Performance of Canberra TruckScan Waste Assay Measurement System – 16361

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ABSTRACT

After the Fukushima accident, large (approximately1 cubic meter) super-sacks of potentially contaminated soil and vegetation were stored at various temporary locations throughout the prefecture. Canberra has developed the TruckScan system to perform rapid and accurate assay measurements for these waste sacks loaded on trucks to determine the individual and total sack activities for Cs-137 and Cs-134. The measurement system consists of eight 3x3 inch shielded and collimated NaI(Tl) gamma-ray detectors. Data collected with the eight detectors is analyzed using a maximum entropy fitting algorithm which optimizes and predicts the mean and maximum possible activity concentration present in each of the sacks. The algorithm uses SuperISOCS to generate detection efficiencies for each detector-sack combination in the measurement, which are then used to solve for the distribution of activity concentrations in each sack that yields the best agreement with the count rates observed in each detector. Throughout the summer and fall of 2015, a prototype system was developed and tested at Canberra's Meriden CT facility. In October 2015, the prototype system was installed and demonstrated in Japan. Results of the demonstration measurements are presented along with estimates of the total measurement uncertainty (TMU) budget.

INTRODUCTION

After the Fukushima accident, potentially contaminated waste – primarily soil and vegetation removed by heavy machinery - from around Fukushima prefecture was placed into woven-poly super-sacks and stored at various temporary locations throughout the prefecture. Canberra has developed the TruckScan system [1] to perform rapid and accurate assay measurements for these waste sacks loaded on trucks. Typical loadings have seven sacks – four on one side and three on the other in a zig-zag pattern – on the truck's bed. An eight-sack loading, with the sacks in a rectangular arrangement of two rows of four sacks, is also possible. The goal is to assay each truck and accurately estimate the individual and total sack activities for Cs-137 and Cs-134, while keeping a high throughput rate. Typical operations allow for one minute total time for each truck, which includes counting time and time for computer analysis and reporting. The activity concentrations in the sacks can range from < 1000 Bq/kg for vegetation to as high as 100,000 Bq/kg for sludges. These sacks will soon be transported to various Interim Storage Facilities (ISF). At these ISFs, different handing and disposition options will be used depending upon the activity concentration in each sack. Likely decision values will be at 3000, 8000, and 100,000 Bq/kg. 8000 Bq/kg is the most important decision level, and therefore the reference value used for these performance assessments. Based on the estimated activity levels, alarm signals issued by the TruckScan system direct the system operators and truck drivers to the appropriate location for the disposition of the sacks.

SYSTEM HARDWARE

The measurement system consists of eight 3x3 inch LED-stabilized NaI(Tl) gamma-ray detectors each surrounded with a 10 cm thick lead collimator / side shield assembly. The LED-stabilized detectors keep the gain constant over the wide range of environmental temperatures expected for the outdoor TruckScan operations. The shield assembly greatly reduces background interference from sources of gamma radiation at the site other than the sacks on the truck, located in front of the detectors. A shadow shield, typically of concrete blocks, is also installed to reduce the background from radioactivity on the opposite side of the truck. The detector and shield assemblies are mounted on hydraulic lift tables, two detectors per table, with four detectors on the left (passenger) side of the truck's travel lane and four detectors on the right (driver) side. The lift tables allow for vertical positioning of the detectors to provide optimum sensitivity for truck beds of different heights. A schematic illustration of the system layout is shown in Figure 1. The actual system undergoing testing is shown in Figure 2.

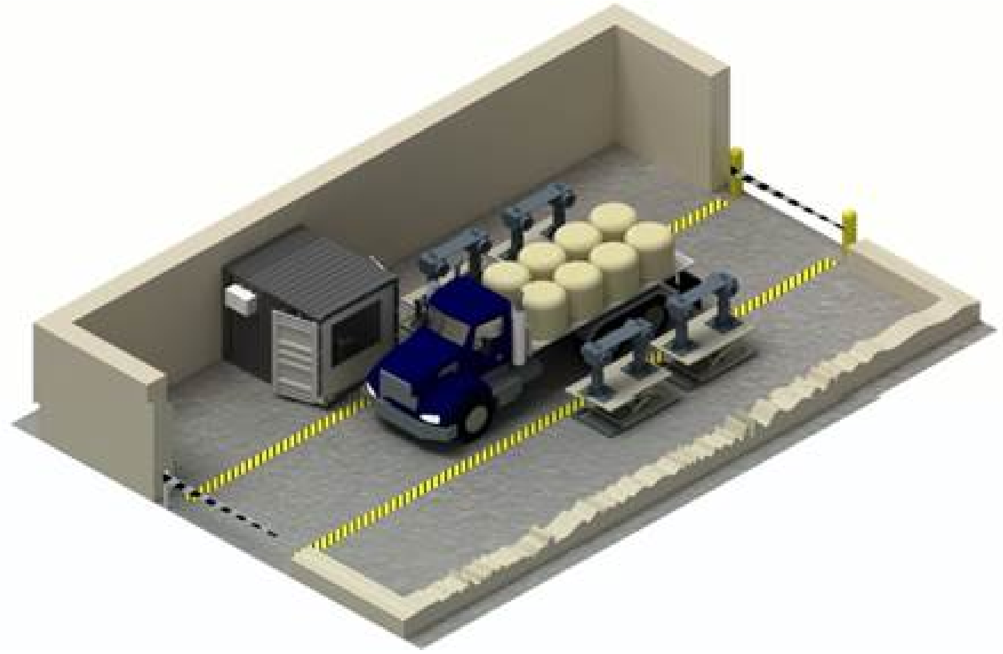

Figure 1 Graphical illustration of TruckScan system at site. Concrete shield wall shown here.

Figure 2 TruckScan during Fukushima testing. The shield wall here is built from sacks filled with clean soil.

ANALYSIS ALGORITHM

To analyze the gamma-ray spectroscopy data collected with the eight detectors, the system uses a maximum entropy fitting algorithm which optimizes and predicts the mean and maximum possible activity concentration present in each of the sacks [5-7]. The input to the maximum entropy algorithm consists of the efficiencies for each gamma energy for each of the sacks present for each detector, and the total count rate in each of the peak windows as measured in each of the detectors.

The efficiencies for each detector-sack combination are automatically created at assay time using SuperISOCS, which itself is provided by the user with a model specifying the details and assumptions about the sack layout and contents and the detector placement for the assay. SuperISOCS is an enhanced version of the Canberra ISOCS^{TM} (InSitu Object Counting System) mathematical efficiency calibration software, which allows multiple radioactive and non-radioactive objects [2-4]. The efficiencies are stored in the form of a response matrix Rij, where i is an index for the detectors, and j is an index for the sacks. Note that the response matrix values Rij also include the intensity of the gamma-ray line and the mass of the sack so that, given a vector of assumed activity concentration values Aj in each sack j, the predicted count rate Pi in each detector i is found from the expression Pi = Sum(j; Rij * Aj). Within the algorithm, a multi-objective optimizer is used to calculate a set of activity concentrations Aj by minimizing the errors between the predicted count rates Pi and the actual measured count rates Mi and simultaneously maximizing the information entropy of Aj.

The output of the analysis is the optimized vector of Aj values. These values are included in the output report and are also presented graphically to the operator in the form of a display depicting the layout of sacks on the truck with those sacks that are above various alarm levels depicted in different colors.

The whole process from truck stopping at the assay station to generation of assay results is approximately one minute, roughly divided equally between counting time and analysis time.

PROTOTYPE SYSTEM – DEVELOPMENT AND ON-SITE DEMONSTRATION

Throughout the summer of 2015, a prototype system was developed at Canberra's facility in Meriden, CT, USA. The hardware was quite straightforward, consisting mostly of off-the-shelf components or slight modifications to existing designs of various components, such as the sideshield / collimator assemblies. Most of the effort during this period concentrated on design and testing of the software, particularly the maximum entropy algorithm. To estimate throughput, analysis time, and accuracy of results, development and testing were performed with a set of standard 200 liter drums in lieu of the cubic-meter sacks expected on-site.

In mid-August 2015, the prototype system was shipped to Japan and installed on-site in Fukushima prefecture. A month-long campaign of demonstration measurements took place in late-August / early-September 2015; this was conducted by Canberra personnel with assistance from the end user. In mid-October 2015, a shorter set of demonstration exercises was conducted, this time witnessed by personnel from the Japanese Minstry of the Environment (MOE), members of the Japanese and international press, and representatives from local governments.

The sacks used for these measurements were selected to be representative of the actual waste stream. Each of the 69 sacks (53 soil, 16 vegetation) were first measured using an ISOCS Germanium gamma-ray system. For each sack, measurements were performed with the ISOCS detector positioned at four locations roughly a meter from the sack at right angles around the sack's symmetry axis. This data was analyzed using the efficiency from the ISOCS software, thereby producing a "known" value for the true Cs-134 and Cs-137 concentration in each sack. This "known" value was validated by extracting 21 samples from each of 3 representative sacks, and comparing the average of those samples against the ISOCS value. These activity values represent the "ground truth" against which the TruckScan results were compared.

For the TruckScan demonstration measurements, sacks were loaded onto the bed of a typical truck and measured with the TruckScan system. In some cases eight sacks were loaded in a 2x4 rectangular arrangement; in other cases seven sacks were loaded in a zig-zag arrangement with three sacks on one side and four sacks on the other. These were the majority of the roughly 100 truck measurements during the testing campaign; many other sack loading configurations, number of sacks, and truck types and sizes were also tested.

MEASUREMENT RESULTS

Quantitative results from the measurement campaign were very encouraging. The sacks used in the measurements ranged roughly from 1000 to 200,000 Bq/kg, with most of the sacks within the 3000-20,000 Bq/kg range. The system was able to quantify the activity of the sacks at the primarly decision value of 8000 Bq,kg with an approximate standard deviation of about 2500 Bq/kg (roughly 25%) when all data was considered, and about 1500 Bq/kg roughly 20%) when trucks with sacks greater than 100,000 Bq/kg were excluded.

Results from a typical truck assay, consisting of six sacks positioned in a zig-zag arrangement, are presented in Table 1 immediately below.

Table 1 Measured Results – Six Sacks in Zig-Zag Arrangement

Position	TruckScan Result (Bq/kg)	True Act. Conc. (Bq/kg)	Ratio TS / True
1	10900	13500	0.81
2	5240	4640	1.13
3	10500	10700	0.98
4	8370	11000	0.76
5	5020	6110	0.82
6	12100	12800	0.95
		Average:	0.91
		Std Dev:	0.14 (15%)

TOTAL MEASUREMENT UNCERTAINTY

Total measurement uncertainty (TMU) and the contributions to it were estimated for the system by modeling the variation of different parameters that play a role in the measurement geometry. In general, measurement errors arise when the actual measurement scenario (e.g. the geometry that produced the counts actually observed in the detectors) differs from the measurement scenario assumed during analysis. A common example is measuring a sample container with a high degree of nonuniformity (e.g. hot spots, etc.) but assuming uniformity when generating the efficiencies to be used during analysis. Using SuperISOCS modeling it’s very easy to explore the effects due to variations in different measurement parameters such as truck positioning, sample density, etc.

Several parameters were examined to estimate their effects on the TMU. For nearly all of the parameters, the approach was the same. A base measurement case was assumed, modeled, and analyzed using the maximum entropy algorithm. Then a single parameter (e.g. bed height) was varied by a specified amount (e.g. bed was raised by 100 mm), the new measurement case was modeled and analyzed. The results – the difference between the perturbed case and the base case – were then compared. Other methods were also used. In some cases the uncertainty contribution was estimated based solely on experience and data obtained during the demonstration measurements. In some cases, such as sack diameter, where a single input parameter had complex effects on various aspects of the measurement, many measurement scenarios were simulated with computer modeling and an overall population standard deviation was obtained from many simulated results. In all cases, the uncertainties were estimated and reported at the 1-sigma level.

The base case consisted of a level truck loaded with seven sacks in a zig-zag pattern (three sacks along one side of the truck bed, four sacks along the other). The sacks had a diameter of 1099 mm, fill height of 750 mm, weight of 1515 kg, and were filled with the “DIRT1” material from the standard ISOCS library. The truck bed was centered (forward-backward and left-right) inside the TruckScan system. The truck bed had a sidewall 486 mm high off the deck of the bed, 19 mm thick, and made of steel (“CSTEEL” material in ISOCS, density 7.97 g/cm3).

Heterogeneous source distribution

In order to estimate the nonuniformity of the distribution in the actual sacks, during the demonstration measurements, the data from the HPGe ISOCS measurements of the soil sacks was used. Each of these fifty sacks was measured with a single HPGe detector at four rotational angles, 90 degrees apart, and the standard deviation of the four measurements from each sack was computed. The average standard deviation of all fifty sacks was 5%.

Bed height

Varying the bed height by ±100 mm from its base height (note – the truck bed itself was kept level), yielded a difference corresponding to a 1-sigma uncertainty of 6.5%.

Sidewall height

In practice, it’s very important that the presence of a thick truck sidewall be accounted for and that the sidewall be accurately characterized in the configuration of the software. The issue to be explored here is how much impact an expected amount of error or uncertainty in the wall height will have on the reported assay results. For these tests, ±25 mm uncertainty seemed reasonable. Varying the wall height by this much yielded a difference corresponding to a 1-sigma uncertainty of 1.5%.

Sidewall thickness

This is a much more critical parameter, and a difficult one to estimate. In practice, the sidewalls of the trucks have complex construction – corrugations, bracing, ribbing, etc. The radiological model used in the maximum entropy algorithm, which is based on SuperISOCS, treated this as a simple uniform slab of absorbing material for the tests and for these calculations. The most important characteristic is the “effective mass thickness” (thickness X material density) of the wall. This can be characterized in practice by either specifying the actual wall thickness and an effective density, or, less commonly, by specifying the actual density of the predominant material (e.g. steel) and an effective thickness. The base case assumed steel walls (7.97 g/cm3) and an effective thickness of 19 mm (mass thickness of 15.1 g/cm2). This thickness was varied between 13 mm and 23 mm, values which are consistent with range of estimated thickness values given during the on-site measurement campaign. This corresponds to roughly 26% variation in mass thickness. This yielded a difference corresponding to a 1-sigma uncertainty of 18%. Given this large uncertainty component from these TMU calculations, it is planned to create a more detailed model of the truck sidewall in the SuperISOCS calculations, and to accurately measure the sidewall effective density with a transmission gage. It is believed that this will reduce the 18% component to 2.5%.

Sack fill height

Variations in the sack fill height affect both the geometry (i.e. the height of the radioactive fill matrix, and how much of the fill matrix extends above the sidewall) and the assumed density of the fill material. The latter is because the system estimates the density from the fill height, sack diameter, and measured sack weight. The base case assumed a fill height of 750 mm; variations were ±125 mm. These values were chosen because the original plan for actual measurements was to simply estimate and report the fill height as one of three possible values: 500 mm, 750 mm, or 1000 mm. Our base case of 750 mm was chosen as a typical value, and ±125 mm was chosen as a range of fill heights outside of which a sack would more likely be characterized as either 500 mm or 1000 mm. Within this range, fill heights were assumed to be distributed uniformly. Modeling this range of fill heights yielded an uncertainty contribution corresponding to a 1-sigma uncertainty of 17%. Such a large uncertainty is due to the fact that the sidewall is quite thick (15.1 g/cm2) and thus is quite effective at shadowing the lower portions of the sack; so the fill height affects how much of the fill matrix extends above the sidewall and is seen unattenuated. If the sidewall were thinner, the effect due to fill height would be less drastic. Given this large uncertainty component it is now planned to estimate and report the fill height within 5cm bands – e.g. 50, 55, 60, … This will reduce the 17% uncertainty to 4%.

Sack diameter and sack positioning

Sack diameter and its effect on sack positioning has the most complex effects on the assay results. As with the fill height, variations in the sack diameter affect both the geometry (i.e. the size of each sample of fill material) and the assumed density of the fill material. In addition, variations in sack diameter also affect the final positions of the sacks on the truck.

When we designed the system and its operation, we assumed that each sack would be positioned centered on a specific location on the truck. This could even be facilitated by placing marks (spray painted dots or circles) on the truck bed to guide placement of the sacks. During the demonstration measurements, it was found that in practice, a very different and understandably simpler method of loading was used. Essentially the loading followed the following steps

- The forwardmost sack is placed as far forward as possible (i.e. it contacts the front wall of the bed) and as far to the side as possible (i.e. it contacts the sidewall of the bed).
- Subsequent sacks are placed as far forward as possible (i.e. it contacts its nearest and forwardmost neighbor sack) and as far to the side as possible (i.e. it contacts the sidewall of the bed).

While this makes loading a very simple, easy, and intuitive process, it introduces variation in sack positioning based on the sizes of the sacks. Wider sacks will cause sacks loaded behind them to be pushed farther backwards, and narrower sacks will cause sacks loaded behind them to be located farther forwards. Also, this variation in position gets worse the farther back the sacks are. The forwardmost sacks are quite reproducibly positioned, because they are “anchored” against the front wall of the bed. The farther back a sack is, the more its position is influenced by the line of sacks ahead of it. For the rearmost sacks, this variation can be as much as several hundred millimeters.

This variation in positioning (i.e. when the sacks are loaded as described immediately above versus the assumption in the model that the sacks are at specific locations as given in the MaxEnt configuration files) can have drastic effects on the accuracy of the assay, and will affect the rearmost sacks much more drastically than the forwardmost sacks. Initial estimates, immediately following the demonstration measurements, for 1-sigma TMU contributions due to this effect range from roughly 5% for the forwardmost sacks to as much as 25% for the rearmost sacks.

In the weeks following the demonstration measurements, a new method for specifying the locations for the sacks has been developed, one which drastically reduces the uncertainty due to the variation in positions of the rearmost sacks. The method is described as follows.

- Load the sacks onto the truck as described above.
- Specify the position of the forwardmost edge of the forwardmost sack on the right (driver) side line of sacks.
- Specify the position of the rearmost edge of the rearmost sack on the right (driver) side line of sacks.
- Specify the number of sacks in the right (driver) side line of sacks.
- Repeat the above (specify forward edge, rear edge, and number of sacks) for the left (passenger) side line of sacks.
- The algorithm specifies the locations and sacks in both lines using the locations of the forward edge and rear edge, and populating the correct number of sacks in the line assuming each sack in the line has equal diameter.

A campaign of test calculations using the above method was performed by populating roughly 1000 modeled trucks with sacks having random diameters ranging from 1050 mm to 1200 mm. Note that these models included the effects of different diameters on the density of the fill material as well as the sack position. The estimated 1-sigma uncertainty contribution due to variations in loading different size sacks was 6.5%

Sack weight
Variations in the sack fill weight affect only the assumed density of the fill material. The latter is because the system estimates the density from the fill height, sack diameter, and measured sack weight. The base case assumed a weight of 1515 kg; variations were ±5% and ±15%. Assuming a ±5% variation in measured sack weight, this corresponds to a 1-sigma uncertainty of 0.25%.

Vehicle location – forward / backward
Positioning the truck accurately within the counter is especially important, and difficult. We explored two different variations to the assumed truck location. First, described here, is variation in vehicle location forward / backward in the counter (i.e. either the truck stops a little late, landing slightly forward in the counter, or a little early, landing slightly backward in the counter). Variations forward / backward of ±100 mm yielded a difference corresponding to a 1-sigma uncertainty of 4.3%.

Vehicle location – left / right
The other variation in truck position was left / right, meaning the truck pulls in slightly off of the centerline of the system. Variations left / right of ±100 mm yielded an uncertainty contribution corresponding to a 1-sigma uncertainty of 8.2%.

Different concentrations per sack
The maximum entropy algorithm was designed to detect and report different activity concentrations in the sacks on the truck. It works quite well when the activity concentrations are all fairly similar – e.g. during the testing when sacks were between 3000 and 25,000 Bq/kg. However, when one sack is markedly more active than the others on the truck, as in those cases when there was one of the >100,000 Bq/kg sacks, that can significantly increase the uncertainty of the neighboring sacks. Data collected during the demonstration measurements indicated that the uncertainty is typically 10% at the 1-sigma level, assuming that all sacks are within the 8000 ± 5000 Bq/kg range. During operations, this will be accomplished by removing the high activity sacks and remeasuring the remainder.

Counting statistics
This is the only parameter expected to depend strongly on the activity in the sacks. Trial analyses were run for three activity concentrations – 3000 Bq/kg, 8000 Bq/kg, and 100000 Bq/kg. The assumed counting time was 10 seconds. Estimated values for the uncertainty in the assay results attributable to counting statistics are given in the table below.

Table 2 TMU Contribution Due to Counting Statistics

Activity (Bq/kg)	1-sigma TMU contribution
3000	7.0%
8000	4.8%
100000	1.5%

For sacks with activity concentrations at the lowest decision limit of 8000 Bq/kg, the 1-sigma uncertainty contribution is estimated to be 4.8%.

Summary of TMU Results

The above results are summarized below in Table 3. TMU contributions are listed at the 1-sigma level, both as a percentage and as an uncertainty on the activity concentration for an 8000 Bq/kg assay result. Finally, all of the listed TMU contributions are added in quadrature to estimate the total measurement uncertainty. Values are listed for those from the original calculations, and for those from the planned improvements.

Table 3 Total Measurement Uncertainty Contribution by Component

Contributing Factor to the Total Measurement Uncertainty	1-sigma TMU Contribution, Original Estimate	1-sigma TMU Contribution, with Planned Improvements
Matrix layering	4% (320 Bq/kg)	4% (320 Bq/kg)
Different matrix material	2% (160 Bq/kg)	2% (160 Bq/kg)
Matrix density inhomogeneity	2% (160 Bq/kg)	2% (160 Bq/kg)
Different material per sack	3% (240 Bq/kg)	3% (240 Bq/kg)
Heterogeneous source distribution	5% (400 Bq/kg)	5% (400 Bq/kg)
Bed height	6.5% (520 Bq/kg)	6.5% (520 Bq/kg)
Sidewall height	1.5% (120 Bq/kg)	1.5% (120 Bq/kg)
Sidewall thickness	18% (1440 Bq/kg)	2.5% (200 Bq/kg)
Sack fill height	17% (1340 Bq/kg)	4% (320 Bq/kg)
Sack diameter and positioning	5-25% (1200 Bq/kg)	6.5% (520 Bq/kg)
Sack weight	0.25% (20 Bq/kg)	0.25% (20 Bq/kg)
Vehicle location – fwd / bkwd	4.3% (340 Bq/kg)	4.3% (340 Bq/kg)
Vehicle location – left / right	8.2% (660 Bq/kg)	8.2% (660 Bq/kg)
Different concentrations per sack	10% (800 Bq/kg)	10% (800 Bq/kg)
Counting statistics	4.8% (380 Bq/kg)	4.8% (380 Bq/kg)
Combined TMU at 8000 Bq/kg	**34% (2700 Bq/kg)**	**19% (1550 Bq/kg)**

CONCLUSIONS

We have developed and tested a prototype TruckScan system to perform rapid and accurate assays on large (cubic meter) sacks of potentially contaminated soil and vegetation loaded in groups of seven or eight on trucks. This system was deployed and demonstrated on-site in Fukushima prefecture. The system consists of eight NaI(Tl) gamma-ray detectors with collimators and sideshields. The data from the detectors is analyzed using a maximum entropy fitting algorithm to estimate the activity concentration in each of the sacks loaded on the truck. Preliminary test measurements show that the system is able to correctly locate hot sacks – those containing more than 8000 Bq/kg of Cs-134 / Cs-137 – and is able to report activities with an uncertainty of roughly 20% and an overall bias of less than 10%. An extensive body of total measurement uncertainty (TMU) estimates has been performed using mathematical modeling. The results of this modeling are quite consistent with the measured uncertainties from the demonstration exercise. The TMU calculations also point out the most significant contributors – uncertainties in truck positioning, characterization of the truck's side walls, fill height of the sacks, and wide variation in activity concentrations amongst the sacks loaded on the truck – and suggests means for improvement that would reduce the TMU.

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