification in the environment and decommissioning and hold-up measurements in nuclear facilities. The instrument, which is known as RadSearch, combines a sensitive and highly collimated LaBr₃ scintillation detector with an optical (video) camera with controllable zoom and focus and a laser range finder in one detector head. The LaBr₃ detector has a typical energy resolution of between 2.5% and 3% at the 662 keV energy of Cs-137 compared to that of NaI detectors with a resolution of typically 7% to 8% at the same energy. At this energy the tungsten shielding of the detector provides a shielding ratio of greater than 900:1 in the forward direction and 100:1 on the sides and from the rear. The detector head is mounted on a pan/tilt mechanism with a range of motion of +/-180 degrees (pan) and +/-90 degrees (tilt) equivalent to 4π steradians. The detector head with pan/tilt is normally mounted on a tripod or wheeled cart. It can also be mounted on vehicles or a mobile robot for access to high dose-rate areas and areas with high levels of contamination. Ethernet connects RadSearch to a ruggedized notebook computer from which it is operated and controlled. Power can be supplied either as 24-volts DC from a battery or as 50 volts DC supplied by a small mains (110 or 230 VAC) power supply unit that is co-located with the controlling notebook computer. In this latter case both power and Ethernet are supplied through a single cable that can be up to 80 metres in length. If a local battery supplies power, the unit can be controlled through wireless Ethernet. Both manual operation and automatic scanning of surfaces and objects is available through the software interface on the notebook computer. For each scan element making up a part of an overall scanned area, the unit measures a gamma ray spectrum. Multiple radionuclides may be selected by the operator and will be identified if present. In scanning operation the unit scans a designated region and superimposes over a video image the distribution of measured radioactivity. For the total scanned area or object RadSearch determines the total activity of operator selected radionuclides present and the gamma dose-rate measured at the detector head. Results of hold-up measurements made in a nuclear facility are presented, as are test measurements of point sources distributed arbitrarily on surfaces. These latter results are compared with the results of benchmarked MCNP Monte Carlo calculations. The use of the device for hold-up and decommissioning measurements is validated.

INTRODUCTION

RadSearch is a radiation detection, survey and measurement device with a wide range of applications in the nuclear industry and in other areas where locating and quantifying radioactivity is important. In nuclear applications RadSearch can be employed to find and quantify radioactive sources, survey radioactive areas and perform a wide range of measurement tasks including nuclear decommissioning and radiation clean-up activities. As part of a category of instruments known as a gamma camera, RadSearch has the unique capability of quantifying the activity of radioactive sources in units of Curie (Ci) or Becquerel (Bq) as well as identifying detected radionuclides and locating areas and objects of both low and high activity. Some of the characteristics of RadSearch have been reported elsewhere [1].

The RadSearch detector head consists of a lanthanum bromide (LaBr₃) scintillation crystal gamma-ray detector, a video camera and a laser range finder. The detector head is mounted on a pan and tilt unit, which itself is mounted on a tripod, trolley or vehicle. The detector head and pan-tilt mechanism are connected to a remote monitoring station consisting of a small power supply unit and notebook computer. The unit is very portable and it can easily be dismantled into separate components, transported in three armoured cases and then reassembled by a single person. Set-up time is typically 10 minutes. The total weight of the components is 53.2 kg (without transport cases).

DESIGN AND OPERATION OF RADSEARCH

RadSearch employs a one-inch lanthanum bromide (LaBr₃) gamma-ray scintillation detector and photomultiplier, which has an energy range of between 30 keV to 2,000 keV, and an energy resolution of typically 2.5% to 3% (FWHM – full width half maximum). LaBr₃ detectors have greater sensitivity, operate at higher count rates and achieve nearly three times the energy resolution of sodium iodide (NaI) detectors, which are normally used for this type of application. The detector is connected to an 8K channel Multi-Channel Analyser (MCA), which accumulates the gamma-ray spectra. A separate spectrum is recorded for each measurement made by the detector.

An optical CMOS video camera, which is aligned with the detector, records video images of the areas and equipment being surveyed and measured. The camera has a controllable zoom lens, autofocus and auto-iris. Also aligned with the detector and camera is a calibrated laser range finder with a range of up to 65 meters and a resolution of +/- 3mm. It is used to determine the distance between the detector and camera and the object being measured or scanned. Scanning of objects and areas is made possible because the detector head is mounted on a pan and tilt mechanism with a range of motion of +/- 180 degrees pan and +/- 90 degrees tilt, giving a total solid angle of view of 4π steradians.

The RadSearch detector head (weighing 20 kg) with collimator barrel fitted (4 kg) is mounted using a quick release mechanism on the pan and tilt unit (13 kg). The entire assembly can be mounted on a vehicle, trolley, tracked or wheeled robot or in a fixed installation, for example on a building. For routine use in the field and in-doors it is normally mounted on a tripod, again using a quick release mechanism. RadSearch was deployed on a tripod for all of the measurements reported in this paper. Figure 1 is a

photograph of the RadSearch detector head and pan and tilt unit mounted on a tripod for measurement.



Figure 1. RadSearch detector head and pan and tilt unit mounted on a tripod for measurement. The collimator barrel is fitted.

The operation of RadSearch is controlled from a remote monitoring station (RMS), consisting simply of a small power supply unit and a rugged notebook computer. The power supply unit weighs 1.4 kg and operates on either 110 or 240 VAC and provides 50 volts DC to power the detector head and pan tilt unit. A single cable carrying both 50 volts DC and Ethernet of up to 80 metres in length connects the RMS to the RadSearch detector head and a short

flexible cable links the detector head to the pan and tilt mechanism. For remote operation the unit can also be powered from a 24-volt battery and controlled by wireless Ethernet.

A thick tungsten shield surrounds the LaBr₃ detector and photomultiplier. The detector is collimated in two configurations. With the stainless steel and tungsten detachable barrel fitted, the detector has a 4-degree field of view (FOV). With the barrel detached the detector FOV is 18 degrees. Using the pan and tilt mechanism, RadSearch operates by scanning an object or surface in a rectangular grid pattern. The scan pitch is user adjustable, however, better results are obtained with a degree of over-scanning. In practice a scan pitch of 3.5 degrees (barrel fitted) and of 15 degrees (barrel detached) work effectively.

Each individual component of the scanned area is called a **Scan Element**, and corresponds to the detector field of view. A rectangular array or grid of Scan Elements comprises the **Scan Area**. As part of the measurement process, the camera zoom feature allows close-up images to be recorded of individual Scan Elements. For each Scan Element, RadSearch captures an 8K-gamma ray spectrum.

When a measurement is completed, RadSearch provides a video image of the object or surface being measured divided up into the rectangular grid of Scan Elements each with a coloured overlay showing the intensity of radioactivity detected in the Scan Element. A gamma-ray spectrum is obtained for each Scan Element. From each measured spectrum a number of different radionuclides can be identified. A different overlay can be produced for each radionuclide that has been identified.

Pre-set libraries of common radionuclides are provided and the operator is able to establish other libraries with additional radionuclides, if required. A separate scan overlay of the Scan Area can be generated for each radionuclide in the selected library. Each scan overlay (which is specific to a particular radionuclide) shows the relative intensity of the

gamma-ray count rate for that radionuclide, distributed over all the Scan Elements of the Scan Area. Measurement data can be re-analysed off-line with the originally selected library of radionuclides or the measurement can be re-analysed with a new radionuclide library if required.

A unique feature of RadSearch is that it calculates the total activity for each selected radionuclide over the Scan Area and the result is quoted in user-selected units of Bq or Ci. It also determines the dose rate at the detector arising from sources distributed over the Scan Area. This data is available in a table on the notebook computer screen and is also available as a comma separated file that can be loaded into a spread-sheet for further analysis and manipulation. The user can generate standard measurement reports selecting the data of interest.

RadSearch has a wide dose rate operating range from 0.003 $\mu\text{Gy/h}$ ($\mu\text{Sv/h}$) up to 500 mGy/h (mSv/h) with filter plug fitted at very high dose-rates. For Cs-137 the minimum detectable activity (MDA) is less than 1 μCi at a distance of 1 meter from the detector.

DESIGN VALIDATION

An earlier report [1] described the use of the MCNP Monte Carlo modelling code [2] that was used to model the detector and shielding as part of the instrument design.

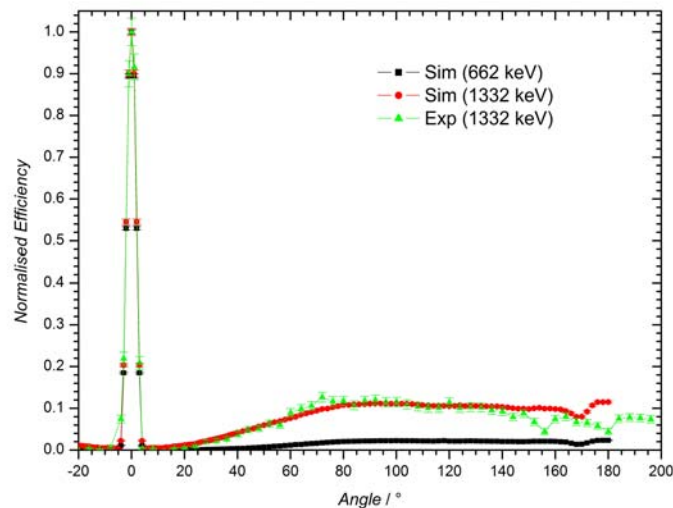


Figure 2. A comparison of shielding effectiveness for the detector and photomultiplier with the tungsten shield is presented. The normalised detection efficiencies are compared for MCNP simulations for Cs-137 (661.7 keV) and Co-60 (1332 keV) with the measured normalised efficiency for Co-60 (1332 keV). Good agreement is achieved between simulation and experiment.

The shielding of the LaBr₃ detector and photomultiplier was designed assuming incident gamma-ray energy of 1,500 keV, such that in the forward direction the shielding-effectiveness was greater than a factor of 50 and at angles greater than 45 degrees a factor

of 10 was achieved. Figure 2 presents the results of a series of measurements that were performed with a calibrated 37MBq (1mCi) Co-60 source at a fixed distance from the detector head. The detector head was rotated and count rate measurements were made at specific angles. The count rates were then converted to normalised efficiency and plotted on the same axes as the results of the MCNP shielding calculations performed for gamma rays of energy 661.7 keV (Cs-137) and 1332 keV (Co-60). It can be seen that good agreement is achieved for simulated and measured Co-60 plots.

The shielding effectiveness for 1332 keV gamma rays from Co-60 as shown by the transmission ratio is less than 5% below angles of 45 degrees and the worst-case transmission is less than 13%. For 661.7 keV gamma rays from Cs-137 the shielding effectiveness is much greater with a transmission ratio of less than 1% below 45 degrees and the worst-case transmission is less than 1.5%.

Medium-count rate tests have been performed with RadSearch using the calibrated 37MBq (1mCi) Co-60 source. Both the LaBr3 detector with photomultiplier and the MCA are rated for count rates well in excess of a million counts per second. Two measurements were made with the source located in the collimator barrel at distances of 323 and 61.5 mm from the detector front face. The measured data is tabulated in Table I.

Table I. Measurement data from high count rate measurements with a 37MBq (1mCi) Co-60 source placed close to the detector.

Source Distance (mm)	Live Time (s)	Dead Time %	Spectrum Integral (kcps)	Gross (kcps)	Net (kcps)	Centre (keV)	FWHM (keV)	Ecal_b (keV/chn)	ROI / FWHM	Activity (mCi)	Dose Rate (mSv.h ⁻¹)
323	30	0	20.2	1.14	1.09	1332.5	32.1	3.312	3	0.99	0.11
61.5	27	10	87.3	4.41	1.41	1331.6	34.3	4.932	4	0.60	3.01

Plots of the two spectra are displayed in Figure 3. With the top plot corresponding to the measurement with the source at 323 mm from the detector and the middle and bottom plots corresponding to the measurement with the source at 61.5 mm from the detector. At 323 mm the activity of the source was correctly measured. At the closest position of 61.5 mm the detector dead time was 10% and the internal dose-rate at the detector was 3 mSv/h. From the spectrum plots (middle and bottom of Figure 3 it is clear that there is a great deal of scattering and with a count rate of 87.3 kcps there appears to be considerable spectral summing as evidenced by the tail above 1332 keV. The high degree of scattering may explain the low activity estimate for the source at this position.

The test with the 37MBq (1mCi) source placed closest to the detector produced a count rate at the detector of 87.3 kcps that is 53% of the design maximum count rate for a source of 18.5GBq (500mCi) at 1 metre. At this count rate the dead time for the detector system was only 10%. This suggests that the upper limit for the measurable activity at one metre has been under-estimated and that RadSearch is capable of accurate measurements at significantly higher activities. Based on the data it is estimated that the upper level of measurable activity at one metre is well in excess of 1 Ci of Cs-137.

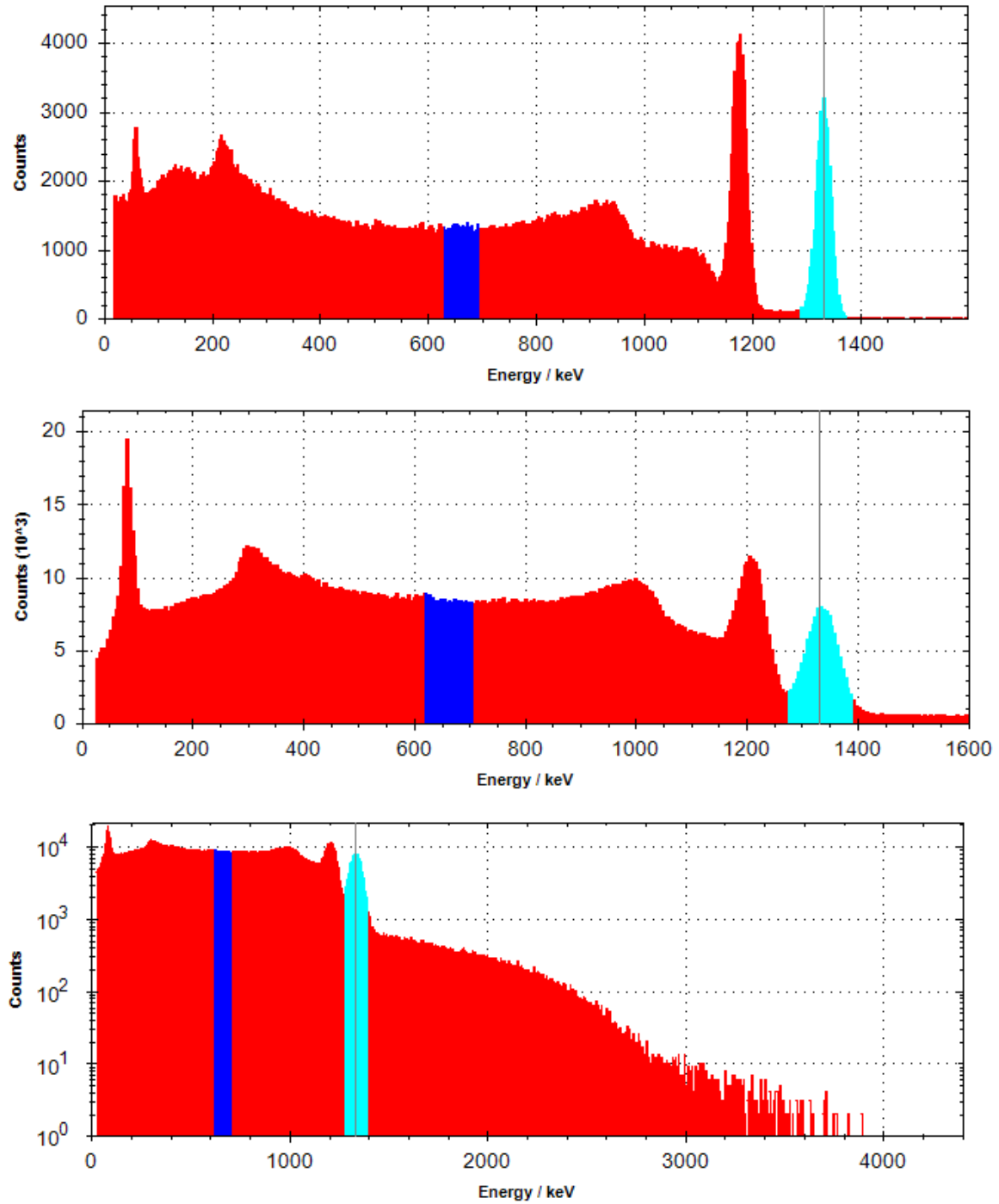


Figure 3. The top linear spectrum plot corresponds to the measurement of the 37MBq (1mCi) Co-60 source placed at 323 mm from the detector at the far end of the barrel collimator. The middle and bottom plots are linear (middle) and log (bottom) spectrum plots of the measurement of the same source at 61.5 mm from the detector within the barrel collimator.

DECOMMISSIONING DEMONSTRATION MEASUREMENTS

A series of decommissioning demonstration measurements have been made with multiple sources distributed in a factory environment. Scanning measurements of these distributed point sources were performed in order to validate the use of RadSearch as a tool for decommissioning. In particular the ability of RadSearch to quantify multiple distributed sources has been confirmed in different measurement geometries. The following calibrated point sources were employed for the tests: Co-60 - 37MBq (1mCi), Cs-137 - 740kBq (20 uCi), Cs-137 - 3.7MBq (100uCi), and Eu-152 - 740kBq (20uCi).

A campaign of measurements was also performed at the Alpha Gamma Hot Cell Facility (AGHCF) at the Argonne National Laboratory (ANL). The ANL measurement campaign represented the first practical deployment of the ANTECH RadSearch instrument in an industrial radioactive environment. The instrument was used to measure distributed radioactive sources and to determine surface activity and identify and quantify different radionuclides distributed within the hot cell. A number of these measurements were reported elsewhere [1], however a scanning measurement in a high activity area at AGHCF is reported in this paper.

The Cs-137 and larger Co-60 sources were measured in typical factory environments and the results are displayed in Figures 4 and 5. The Eu-152 and smaller Cs-137 sources were also were measured in typical factory environments and the results are displayed in Figures 7. The measured data is summarised in Table II.

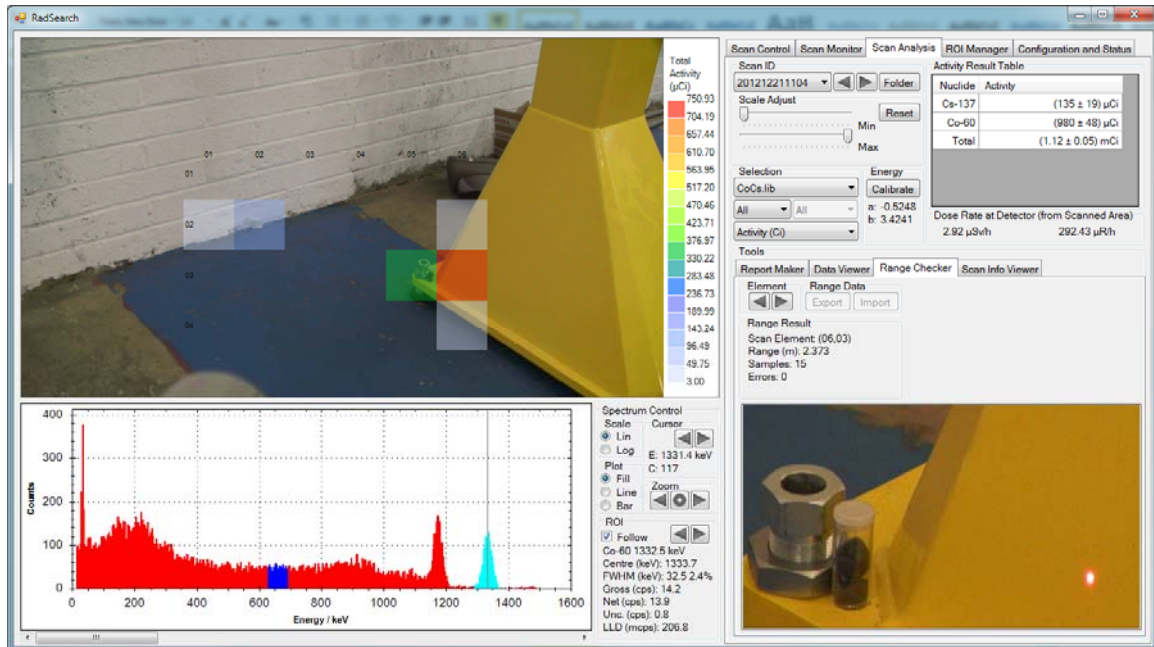


Figure 4. Measurement of Point Sources in a factory environment. Sources: Co-60 (37MBq), Cs-137 (3.7MBq), Scan grid: 6x4, Pre-set counting time per scan element: 90 s, Scan pitch 4.0°, Average range: 2.78 m. Spectrum for scan element (05,03) for Co-60, range 2.373 m.

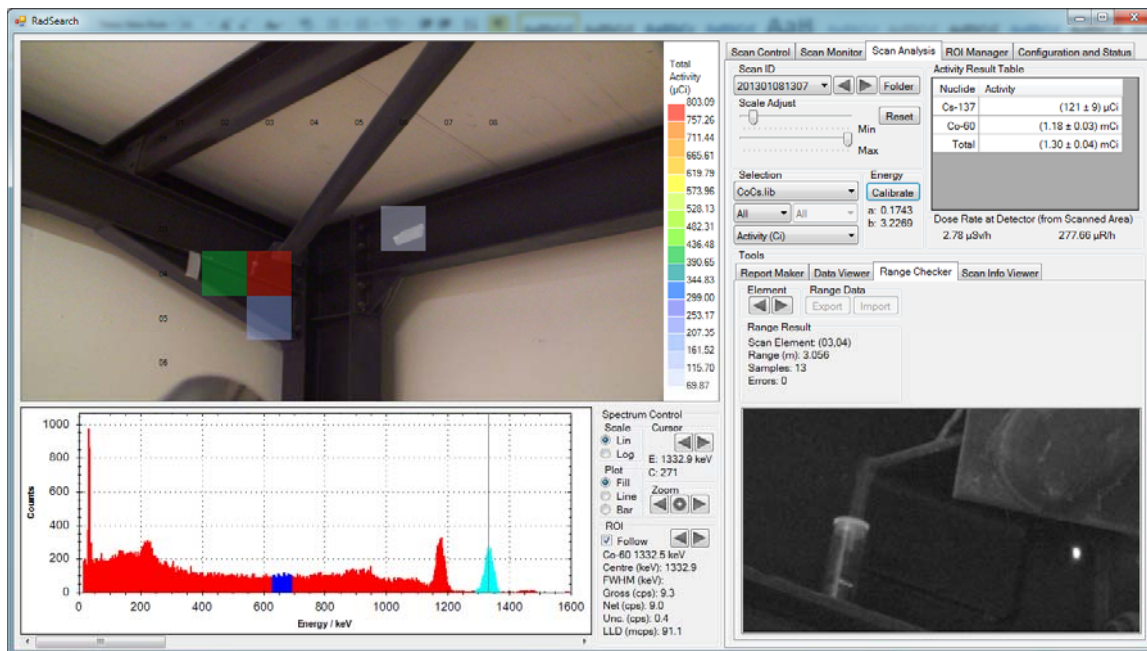


Figure 5. Measurement of point sources in a factory environment. Sources: Co-60 (37MBq), Cs-137 (3.7MBq), Scan grid: 8x6, Pre-set counting time per scan element: 300 s, Scan pitch 3.5°, Average range: 2.78 m. Spectrum for scan element (08,04) for Co-60, range 3.056 m.

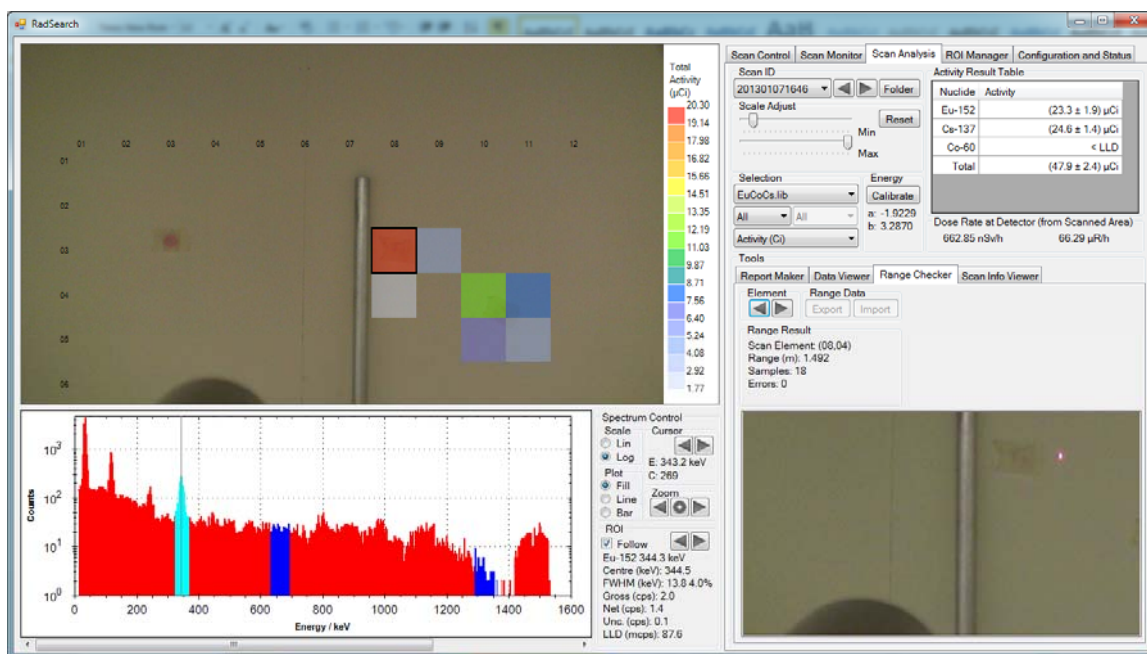


Figure 6. Measurement of Point Sources in a factory environment. Sources: Eu-152 (740kBq), Cs-137 (740kBq), Scan grid: 12x6, Pre-set counting time per scan element: 800 s, Scan pitch 3.5°, Average range: 1.54 m. Spectrum for scan element (08,04) for Eu-152, range 1.492 m.

Table II. This is a comparison of results for decommissioning demonstration measurements for small point sources distributed in a factory environment.

Measurement No.	Figure No.	Nuclide	Reference Activity (uCi)	Measured Activity (uCi)	Error Activity (uCi)	Deviation %
201212211104	4	Cs-137	108.3	135	19	24.7%
	4	Co-60	954.6	980	48	2.7%
201301081307	5	Cs-137	108.3	121	9	11.7%
	5	Co-60	954.6	1180	30	23.6%
201301071646	6	Eu-152	20.72	23.3	1.9	12.5%
	6	Cs-137	21.25	24.6	1.4	15.8%

The measurement results contained in Table II demonstrate clearly the ability of RadSearch to locate radioactive sources and “hot spots” and to identify different radionuclides. More importantly, RadSearch is able to accurately quantify the activity of the distributed sources. This is an important feature not normally available in instruments of this type. A knowledge of source activities is important in decommissioning both from the perspective of health and safety as well as waste disposal planning.

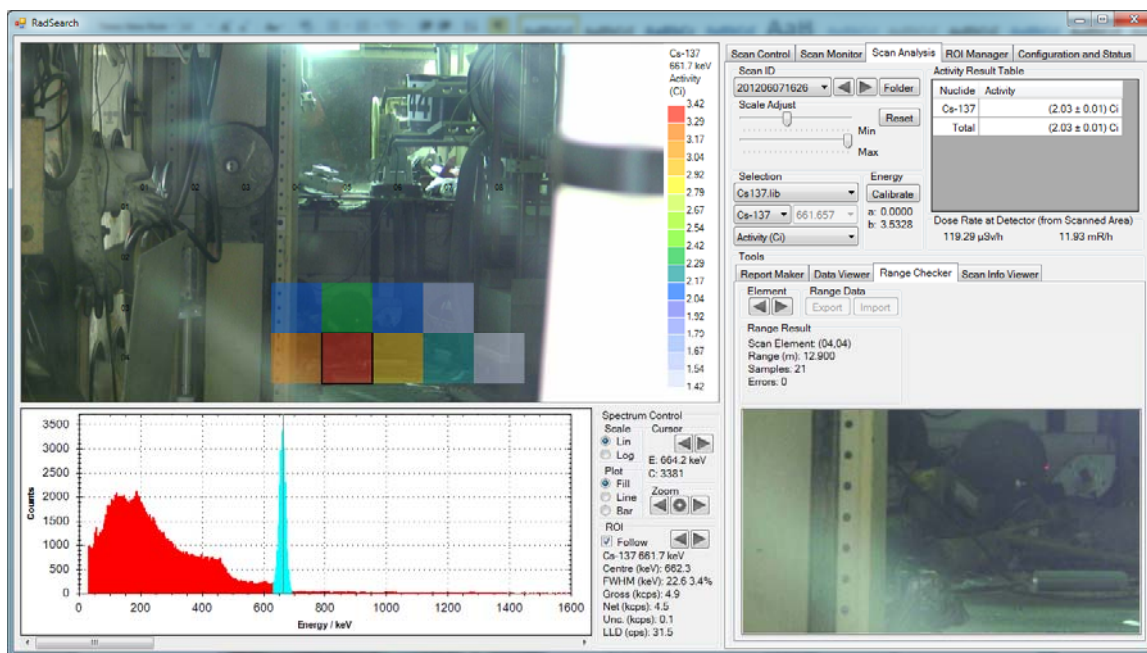


Figure 7. Measurement of distributed sources in the AGHCF at ANL. Sources: Cs-137 (quantity unknown), Scan grid: 8x4, Pre-set counting time per scan element: 5 s, Scan pitch 4.0°, Average range: 10.85 m. Spectrum for scan element (05,04) for Cs-137, range 12.9 m.

Figure 7 displays a result of a high activity sample measurement at AGHCF at ANL. The measurement was made through a transparent contamination barrier and it was one of a number of measurements made as part of a survey of the hot cell facility. The measurement was made at an average distance of 10.85 metres and identified a Cs-137 source distributed over the Scan Area of 68.8GBq (1.86Ci).

A useful feature of the device is the extensive library, which includes over 50 radionuclides but is not limited to that number. Additional radionuclides can be added as required. Since a spectrum is saved for each Scan Element of a measurement, data can be re-analysed and this can be done with a different library if it is suspected that specific radionuclides may have been overlooked.

The instrument employs a factory efficiency calibration to determine measured activity. This is performed using NIST and NPL traceable sources and confirmed with MCNP modelling. The energy calibration, however, changes with both temperature and count rate. To facilitate the process of energy calibration the unit contains algorithms that provide an automatic energy calibration based on counting (when not in use for measurements) the internal Lanthanum source, which produces gamma rays with a energy of about 1460 keV. The user is also able to perform a manual energy calibration. This process can be done quickly and easily if, for example, a strong Cs-137 or Co-60 source is present in a measured spectrum.

CONCLUSIONS

RadSearch is a radiation detection, survey and measurement device with a wide range of applications in the nuclear industry. It has the unique capability of being able to quantify the radioactivity from distributed sources in activity units of Bq and Ci and not simply in terms of count rates. It is also capable of performing the conventional tasks of a gamma camera in finding radiation “hot spots”, identifying radionuclides and showing where radioactivity is distributed by displaying count-rate overlay data.

The tungsten shielding design has been confirmed by a comparison of measurement and simulation for Co-60 using the 1332 keV gamma ray. The shielding is even more effective at the energy of Cs-137 gamma rays (661.7 keV). This is important, as Cs-137 is likely to provide the largest contribution to the background in the majority of applications.

The decommissioning demonstration measurements confirm that RadSearch is able to make accurate quantitative measurements of multiple sources in an industrial setting. The importance of good counting statistics is highlighted by the significantly improved results for measurements with longer counting times, even for small sources. The measurements have also demonstrated the ease of use of the instrument.

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