Validation Testing of Canberra-Obayashi TruckScan Calculation Method – 15409

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ABSTRACT

Canberra Industries, Inc. [CI] has designed a new truck monitoring system 'TruckScan' for Interim Storage Facilities [ISF] in Japan. CI and Canberra Japan K.K. [CJKK] have performed validation testing of it with Obayashi Corporation at a temporary storage area in Fukushima prefecture. Decontaminated waste was put into flexible containers called Super Sacks [SS]. The customer desires to quantify the Cs-137 and Cs-134 content of each individual SS, while a group of them are on a truck. This would be done when leaving a temporary waste consolidation area and entering an ISF. The content of SSs is some combination of sand, soil, and vegetation with densities ranging from 0.3 g/cc - 1.6 g/cc. The typical weight of the trucks will be approximately 10 tons, but can vary between 4 and 20 tons. The system must be sensitive enough to detect 100 Bq/kg in 10 - 30 seconds but still have enough dynamic range to measure 1,000,000 Bq/kg material. The system will be operated in an outdoor environment.

The desire to separately quantify Cs-137 and Cs-134 favors the use of a spectroscopic system as a solution. The full-scale TruckScan will consist of eight 3x3" NaI detectors, each in a lead shield with a collimated view of the truck. Four detectors are on each side of the truck, at about 1 meter from the truck, spaced at equal distances. These NaI detectors and collimators were calibrated by In Situ Object Counting System (ISOCS) mathematical efficiency calculation tool. The truck stops in-between the two sets of detectors for the short measurement period – typically 15 seconds. The special software performs gamma spectroscopy on each of the 8 spectra, and then decodes the results to determine the activity in each of the 8 [typically] SSs using a Maximum Entropy Analysis Method.

Validation testing was done by using SSs filled with known material types and known concentrations of material. The results of the TruckScan assay indicate good accuracy for the wide range of conditions. In spite of the conditions being more severe than normal operations, the combined standard deviation was 20.1% for the 6 detector version and 16.6% for the 8 detector version TruckScan. When the TruckScan results were compared to the known concentrations, there was minimal bias and good correlation [$y = 1.0029x$, $R^2 = 0.914$].

INTRODUCTION

In Japan, as a result of the Fukushima NPP accident, there are a large number flexible bags, commonly called SuperSacks [SS] containing radioactive debris that has been removed from land in the surrounding area. The primary radionuclides remaining today are Cs-137 and Cs-134. These SSs are nominally 1.1m diameter by 1m tall, and typically weigh between 0.5 and 1.5 metric tons. These SSs will soon be consolidated into several Interim Storage Facilities [ISF] within the Fukushima Prefecture.

The SSs will be loaded onto trucks, and transported to the ISF. Typically 8-10 SSs are loaded onto each truck. To determine the disposition of the SSs within the ISF, CI has developed a system called TruckScan. This system is expected to measure the SSs on the truck as it arrives at or leaves for the ISF, and to report the activity of each individual SS. This document reports the testing results from a small-scale demonstration of the primary components of the TruckScan.

VALIDATION TESTING

Table 1 shows the predicted performance for the Total Measurement Uncertainty [TMU] for the average concentration of entire truck. After these estimates were performed, it was learned that the real requirement was to determine the concentration in each individual SS, and the associated TMU. That requirement caused the introduction of a new analysis method, Maximum Entropy [ME]. Testing the performance of the TruckScan with the ME algorithm was the objective of the validation tests.

Table 1 Total Measurement Uncertainty in average concentration of entire truck

TMU Component	**Cs-137 Efficiency*Mass 1σ RSD**		
	4-detectors	**6 detectors**	**8 detectors**
Matrix layering	4%	4%	4%
Different matrix material	2%	2%	2%
Matrix density inhomogeneity	2%	2%	2%
Heterogeneous source distribution	7%	7%	7%
SS arrangement on truck	0%	0%	0%
Different concentration per Sack	14%	8%	9%
Different material per Sack	3%	3%	3%
SS fill height variations	6%	6%	6%
Counting statistics	5%	4%	3%
Vehicle location imprecision	47%	12%	4%
Combined Standard Deviation	**50%**	**19%**	**15%**

Validation test procedure

To demonstrate the validity of the ISOCS calibration method the following process was used:

- A Ge detector was calibrated for a U8 container [cylinder, 100cc volume]. Calibrations were both with the ISOCS [1, 2, 3] and with a certified standard source traceable to Japan Calibration Service System [JCSS]. A NaI detector was also calibrated for this container using ISOCS.
- A 100cc sample of typical soil was prepared in a U8 container.
- The soil sample was analyzed with both detectors against all three calibrations for Cs-134 and Cs-137.

Table 2 lists the results of the measurement.

The data in Table 2 indicate no significant difference between the results from the ISOCS calibration and the results using the JCSS calibration. The data also indicate no significant difference between the NaI results and the Ge results. It was confirmed that both the Ge detector and the NaI detector had a good accuracy regardless of calibration methods.

Table 2: Concentrations [Bq/kg] of Cs-137 and Cs-134 in contaminated soil using a U8 container

Detector	Calibration	time	Cs-137	Er*1	ratio*2	DL*3	Cs-134	SD	ratio	DL*3
Ge	JCSS standard	1800s	1420	21	-	12.1	612	16	-	12.0
	ISOCS	600s	1466	36	-	23.0	615	27	-	21.6
NaI	ISOCS	600s	1441	48	1.015	96.8	529	83	0.865	168

*1 Er is the statistical counting error.
*2 Ratio means NaI / Ge value.
*3 DL is Detection Limit (Currie method)

To demonstrate the validity of the NaI detector calibration in the TruckScan for the large 1 m^3 SS bags the following process was used:

- A large volume of SS material that was primarily soil was obtained and thoroughly mixed.
- A large volume of SS material that was primarily vegetation was obtained and thoroughly mixed.
- Samples of each type were taken to determine the average concentration and to show the level of uniformity of the concentration. These were counted on either the NaI or Ge laboratory system to determine the reference concentration. The vegetation samples showed that even though the material was mixed, it was not very uniform.
- The soil and vegetation material was used to fill several of the large bags. These bags were analyzed, one at a time, by the shielded collimated TruckScan NaI detector. The NaI detector was calibrated by the ISOCS method.

The mixed up soil and vegetation material was used as fill for SSs. SSs that were 50% full, 75% full, and 100% full were prepared, in order to represent the range of conditions expected. The weight of each SS was also measured.

The SSs were measured from four directions with a collimated TruckScan NaI detector. The face of the detector was 1 m from the SSs, and 35cm above the bottom of the SSs. The SS was rotated 90 degrees between each of the 4 measurements. Tables 3-1 and 3-2 show the results for the average value from the 4 measurements.

Table 3-1 The concentration of soil in SSs measured with 1 TruckScan detector Unit: Bq/kg

Fill height	Directions	time	weight(kg)	density(g/cm^3)	Cs-137	SD*	Cs-134	SD	Total-Cs
50%	4	600s	542	1.01	1438	11	680	6	2118
75%	4	600s	755	1.01	1373	13	627	31	2000
100%	4	600s	1008	1.08	1315	109	598	53	1913
Average	-	-	-	-	1375	67	635	42	2010
Reference	-	-	-	-	1420	21	612	16	2032

Table 3-2 The concentration of vegetation in SSs measured with 1 TruckScan detector Unit: Bq/kg

Fill height	Directions	time	weight(kg)	density(g/cm^3)	Cs-137	SD*	Cs-134	SD	Total-Cs
50%	4	600s	471	0.942	887	48	406	42	1293
75%	4	600s	650	0.867	800	55	366	46	1166
100%	4	600s	794	0.794	800	23	371	18	1173
Average	-	-	-	-	829	66	381	42	1210
Reference	-	-	-	-	885	18	403	14	1288

* SD of fill height samples means standard deviation of 4 measurements and SD of reference means statistical counting error.

The total SSs analysis for Total Cesium was within 1% of the sample value for the soil and within 6% for the vegetation.

To demonstrate the validity of counting the entire truck and then assigning the activity to each individual bag, the following process was used.

- Using stockpiles of soil and vegetation of various concentrations, multiple SSs were created with known concentrations. These SSs varied in concentration, fill-height, density, and material.
- These SSs were loaded onto a truck, generally 6 SSs on one truck. Due to the confined size of the site, only small trucks could be used, not the larger ones that would hold typically 8-10 SSs. Since only 2 shielded NaI detectors were available, one on each side, the truck was counted 3 times, moving between each count, to simulate the performance of a 6-detector version of the TruckScan system.
- The truck geometry was calibrated using the ISOCS software. The number of sacks on the truck was assumed to be known, but all other parameters were assumed to not be known. Therefore default values for material, density, fill-height, radioactivity distribution within the sack, were used.
- The spectra were analyzed and subjected to a preliminary version of the Maximum Entropy [ME] algorithm to determine the Total Cesium activity of each individual sack.
- The ME measured results were compared with the reference concentrations.

Maximum Entropy algorithm analysis method

The maximum entropy deconvolution technique is an optimization routine that when used with a series of detector measurements viewing a scene, solves for the activity distribution at any number of possible locations within the scene. The possible locations of activity can be greater than the actual number of measurements performed. In order to pick a solution among many that are statistically consistent with the measurements, the algorithm uses a selection rule based upon the entropy of the activity distribution, a concept borrowed from statistical mechanics. Similar to concept of spreading a cloud of hot gas among possible volumes, the algorithm spreads the activity among the possible locations [sacks] as equally as possible, while still being statistically consistent with the measurements (Figure 1). In mathematical terms, the deconvolution step iteratively minimizes L,

$$L = -\sum_{sack}\left[A_{sack}\log\frac{A_{sack}}{A_{initial}} + A_{initial} - A_{sack}\right] - Q\sum_{detector}\frac{(M-D)^2}{\sigma^2},$$

where: A_{sack} is the activity of each sack,

$A_{initial}$ is the initial guess of the sack activity,

Q denotes the Lagrange multipliers used in the optimization,

M is the calculated count rate of a detector from the calibration and A_{sack},,

D is the measured count rate of a detector, and

σ is the uncertainty in the detector count rate.

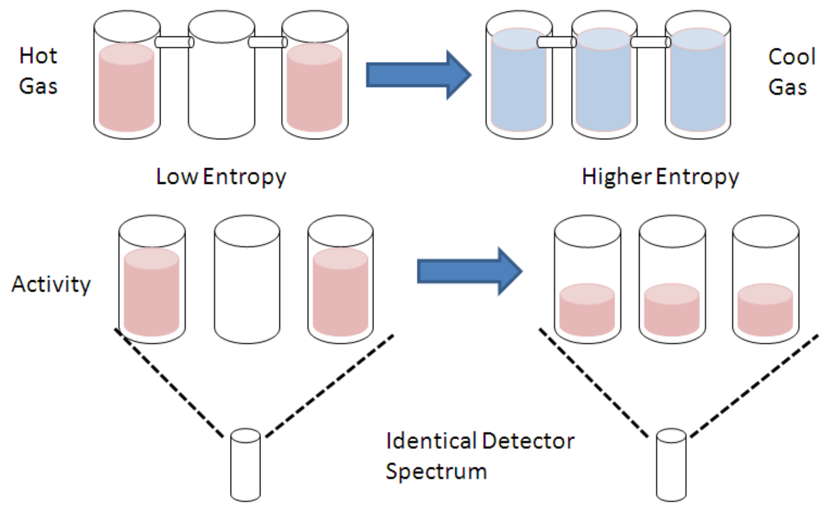


Fig.1. Maximum Entropy Technique Analogy

In the case of the TruckScan, the spatial locations of activity distributions are the coordinates of each sack. The calculated count rates *M*, use a predetermined calibration matrix that incorporates the response of each detector due to the characteristics of each individual sack. The initial guess for all the sack activities ($A_{initial}$) is computed using the average count rate of the detectors and the calibration matrix.

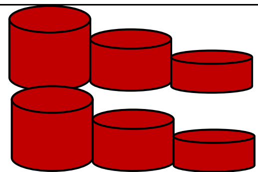
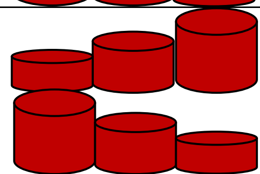
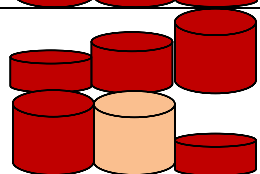
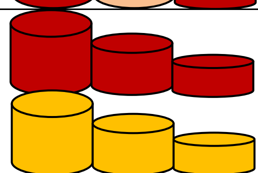
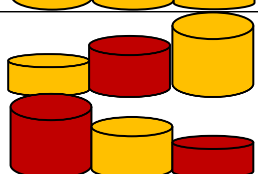
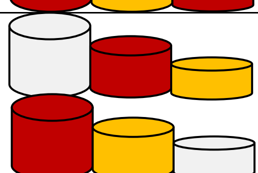
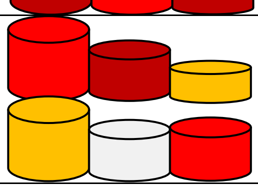
For the results shown in this report, we have focused on the accurate estimation of each sack activity. Therefore, we have constrained the problem further by only solving for the activity within each sack (A_{sack}), assuming a known potential location of each sack, and a known calibration matrix; the algorithm then maximizes the entropy of the activity distribution. Similar to Figure 1, this maximization tends to distribute activity as close to equally among the sacks as is statistically possible, using the uncertainty in the spectral analysis results as the guide.

The referenced articles [4, 5, 6.] take the analysis one step further, in trying to report the Maximum activity in each possible location. This is important in a highly regulated environment. This feature will allow the decisions about the fate of each sack to be determined in a conservative manner, as the user will be confident that the true activity is lower than what is reported. In future developments of the TruckScan algorithm, we will incorporate this second analysis step and give conservative values of each sack's reported activity. This development will take the results of the first estimate of the activity and re-configure the activity within a single sack to a higher level that is still consistent with the measurements. The maximum entropy algorithm is re-run, using this re-configuration of activity as the initial guess of the activity distribution. This will be performed for each sack in the truck, and the results will provide a conservative estimate of the activity.

Analysis of data

The following Table 3 presents a summary of the key data. The graphic in the first column of the table shows a simplified description of the loading geometry for the 6-sack measurements. The height of the cylinder symbol is proportional to the fill height of the sack [50, 75, and 100% of maximum]. The color identifies the contents; Soil (Dark Brown), Vegetation (Brown), High Density Material (Red), Clean Aggregate (Light grey) and Clean Sand (Light Brown) that was not contaminated. The next columns show the sack number, the contents of the sack, and the %full of the sack.

Table 3 Summary of key data.

Position	No.	Contents	% full	Ratio [measured / reffernce]					
				Generic calibration			Exact fill-height calibration		
				Cs-137	Cs-134	Total-Cs	Cs-137	Cs-134	Total-Cs
1 	1	Soil	100	1.08	1.16	1.10	0.86	0.93	0.88
	2	Soil	75	1.07	1.27	1.13	1.06	1.26	1.12
	3	Soil	50	0.58	0.63	0.60	0.85	0.91	0.87
	4	Soil	100	1.08	1.16	1.10	0.86	0.93	0.88
	5	Soil	75	1.07	1.27	1.13	1.06	1.26	1.12
	6	Soil	50	0.58	0.63	0.60	0.85	0.91	0.87
2 	1	Soil	100	1.12	1.17	1.14	0.91	1.01	0.94
	2	Soil	75	0.93	1.03	0.96	0.91	1.01	0.94
	3	Soil	50	0.77	0.93	0.82	0.91	1.01	0.94
	4	Soil	50	0.77	0.93	0.82	0.91	1.01	0.94
	5	Soil	75	0.93	1.03	0.96	0.91	1.01	0.94
	6	Soil	100	1.12	1.17	1.14	0.91	1.01	0.94
3 	1	Soil	100	1.20	1.24	1.21	0.93	0.97	0.94
	2	Clean Sand	100	-*1	-	-	-	-	-
	3	Soil	50	0.79	0.87	0.81	0.98	1.08	1.01
	4	Soil	50	0.75	0.89	0.79	0.91	1.10	0.97
	5	Soil	75	0.92	1.02	0.95	0.91	1.02	0.94
	6	Soil	100	1.16	1.22	1.18	0.90	0.96	0.92
4 	1	Vegetation	100	1.26	1.36	1.29	1.00	1.08	1.03
	2	Vegetation	75	0.88	0.84	0.87	0.88	0.85	0.87
	3	Vegetation	50	0.49	0.62	0.53	0.72	0.89	0.77
	4	Soil	100	1.07	1.15	1.09	0.85	0.92	0.87
	5	Soil	75	1.06	1.25	1.12	1.06	1.23	1.11
	6	Soil	50	0.58	0.63	0.60	0.83	0.90	0.85
5 	1	Soil	100	1.09	1.37	1.17	0.86	1.08	0.93
	2	Vegetation	75	1.12	1.08	1.11	1.12	1.08	1.11
	3	Soil	50	0.57	0.63	0.59	0.74	0.83	0.77
	4	Vegetation	50	0.88	1.02	0.92	0.97	1.11	1.01
	5	Soil	75	0.88	1.04	0.93	0.87	1.03	0.92
	6	Vegetation	100	0.72	0.68	0.71	0.57	0.54	0.56
6 	1	Soil	100	1.31	1.59	1.40	1.03	1.24	1.09
	2	Vegetation	75	1.32	0.95	1.09	1.28	0.91	1.16
	3	Clean Aggregate	50	-	-	-	-	-	-
	4	Clean Aggregate	100	-	-	-	-	-	-
	5	Soil	75	1.14	1.19	1.16	1.16	1.21	1.18
	6	Vegetation	50	0.72	0.96	0.80	1.02	1.39	1.14
7 	1	Soil	100	1.36	1.55	1.42	1.05	1.20	1.10
	2	High Dose Vegetation	75	1.21	1.34	1.25	1.24	1.37	1.28
	3	Soil	50	0.74	0.90	0.78	0.95	1.17	1.02
	4	Vegetation	100	1.70	2.10	1.82	1.28	1.58	1.37
	5	High Dose Vegetation	100	1.10	1.19	1.13	0.88	0.95	0.90
	6	Vegetation	50	0.79	0.98	0.85	0.93	1.19	1.01
8 	1	Vegetation	100	1.05	2.00	1.32	1.05	1.57	1.20
	2	Clean Aggregate	75	-	-	-	-	-	-
	3	High Dose Vegetation	75	1.07	1.24	1.12	1.07	1.24	1.12
	4	High Dose Vegetation	100	0.97	1.24	1.05	0.97	0.98	0.97
	5	Soil	75	0.72	0.91	0.78	0.72	0.87	0.77
	6	Vegetation	50	0.98	0.93	0.96	0.98	1.02	0.99

*1 The Cs concentrations of Clean Sand and Clean Aggregate were less than detection level.

The concentration of each sack was determined by counting a truck with 6 sacks, followed by analyzing each spectrum with Genie, and then analyzing the group of 6 spectra with the first part of the Maximum Entropy algorithm. Shown in the last 6 columns of the table are the ratios of each “reported” SS activity to the “reference” activity. These ratios are only shown for those sacks where there was Cs activity, not

for the aggregate data will be presented separately. Ratios are shown for the initial data analysis, where a default calibration was used, and for a reanalysis where the exact fill-height calibration was used.
The initial default calibration assumed:

- 110 cm sack diameter
- 75cm sack height [75% full]
- cellulose contents
- 0.8 g/cc density

The fill height calibration columns will be discussed later.

Calibrations for the TruckScan were done using the massimetric method. This method presents the full energy peak efficiency as (counts per second)/(Bq/kg), rather than the convention method of (counts per second)/(Bq). The massimetric efficiency is nearly invariant to density, for large samples like this. To confirm this, comparisons were made among different materials. The average densities were 1.2 for soil, 1.0 for vegetation, and 0.77 for the high-dose material. The default density was 0.8 g/cc. Table 4 shows the results.

Table 4 The results from different materials with different average density

Contents	Cs-137		Cs-134	
	Average Ratio	SD (%)	Average Ratio	SD (%)
Soils	0.96	21	1.09	24
Vegetation	0.94	26	1.04	39
High Dose Vegetation	0.98	33	0.98	36

The results indicated no significant differences between the average of the measured values and the reference value in the soil, vegetation, and high dose vegetation samples.

To examine the effect of fill height variations of the SSs, the average result was compared to the reference values for each fill height. Table 5 lists the results.

Table 5 The results from different fill heights

Fill height	Cs-137		Cs-134	
	Average Ratio	SD (%)	Average Ratio	SD (%)
50% full	0.76	15	0.88	17
75% full	1.02	14	1.10	13
100% full	1.13	26	1.30	12

The results in Table 5 indicate deviations from the reference activity as a function of the fill height. Near a filling volume of 75%, the values almost coincided. Underestimation of the activity occurred at 50% full and overestimation at 100% full.

Of the10 parameters we evaluated that could contribute to the TMU, the fill height variation has a large contribution. If the fill height could be determined prior to the analysis, that portion of the TMU could be reduced. To validate this assumption, the measurements from Table 3 were reanalyzed this time with the known fill height. That data is in the last 2 columns of Table 3. Table 6 shows the improved results, where there is no longer a variation with fill height.

Table 6 The results of different fill height with the exact fill height calibration

Fill height	Cs-137		Cs-134	
	Ratio	SD (%)	Ratio	SD (%)
50%	0.93	10	1.07	14
75%	1.00	14	1.09	15
100%	0.92	11	1.04	20

The average and standard deviation from all the sacks were calculated for both the default calibration and with the known fill height calibration. The results for Cs-137, Cs-134 and Total cesium are presented in Table 7.

Table 7 The results of default calibration and the exact fill height calibration

	General calibration			Fill height calibration		
	Cs-137	Cs-134	Total-Cs	Cs-137	Cs-134	Total-Cs
Difference from the reference value	-2%	11%	2%	-4%	8%	-1%
SD of the group of results	23%	29%	19%	13%	17%	10%

The standard deviation has been significantly reduced. The SD went from 23% to 13% for Cs-137, from 29% to 17% for Cs-134, and from 19% to 10% for total cesium. This indicates a potential area for reduction of the TMU, if the ME analysis algorithm could be given a close approximation of the actual fill height of each sack.

Comparison at different activity levels

It is desired to show that the TruckScan results are valid over wide ranges of activity. Due to the location where these measurements were done, high activity material was not available. Nevertheless, the measured activity is plotted versus the reference activity in Fig.2 for total-Cs. The correlation factor ‘y=1.0029x, R^2=0.9136’ is very good, showing no bias as a function of activity.

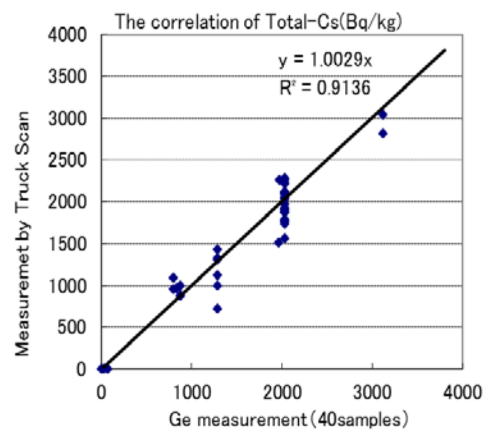


Fig. 2.

Non-uniformity of activity in a SS

We checked uncertainty due to non-uniformity of the radioactivity by performing in-situ measurements on 8 SSs from four directions at 90 degrees apart, with the collimated TruckScan NaI detectors. The contents were not mixed before filling, which is similar to actual practical operations. The relative standard deviation from each of the 4 measurement on each sack was computed. These ranged from 2% to 33% relative standard deviation. The average of the eight SSs was 10%. This is more realistic than the 7% “educated guess” estimate in Table 1.

Revised TMU estimate

The TMU is the combined standard deviations of the individual uncertainties, summed in quadrature. In the original prediction shown in Table 1, the TMU was estimated for the average contents of the truck. The estimated TMU when using the ME analysis to determine the individual sack activity was computed in a similar manner. Most of the original parameters remain unchanged. The new values were for heterogeneous source distribution and for SS fill height variation. Values were estimated for the

6-detector version of TruckScan [Table 8-1] and the 8-detector version [Table 8-2]. TMUs for both the default and the exact fill-height calibrations are shown. These revised TMUs were compared with the uncertainty from these measurements, as presented in the last row of the tables.

Table 8-1 Cs-137 Efficiency*Mass 1σ RSD in case of 6 detectors

TMU Component	Prediction	Validation test	Validation test
	Generic calibration	Generic calibration	Accurate calibration*
Matrix layering	4%	4%	4%
Different matrix material	2%	2%	2%
Matrix density inhomogeneity	2%	2%	2%
Heterogeneous source distribution	7%	10%	10%
SS arrangement on truck	0%	0%	0%
Different concentration per Sack	9%	9%	9%
Different material per Sack	3%	3%	3%
SS fill height variations	6%	10%	6%
Counting statistics	4%	4%	3%
Vehicle location imprecision	12%	12%	12%
Combined Standard Deviation	**19%**	**21.8%**	**20.1%**

* This means the result was corrected by Exact fill-height calibration for all of the sacks.

Table 8-2 Cs-137 Efficiency*Mass 1σ RSD in case of 8 detectors

TMU Component	Prediction	Validation test	Validation test
	Generic calibration	Generic calibration	Accurate calibration*
Matrix layering	4%	4%	4%
Different matrix material	2%	2%	2%
Matrix density inhomogeneity	2%	2%	2%
Heterogeneous source distribution	7%	10%	10%
SS arrangement on truck	0%	0%	0%
Different concentration per Sack	9%	9%	9%
Different material per Sack	3%	3%	3%
SS fill height variations	6%	10%	6%
Counting statistics	3%	3%	3%
Vehicle location imprecision	4%	4%	4%
Combined Standard Deviation	**15%**	**18.4%**	**16.6%**

* This means the result was corrected by exact fill-height calibration for all of the sacks.

From the comparison of the found concentrations to the known concentrations for this wide range of measurement conditions, portions of the uncertainty that feed into the Total Measurement Uncertainty can be better estimated. Based purely upon simulations we estimated the TMU at 19% for the 6-detector arrangement and 15% for the 8-detector arrangement. From these measurements the TMU was 21.8% and 18.4% respectively. This confirms the reasonableness of our original simulations. The major improvement in TMU with the 8-detector geometry is by less sensitivity to the position of the truck in front of the detectors. It was further shown that if accurate fill heights could be obtained for each bag, the TMU could be reduced to 20.1% and 16.6%, respectively.

CONCLUSIONS

These validation tests used 2 detectors, 1 on each side of the truck, to simulate the planned unit, shown in Figure 3. The TruckScan has 8 collimated NaI detectors configured by both sides of truck deck. Above it is a laser scanning device to determine the actual SS location and the fill height of each SS. This device was developed and will be provided by Obayashi Corp. This will be input into the TruckScan software for automatic selection of the correct calibrations parameters to be used by the Maximum Entropy algorithm.

These validation tests confirmed the accuracy of the original predictions and provided data showing where the TMU could be reduced. These tests provided data showing that the choice of massimetric efficiency was appropriate. And these tests show that the Maximum Entropy algorithm analysis method was suitable to analyze the individual activity in each sack from multiple overlapping measurement of the entire truck.

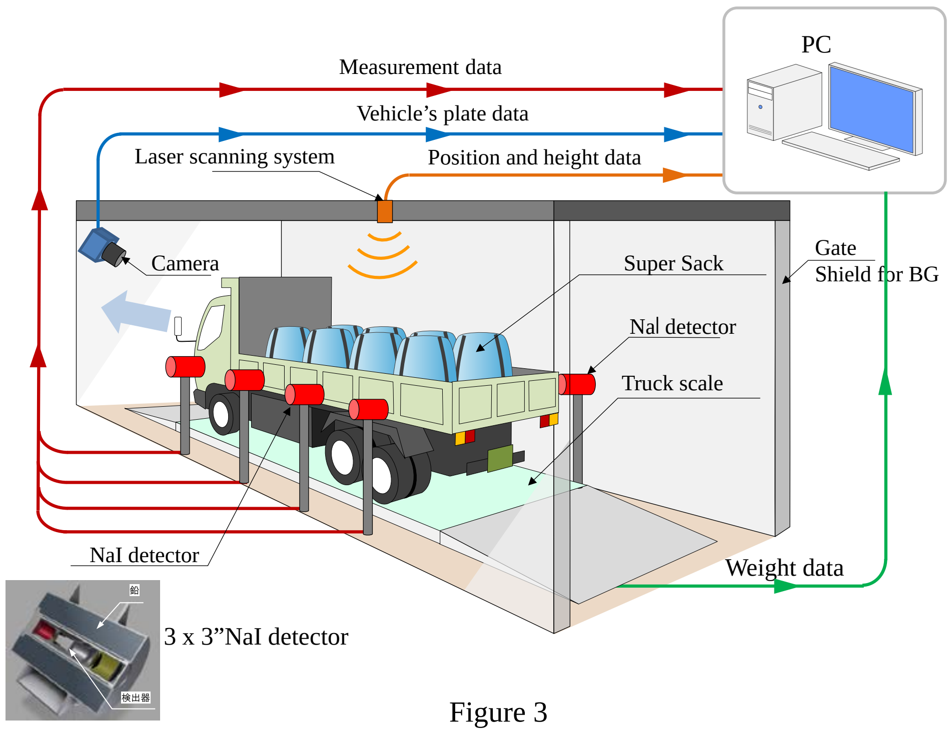


Figure 3

We next plan full scale validation tests in the near future to allow further validation of the accuracy of the measurements and understanding of the components of the TMU.

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