

Design and Development of an Automated Instrument for Measuring Radioactivity in an Excavator Bucket – 16246

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ABSTRACT

Increasing interest and emphasis is being given to the presence of radioactive contamination in the environment and the methods by which this contamination can be remediated. Radioactive contamination may arise from industrial process including the operation of nuclear facilities. It may also arise from the enhancement of naturally occurring radioactive material by industrial processes. An area of particular concern is the remediation of soil and rubble with radioactive contamination. Traditional methods of soil remediation involve sampling followed by the excavation of areas where contamination is found. The soil removal process is normally very inefficient and can involve multiple handling of excessive quantities of soil and ultimately an over estimate of the quantity of soil with radioactive contamination. In order to both minimize material handling and to reduce the final volume of contaminated material, which must be handled for disposal, a sensitive instrument has been developed and tested which is designed to measure the radioactive content of an excavator bucket. The instrument detector is positioned automatically just above the open top of the bucket and the measurement employs a high efficiency sodium iodide crystal which has a graded shadow shield to reduce the effect of background radioactivity. The measurement efficiency is enhanced as the detector is located in close proximity to the soil in the bucket and the thick steel shell of the bucket acts as a shield to further reduce the effect of background from the ground below. The method has obvious advantages over methods, which attempt to measure the potentially radioactive soil through the shielding provided by the thick steel bucket shell. As the first stage of the bucket measurement the excavator operator fills the bucket and locates it in a designated position with the open top of the bucket facing upwards, close to the operator cab. A measurement technician, located outside the danger area of the excavator boom, begins the measurement using a tablet computer with a wireless connection to the instrument. The shielded detector is moved from a storage position above the operator cab to the measurement position close to the open surface of the excavator bucket. Once the measurement is completed in typically one to two minutes, the detector is repositioned in its storage location and the measurement data is transmitted to the tablet computer. At this point the measurement technician makes the decision based on the measurement results as to how to disposition the bucket contents. Typically contaminated material will be transferred to a vehicle for off-site disposal. Alternatively, and this is the great advantage of this technique, uncontaminated material may be returned directly to the site of the excavation without the need for

further handling. The development, detailed design and preliminary testing of the instrument are described.

INTRODUCTION

During site characterization and remediation operations Studsvik identified a requirement for the real time in-situ assay of land potentially contaminated with Naturally Occurring Radioactive Material (NORM) or Technically Enhanced NORM (TENORM). Characterization of an area of land is routinely achieved by:

- Walk-over gamma survey;
- Sampling.

Walkover surveys normally cover more of the land than do sampling campaigns. However, neither of these techniques can guarantee 100% coverage of the material requiring characterization. Statistical methods exist which allow a level of confidence in the above characterization techniques to be determined. However, the level of confidence will always be below 100%, unless 100% of the material is sampled. A further complication is determining the depth to which any potential contamination has penetrated.

100% coverage can be achieved by remediating all of the material that is suspected to be contaminated (and then confirming that the remaining land is not contaminated) and subsequently assaying the entirety of this material (via, for example a conveyor assay system, or by bagging up the material and assaying the bags). To do this requires a lot of space to store, process and assay the remediated material. Lots of sites which have potential NORM contaminated areas of land do not have the available space. Also, some processing options required to facilitate the assay of the material, such as the bagging of material, may inadvertently dilute the contamination which may be present. Further, multiple handling of the remediated material is required, which increases operational time and expense (hire and operation of vehicles to move the remediated material), and exposure of the workers to internal and external radiological hazards.

Another consideration is access to the areas of land with potential NORM contamination. In Studsvik's experience, many sites with NORM contamination are historical sites where there was no knowledge of NORM contamination during the operational phase of the site's existence. The sites have subsequently been left unmanaged, thereby allowing trees etc to block potential access routes to working areas in the NORM contaminated areas of the sites. Environmental concerns usually dictate that trees should not be removed to facilitate access or remediation operations unless as a last resort. Such access restrictions can (and most often do) hinder the efficient remediation and transportation of the potentially contaminated material.

It should not be forgotten that it is usually desirable to return any remediated material that is proven to be uncontaminated to its point of origin.

For areas of land that require 100% coverage and land that is difficult to access and where it is not feasible to transport the material away for processing and assay (followed by the return of any uncontaminated material), there exists a requirement to assay excavated material at its point of origin. Studsvik (with expertise in site characterization operations) and ANTECH (with experience in designing, operating and building assay systems) decided to collaborate in order to design, build and operate an assay system based on ANTECH scintillation detector technology [1] that meets this requirement.

OPTIONEERING

The initial stage of the project comprised a managed optioneering study. The study involved personnel from Studsvik, ANTECH and also consulted excavator operators. Initial consideration was given to the volume of material that can be adequately assayed.

Site remediation is conventionally undertaken using excavators, such as those supplied by CAT and Komatsu. Excavated material is normally loaded onto vehicles, such as dumper trucks, for transportation and processing. This leads to two options for the assaying of the excavated material at the site:

- Assay the contents of an excavator bucket;
- Assay the contents of the transport vehicle.

The volume of material that an excavator bucket holds during land remediation operations is typically 0.5m^3 . The vehicles normally transport multiple excavator buckets of material, with payload volumes in excess of 5m^3 . Excavated material will normally exhibit an amount of inhomogeneity. Any such inhomogeneity will affect the assay of the material. Inhomogeneity in the material will be much harder to determine, and account and correct for in the assay of the transport vehicle than in the assay of an excavator bucket, due to the much larger volume of material in the transport vehicle. Also, due to the gamma energies emitted by NORM, large volumes of material, such as those of the transport vehicles, will significantly attenuate the gamma ray signal from a large proportion of the bucket or vehicle volume, adding uncertainty to the assay. This NORM gamma ray signal attenuation effect is less significant in the material contained in an excavator bucket. Therefore, the option of assaying the contents of the excavator bucket was selected.

Consideration was then given to the positioning and orientation of the assay system. There are three potential options:

- 1) Stand-alone system to assay the bucket contents from below;
- 2) Stand-alone system to assay the bucket contents from above;
- 3) System mounted on excavator to assay the bucket contents from above.

Option 1: Stand-Alone System to Assay the Bucket Contents from Below

The following observations were made regarding this option.

Excavator buckets are nominally at least 1cm thick and made of steel. This thickness of steel is enough to attenuate a significant fraction of the gamma rays arising from NORM in the bucket. Therefore, assaying through the base of the bucket will result in increased counting times to reach the Minimum Detectable Activities (MDAs) required for sentencing of the bucket contents.

The gamma ray signal arising from NORM contained in the land on which the assay system is positioned will contribute to the radiation background which will require shielding.

This assay system will require the bucket to be accurately positioned directly above the detector, in both the vertical direction and horizontal plane. Unless the assay system is of sufficient height (i.e. the top of the assay system needs to be at a similar height to the eye-line of the excavator operator) the operator will not be able to see the nadir of the bucket (due to the curvature of the bucket) and will therefore be unable to determine effectively the vertical height of the bucket from his position in the excavator cab. In this situation there is potential for the operator to damage the assay system in the process of positioning the bucket for a measurement. Whilst positioning of the bucket in the horizontal plane can be facilitated by providing suitable reference markings on the bucket and/or assay system, reproducibility of the positioning of the bucket within the required tolerance will be difficult to achieve.

A stand-alone system will require a source of power, which may require trailing cables that may present a hazard to site operations.

Option 2: Stand-Alone System to Assay the Bucket Contents from Above

The following observations were made regarding this option.

Assaying the bucket contents from above allows for the direct measurement of the bucket contents without any shielding material (i.e. the bucket) attenuating the gamma ray signal.

The steel of the excavator bucket will act as a shield to reduce the background arising from NORM gamma rays from the land over which the assay is taking place.

This assay system configuration requires the positioning of the bucket below the detector, in both the vertical direction and horizontal plane. The assay system will need to be of sufficient height for the bucket to fit under the assay system detector. In this case the vertical positioning of the bucket will be easier for the operator to see than for the previous option and the problem with the reproducibility of the horizontal positioning of the bucket will be less severe.

The bucket is required to be positioned under the assay system. The assay system will need to be mounted on a frame to position it above the ground. Locating of the bucket in the measurement position will involve maneuvering the excavator arms around the frame holding the assay system. There is therefore the potential for the bucket to make contact with the assay system, potentially resulting in damage.

A stand-alone system will require a source of power, which may require trailing cables that may present a hazard to site operations.

Option 3: System Mounted on Excavator to Assay the Bucket Contents from Above

The following observations were made regarding this option.

The arms of an excavator are constricted to move in a vertical plane. This removes the uncertainty in the positioning of the bucket in one direction.

Assaying the bucket contents from above allows for the direct measurement of the material in the bucket without any shielding material (i.e. the bucket) attenuating the gamma signal.

The steel of the excavator bucket will act as a shield to reduce the background arising from NORM gamma rays from the land over which the assay is taking place.

An assay system mounted on the excavator can be powered by the excavator. This removes the requirement for trailing cables that may present a hazard to site operations.

When performing excavation operations the excavators are subject to stresses and vibrations. These stresses and vibrations will affect the detector(s) used in the assay system and must be considered if this option is pursued.

Optioneering Study Conclusion

The following conclusions were drawn from the optioneering study:

- An excavator mounted system offers better operational safety than stand-alone systems due to the lack of trailing cables and removal of the possibility for collisions between the bucket and the assay system.
- Measuring the bucket contents from above will result in lower counting times to reach the MDAs required for sentencing of the bucket contents than measuring the buckets from below.
- Measuring the bucket contents from above uses the bucket steel to shield unwanted background gamma ray signals from NORM present in the land over which the assay is taking place.
- An excavator mounted system offers increased reproducibility of measurement position over stand-alone systems.
- The conclusion to the optioneering study was that an assay system mounted on the excavator that assays the bucket contents from above offers the best solution in terms of accuracy of positioning and detection efficiency. As noted above, the stresses and vibrations to which an excavator is subject whilst performing excavation operations will need to be considered.

CONCEPT DESIGN OF THE EXCAVATOR MOUNTED BUCKET ASSAY SYSTEM

Following the optioneering study Studsvik and ANTECH developed a concept design for the Excavator Mounted Bucket Assay System and the instrument was assigned the acronym "EMBASSY". The concept design required the following:

- A highly efficient detector – to allow for reduced measurement times in reaching the required MDAs;
- A spectroscopic detector is required to determine the activity of the specific isotopes of Radium (Ra-226 and Ra-228) and to correct for interfering peak areas in the gamma ray spectrum. The spectroscopic data is employed in combination with the fingerprint to determine the integrated activity;
- Good coverage of bucket contents – to better account for inhomogeneity;
- Collimation/shielding – to reduce the background from NORM present in the local area of the assay;
- Means to account for variation in soil moisture content;
- Demountable detector – for when the excavator is tracking over hard surfaces (An excavator experiences intense vibrations when tracking over hard surfaces, such as concrete, that could potentially damage the detector).
- Assay system to be operated by a knowledgeable measurement technician and not controlled by the excavator operator;

- Assay system requires a knowledgeable measurement technician to review the gamma ray spectrum for each assay – to give confidence in each assay result;
- Measurement technician to control the assay system by wireless communication – no trailing cables;
- Use of wireless communication of the assay system – to enable the measurement technician to be positioned out of the working danger area of the excavator;
- Measurement technician to inform excavator driver of sentencing decision;
- Positioning of detector during excavation operations - the detector is positioned such that it is in a safe location during excavation operations so it does not interfere with the operation of the excavator and the detector must be, as far as is possible, out of the field of view of the excavator operator during excavation operations;
- Power to be drawn from the excavator – no trailing cables.

Excavator operators were consulted in order to ascertain the best place to position the assay system during excavation operations. It was determined that mounting the assay system on either of the excavator's arms (boom arm and jib arm) would not only interfere with excavation operations, but it would also place the assay system in the so-called "splash zone" – where the assay system has a high chance of being struck by material that is being excavated. The base of the cab is also in the splash zone. Therefore, mounting the assay system at the base of the cab was also not feasible.

The best place for the detector during excavation operations was determined to be at the top of the cab. This position is out of the splash zone of the excavator and largely out of the operator's field of view. Further, in this position the excavator bucket or arms cannot make contact with the detector. However, storing the detector in this position will require the detector to be moved from the storage position to the measurement position for each measurement cycle.

The operation sequence for the assay system is shown in Fig. 1. The sequence includes the excavator operator loading and leveling the bucket contents and positioning the bucket in the measurement position. The measurement technician lowers the detector to the measurement position and begins the measurement. When the measurement is completed the measurement technician confirms the assay result, returns the detector to the storage position and informs the excavator operator of the appropriate disposition of the bucket contents. The sequence is then repeated.

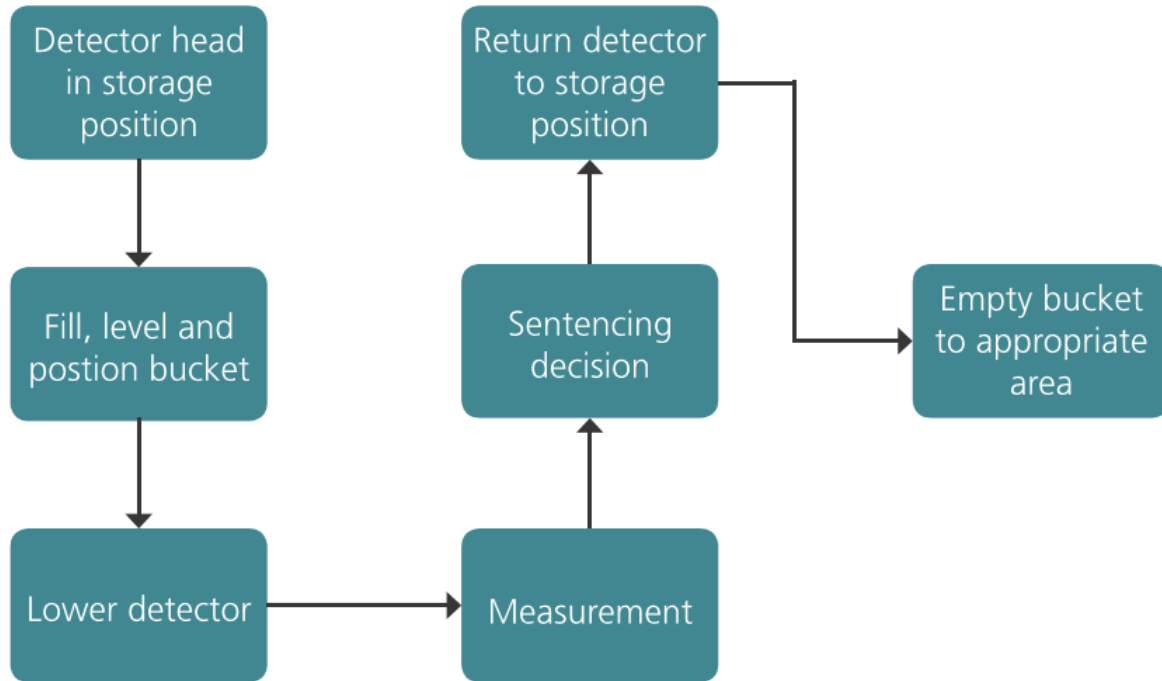


Fig. 1. Operation Sequence of the excavator bucket assay system.

DETAILED DESIGN

The concept design was developed into a detailed design. The EMBASSY instrument was assigned the ANTECH model number G3102.

A ruggedized tablet computer allows the measurement technician to control the assay system via a wireless link. Bespoke software was developed by ANTECH to control the motion of the detector, perform the measurement and analyze the data. The software displays the measured spectrum alongside measurement parameters. By examining the gamma ray spectrum, the technician verifies the provenance of the measurement and accepts (or rejects) the assay result. The waste category is calculated and the detector is returned to the storage position. The tablet screen is turned a color dependent on the waste category and the tablet color is then used as a signal to the excavator operator to appropriately disposition the bucket contents and fill the bucket to begin a new measurement cycle.

The detailed design incorporated the following specification for the detector:

- Detector to be a 41 cm (16") x 10 cm (4") x 5 cm (2") NaI detector to allow for optimum coverage of bucket contents (this detector has a relative efficiency of ~200%);
- Detector to be shock mounted to provide optimum protection from vibrations during excavation operations;

- Detector to be temperature stabilized to mitigate against drift in energy and efficiency.

During excavation operations the detector will be located in a storage position at the top of the cab of the excavator. The measurement position will be lower and over the center of the excavator bucket. The detector and assay system is mounted on the protective guard that is fitted to the excavator to protect the excavator operator from falling objects. A cam shaft is employed in order to guide the movement of the detector between the storage and measurement positions. As the detector travels vertically along the cam shaft, it rotates in order to achieve the required positioning. An electric winch is used to raise and lower the detector.

Fig. 2 shows the assay system mounted on an excavator. The detector is housed in a shadow shield made of steel and lined with lead (red box). The control electronics and signal processor are mounted with the detector (attached grey box). A cable reel (orange cylinder) manages the deployment of the power and data cables. The winch control and power electronics (grey box) are located on top of the grille and provide and control the power to the system. The winch is located between the power electronics and the cable reel. It can be seen that in its storage position (left image) the assay system does not interfere with excavation operations and is out of the line of sight of the excavator operator.

The detailed design also includes a means to ensure reproducible positioning of the bucket for measurement. A flexible guide post, which the excavator operator uses to position the bucket, shown in Fig. 3. The end of the flexible guide post has a diameter of 50 mm (2") and it can move 40 mm (1.5") in all directions if it is nudged. The location of the flexible guide post can be changed to account for different buckets. In Fig. 3, the outer tooth of the bucket is used as the reference datum on the bucket for positioning. Note that other reference points can also be used.

Fig. 4 presents a drawing of the detailed design (left-hand image) and final product (right-hand photograph).

Fig. 5 shows the system mounted on an excavator with the detector in the measurement position. The winch and winch control can be seen mounted on a platform positioned above the operators cab. When the detector is returned to the storage position the operator's view is not obstructed.

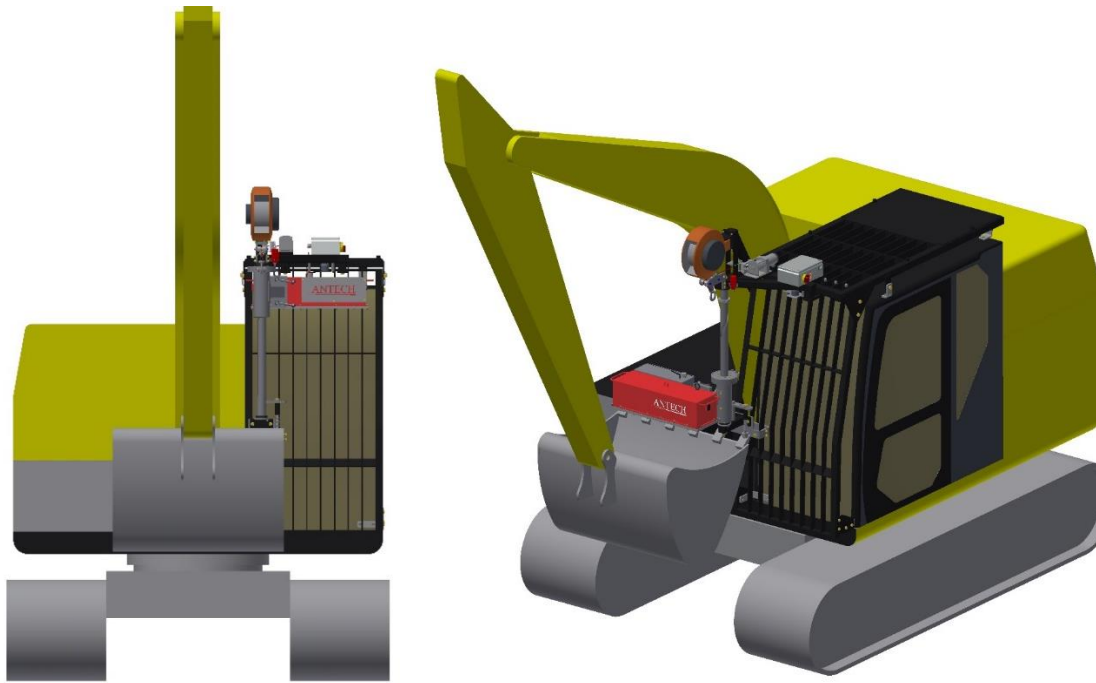


Fig. 2. Detailed Design. The detector is shown in the storage position in the image on the left and in the measurement position in the image on the right.

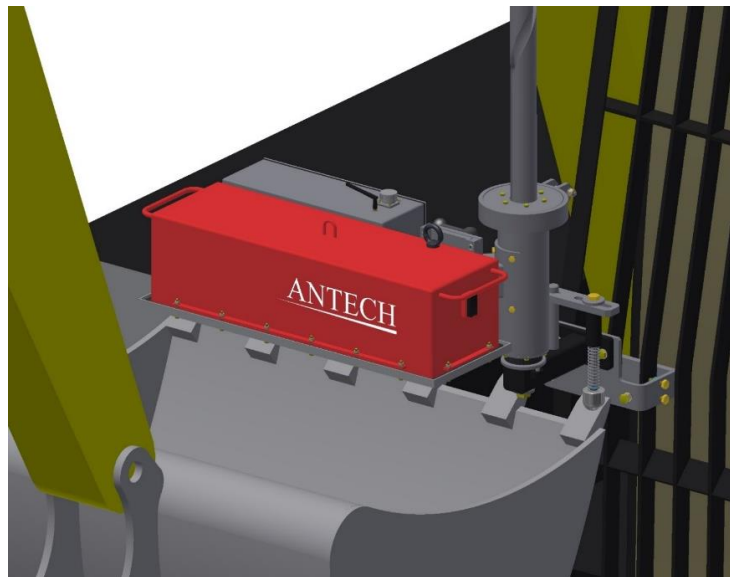


Fig. 3. Flexible guide post used for reproducible positioning of the detector.



Fig. 4. A design drawing of EMBASSY (left image) is compared to a photograph of EMBASSY mounted in a test rig (right image).



Fig. 5. EMBASSY mounted on an excavator. The detector is in the measurement position.

PRELIMINARY MEASUREMENTS

In order to perform measurements to test the operation of EMBASSY, a uniformly distributed radioactive source of constant density was required to simulate the material in an excavator bucket. A solution of potassium chloride dissolved in water was chosen as homogeneity was guaranteed and the specific activity and concentration of the radioactive material (K-40) could be calculated and determined.

The detection efficiency and energy calibration of the detector was established using point sources traceable to national standards. The distributed detector and distributed sample geometry was established using an MCNP model.

A 130 liter K-40 solution was housed in a plastic water tank which simulated the bucket of an excavator. The sample characteristics are summarized in TABLE I. A specific activity of less than 0.5 Bq/g was used, as a sensitivity target for NORM measurement is 0.5 Bq/g of Ra-226.

TABLE I. Characteristics of the Measured Sample.

Quantity	Value
KCl Mass (g)	3138
K Mass (g)	1646
K-40 Mass (g)	0.1925
K-40 Activity (Bq)	4.891E+04
Water Volume (l)	130
Water Mass (g)	1.298E+05
K-40 Specific Activity (Bq.g ⁻¹)	0.377

Measurements were made of the potassium chloride solution with the EMBASSY instrument. Fig. 6 is a gamma ray spectrum from a measurement showing the K-40 region of interest (Area shaded in blue).

In the spectrum displayed in Fig. 6, the K-40 gamma ray peak at 1460.83 keV is visible within the highlighted region of interest that is used for determining the peak area, and hence the activity, of the K-40 in the sample.

Other peaks due to radioactive daughters of Radium are also clearly visible in the measured spectrum. The most prominent ones which can be seen are listed in TABLE II.

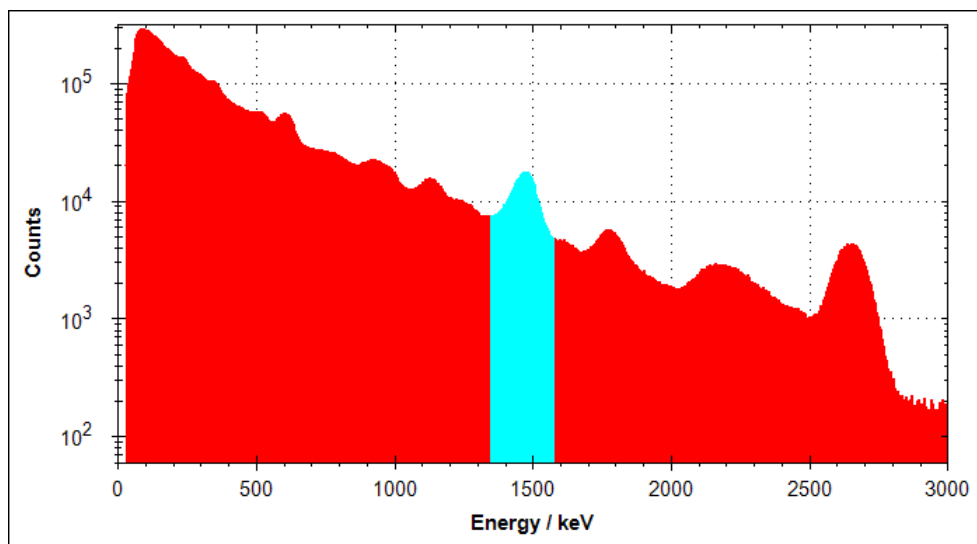


Fig. 6. Gamma ray spectrum from the measurement of potassium chloride solution.

TABLE II. Prominent Radium daughter peaks visible in the spectrum displayed in Fig. 6.

Radium Daughter	Gamma Ray Peak Energy keV	Radium Parent
Ac-228	338	Ra-228
Bi-214	609.3	Ra-226
Ac-228	911	Ra-228
Bi-214	1120	Ra-226
Bi-214	1764.5	Ra-226
Tl-208	2614	Ra-228

An elevated K-40 background due to the presence of potassium in the floor and walls of the test room necessitated long measurements. Fig. 7 shows an overlay plot of the measured sample and the background. One can observe that the background is suppressed by the shielding effect of the water (K-40 solution) in the plastic container which simulates the excavator bucket.

In order to correct for the background K-40 signal from the wall and floor, the transmission of the background through the water of the sample was measured using the Bi-214 peak at 1764.5 keV. The correction was calculated at the K-40 energy of 1460.83 keV and applied to establish the net counts per second in the peak of 4.35 s⁻¹ with the background removed. Using the detector efficiency at 1460.83 keV and the branching ratio for the decay of K-40, the net activity for the K-40 dissolved in the solution in the bucket was calculated as 5.370E+04 Bq. This compares favorably with the calculated value for the activity in the bucket of

4.891E+04 Bq. The measured activity is thus 9.8% higher than the reference activity.

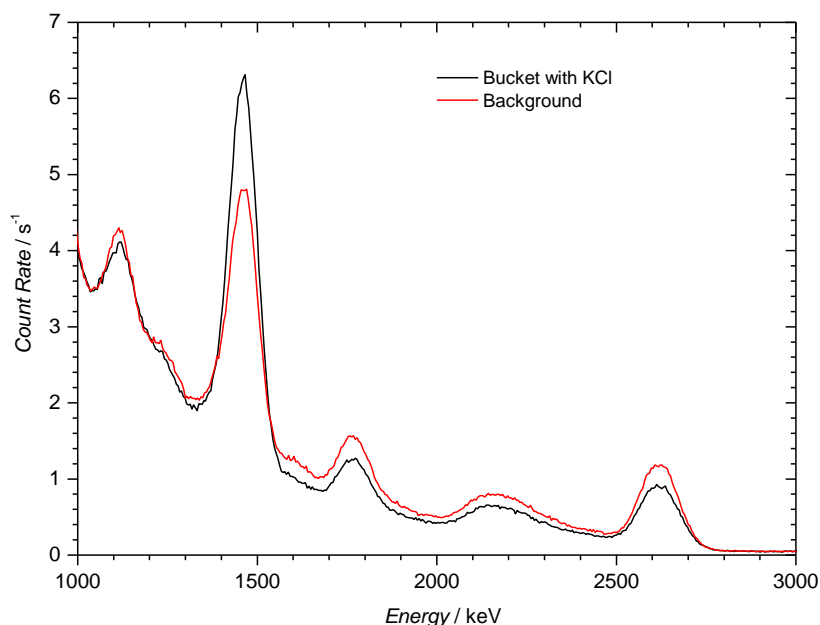


Fig. 7. An overlaid plot of the background spectrum (no bucket or K-40 solution present) and the measured sample spectrum with the bucket and K-40 solution present.

This bias can be explained by the simplification of the bucket geometry used in the analysis of contributions from K-40 in the bucket. The source volume in the analysis was considered as a single cuboid, whereas in reality the bucket tapered in at the bottom. The assumed larger volume at the bottom of the bucket results in a smaller detection efficiency and hence in an over estimation in the K-40 activity.

CONCLUSIONS

The design, development and initial testing of a novel "Excavator Mounted Bucket Assay System" designated "EMBASSY" have been described. EMBASSY has been developed to measure the radioactive content of excavator buckets in the field. Although EMBASSY was designed to measure NORM, it is applicable to the measurement a wide range of radioactive contaminants, such as Cs-137 or Co-60, in various matrices encountered during site remediation operations, such as soil or rubble. The great advantage of EMBASSY is that uncontaminated material that is out of scope of regulatory control can be returned to the excavation site immediately following the measurement and no further handling or processing is required.

Radioactive material which is in-scope of regulatory control can be transported from the excavation site for appropriate disposal depending on the results of the

EMBASSY measurement. The unit is sufficiently sensitive, and the measurement errors quantified, that it can be employed to sentence radioactive material at different regulatory thresholds. Calibration of the large scintillation detector is traceable to national standards. The measurement process has been verified and validated with test samples whose radioactive content has been confirmed using a calibrated high purity Germanium (HPGe) detector and by benchmarked Monte Carlo (MCNP) calculations.

EMBASSY comprises a highly efficient and shielded spectroscopic gamma ray scintillation detector and deployment mechanism. This allows for the timely determination of the activity of the bucket contents and of the waste classification of the material. The process of segregating at the point of excavation and returning uncontaminated material to the site speeds the remediation process and removes the requirement for an extensive and expensive sampling campaign.

Initial measurements have been made using K-40 to confirm the correct operation of the EMBASSY instrument. Measurement errors in the presence of a high background for K-40 are about 10%.

EMBASSY has been designed to optimize operational safety. The design of EMBASSY does not significantly impede excavation operations and does not introduce additional hazards to site operations, such as trailing cables. The use of wireless communication means that the measurement technician is removed from the danger area of the excavator.

The system enables robust real time sentencing decisions to be made that will ensure compliance with transport and disposal regulations and optimize site clearance projects. The use of EMBASSY speeds up the sentencing process and can shorten project duration. Eliminating the need for sampling, reducing material handling and saving time all contribute to reducing the cost of land remediation projects.

REFERENCES

1. John A. Mason, Marc R. Looman, Adam J. Poundall, Daniel Pancake and Richard Creed, "*Development and Testing of a Novel Gamma Ray Camera for Radiation Surveying, Contamination Measurement and Radiation Detection*", Proceedings of INMM2012, Orlando, Florida, July 2012. (12-A-409-INMM)