Design Study of an Incinerator Ash Conveyor Counting System – 13323

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ABSTRACT

A design study has been performed for a system that should measure the Cs-137 activity in ash from an incinerator. Radioactive ash, expected to consist of both Cs-134 and Cs-137, will be transported on a conveyor belt at 0.1 m/s. The objective of the counting system is to determine the Cs-137 activity and direct the ash to the correct stream after a diverter. The decision levels are ranging from 8000 to 400000 Bq/kg and the decision error should be as low as possible. The decision error depends on the total measurement uncertainty which depends on the counting statistics and the uncertainty in the efficiency of the geometry. For the low activity decision it is necessary to know the efficiency to be able to determine if the signal from the Cs-137 is above the minimum detectable activity and that it generates enough counts to reach the desired precision. For the higher activity decision the uncertainty of the efficiency needs to be understood to minimize decision errors. The total efficiency of the detector is needed to be able to determine if the detector will be able operate at the count rate at the highest expected activity.

The design study that is presented in this paper describes how the objectives of the monitoring systems were obtained, the choice of detector was made and how ISOCS (In Situ Object Counting System) mathematical modeling was used to calculate the efficiency. The ISOCS uncertainty estimator (IUE) was used to determine which parameters of the ash was important to know accurately in order to minimize the uncertainty of the efficiency. The examined parameters include the height of the ash on the conveyor belt, the matrix composition and density and relative efficiency of the detector.

INTRODUCTION

A nuclear waste facility is burning radioactive waste and needs to measure the activity remaining in the ash after the waste is burned. The potentially radioactive waste will be transported on a conveyor belt at a speed of 0.1 m/s and it needs to be measured on the belt. The conveyor belt will be placed outdoors which requires the measuring station to be weatherproof and with the ability to control the temperature inside the station. It should also be flexible to accommodate different conveyor belt and diverter designs. At least two radionuclides are expected to be present in the ash, Cs-134 and Cs-137. The decision levels will be based on the activity of Cs-137. After the measurement the ash will be diverted into one of four streams depending on the level of activity of the ash.

The current design of the system requires 4 different decision levels for the Cs-137 activity of the ash $A_{Cs\text{-}137}$ as follows:

- $A_{Cs\text{-}137} < 8000$ Bq/kg
- $8000 < A_{Cs\text{-}137} < 100000$ Bq/kg
- $100000 < A_{Cs\text{-}137} < 400000$ Bq/kg
- $A_{Cs\text{-}137} > 400000$ Bq/kg

The uncertainty of the measurement should be below 10% at the decision levels.

The length of the conveyor belt between the measurement station and the diverter is 20 m and with a speed of 0.1 m/s limits the maximum possible count time to 200 s. A shorter count time is preferred because it will give results that are averaged over a smaller sample size. The method for this study is to use mathematically calculated efficiencies to decide if a proposed measurement system can fulfill the requirement mentioned above.

The preferable way of transporting ash on a conveyor belt is to use a V-shaped conveyor to minimize the amount of ash falling off the belt. Figure 1 shows a V-shaped conveyor belt with the detector located in a weatherproof container and looking down on the belt.

Figure 1, a drawing of the measurement system with the detector looking down on the conveyor belt.

The ash is assumed to be filled from the top of the conveyor belt and it will fill the bottom and form a triangular shaped top. A cross section of the ash on the belt together with the collimated detector is shown in Figure 2.

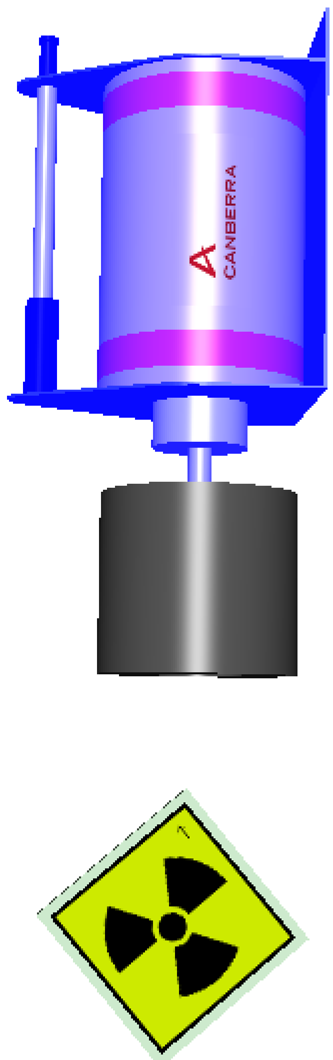

Figure 2, the collimated detector looking down on a cross section of the ash.

Positioning the detector above the conveyor belt gives the flexibility to operate with different types of conveyor belts, if necessary in the future, and to protect the detector from damage from the conveyor belt and weather. The initial best estimate of the geometry is 90 degree conveyor belt angle, 400 mm distance from bottom of the belt to the detector and an ash density of 0.2 g/cm^3. A 50 mm thick cylindrical lead collimator shields the detector from the ambient background.

The ISOCS [1,2,3] code calculates the efficiency for detector – geometry combinations based on 21 templates. The code generates points in the radioactive parts of the geometry and calculates the efficiency of the points from the attenuation and the detector vacuum response. The detector vacuum response is different for every detector and a combination of source measurements and MCNP [4] calculations are used to determine it. The detector response is defined from the end cap up to a distance of 500 m and cylindrical symmetry is assumed. The peak efficiency for the entire sample is calculated from the weighted average of the efficiencies from the individual points. Efficiencies are only correct if the geometry used for the measurements is the same as the one used for the calibration, this is true for both mathematical and source calibrations, but for many measurements this may not be the case. The geometry can vary from one measurement to another or it is not possible to accurately measure some parameters, for example the sample height or density may be difficult to measure and these are then considered as not well known parameters (NWK). The ISOCS Uncertainty Estimator IUE [5] can be used to calculate the sensitivity to changes in one parameter or the efficiency and uncertainty of geometries with NWK parameters. The NWK parameters are defined with lower and upper limits, a best estimate and a probability distribution. In sensitivity mode the efficiency is calculated for the upper and lower limit for every NWK parameter with all other parameters at their best estimate value. The efficiencies for the lower and upper limits are then compared to the efficiencies where all parameters are at their best estimated value. In uncertainty mode geometry models are created with the NWK parameters varying according to the assigned probability distributions and the efficiency is calculated for each model. The efficiencies are averaged and the standard deviation is calculated.

PERFORMANCE ESTIMATION

The goal is to have a system that gives reliable results even if the parameters of the ash vary. It is expected that the material composition, the amount of ash on the conveyor and the density of the ash can vary. The variations will affect the efficiency and hence the accuracy of the result. The system should be designed so that the expected variations do not affect the results more than the required uncertainty.

Detector choice

The requirement to determine the activity of Cs-137 in the ash and an expected significant contamination of Cs-134, and possibly other nuclides, favors a High Purity Germanium (HPGe) with better energy resolution than a NaI detector. With comparable amounts of Cs-134 it is difficult to accurately determine the activity of Cs-137 with a NaI detector because the peaks are interfering with each other. With the energy resolution of a HPGe detector there are no interference between the peaks from Cs-134 and Cs-137. In addition, the detector needs to cover a wide range of count rates from 10% of the lowest decision level to 10 times the highest decision level, a dynamic count rate range of 5000. The dynamic range of the count rate for a HPGe detector is wider than for a NaI detector, again favoring a HPGe detector. The public believability of HPGe detector is larger because the well separated peaks makes the spectra easier to interpret and to manually calculate the peak areas. The detectors that were decided to be evaluated were 20% and 60% relative efficiency coaxial HPGe detectors.

Count rates and statistical uncertainty

ISOCS was used to calculate the efficiency for 662 keV, the most intense photon energy emitted from the decay of Cs-137. The most likely parameters for the measurement geometry were used in the calculations. The count rate at the lowest decision level needs to be high enough so that the statistical uncertainty is less than the required precision of the system for the decided measurement time. The number of counts, c, in the peak is calculated by the formula

$c = Aymet.$

where e is the efficiency, m is the mass, y is the yield of the line of interest, A is the activity per unit mass of Cs-137 and t is the measurement time in seconds. The statistical uncertainty was determined from the square root of the counts in the peak. The efficiency and the mass of the ash were calculated by ISOCS. The counts in the peak and the statistical uncertainty for the 3 decision levels and the two detectors are given in Table I for a count time of 60 seconds.

Table I, The peak counts and statistical uncertainty for the two detectors and the three decision levels for a 60 seconds count time.

Detector	8000 Bq/kg	Statistical uncertainty	100000 Bq/kg	Statistical uncertainty	400000 Bq/kg	Statistical Uncertainty
20% relative efficiency	607	4.1 %	7580	1.1 %	30300	0.57%
60% relative efficiency	1690	2.4%	21100	0.69%	84400	0.34%

The statistical uncertainty for both detectors and for all three decision levels are below the required precision of the system.

The total count rate of the system at ten times the highest decision level should not cause so high dead time that the results become unreliable. To be able to determine the total count rate, the total efficiency is needed. The total efficiency was estimated from the peak-to-total ratio previously measured for similar detector sizes and 0.25 and 0.34 was used for the 20 and 60%

relative efficiency detectors respectively. The Cs-134 total count rate was estimated to be a factor 2 of the Cs-137 contribution. The total count rate was estimated to be 60000 and 125000 count per seconds for the two detectors which is within the limits of what the detector and MCA combination can handle.

Influence of matrix composition

The matrix composition of the ash on the conveyor belt could vary and the influence of matrix composition has been investigated for 6 possible matrix compositions keeping all other parameters constant, the density included. The matrix compositions were concrete, aluminum, steel, sand, soil and cellulose. Three energies were chosen, 300, 660 and 1000 keV, in case the system will be used to measure other nuclides in the future. Figure 3 shows the ratio of the efficiencies for the 6 matrix compositions and the efficiency of concrete for the three energies.

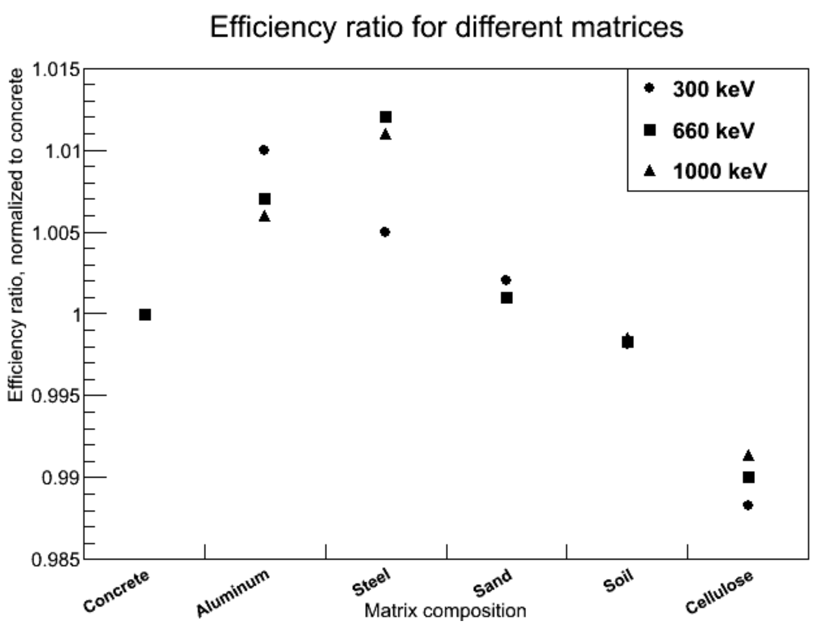

Figure 3, the efficiency ratio of the six ash matrix compositions and concrete for 300 (circles), 660 (squares) and 1000 (triangles) keV.

The ratio does not differ with more than 1.5% compared to the concrete for any of the matrix compositions for the 3 energies. 1.5% is lower than the required precision and therefore a change in matrix composition will not influence the total measurement uncertainty and it is not critical to control the matrix composition.

Influence of matrix density

The density of the ash is expected to be varying from the best estimate value of 0.2 g/cm^3. Figure 4 shows the efficiency when the density is varied between 0.05 and 1 g/cm^3 while keeping all other parameters fixed.

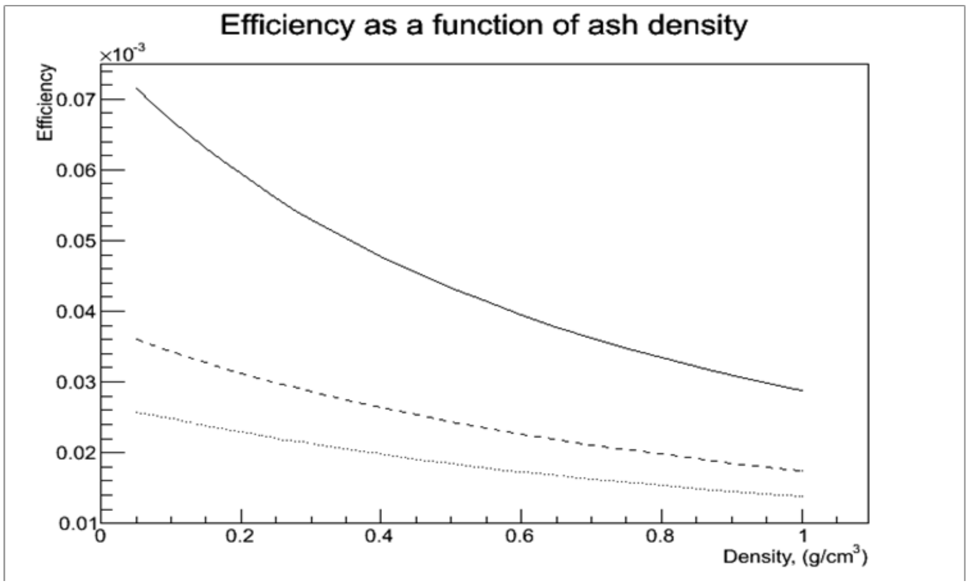

Figure 4, varying density keeping all other parameters constant for 300 (solid line), 660 (dashed line) and 1000 keV (dotted line).

The efficiency varies by a factor of two for 660 keV which is larger than the required precision. However, the requirement is not to measure the total activity but the activity per kg and varying the density also varies the mass of the sample. Therefore it might be better to use the massemetric efficiency (efficiency times mass) rather than the efficiency. For large samples the massemetric efficiency approaches a constant value when for example the density or fill height is changed. Figure 5 shows the massemetric efficiency for the same density range.

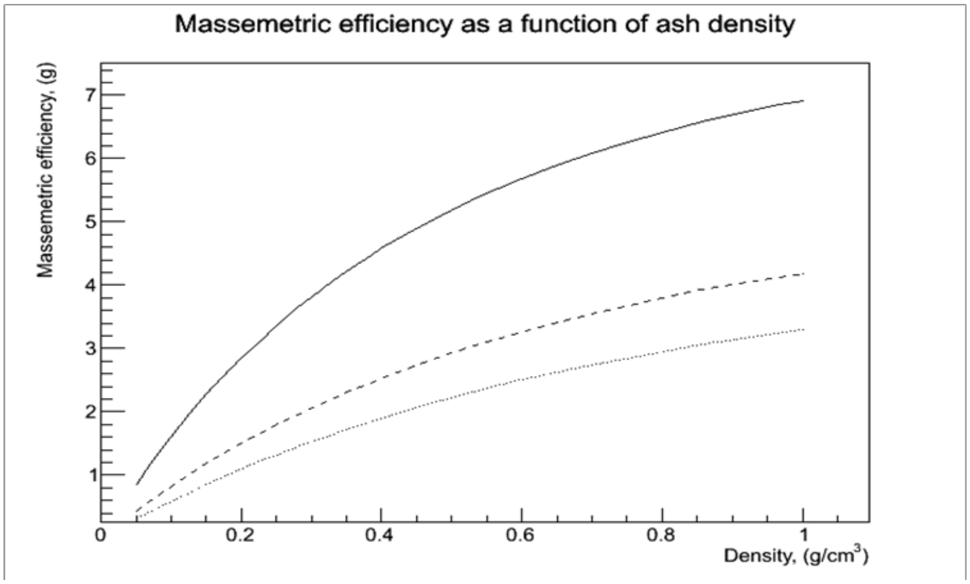

Figure 5, The change in massemetric efficiency for varying density;

The massemetric efficiency varies strongly with density, almost a factor of 10 for 660 keV in the 0.05 to 1 g/cm^3 range, and the density has to be controlled to a narrow range around the density used in the efficiency calculation for the uncertainty to be below the 10% design goal. It can be seen in the figure that all three curves level off and it looks like if the density is increased enough they will approach a constant value, hence the sample is not large enough to give a constant massemetric efficiency. But since the decision levels are in Bq/kg it is still convenient to look at the massemetric efficiency.

Influence of fill height

The fill height will influence the efficiency in two ways, higher fill height will reduce the distance between the source and the detector but it will also increase the self-attenuation of the sample. The efficiency and massemetric efficiency as a function of fill height is shown in Figure 6.

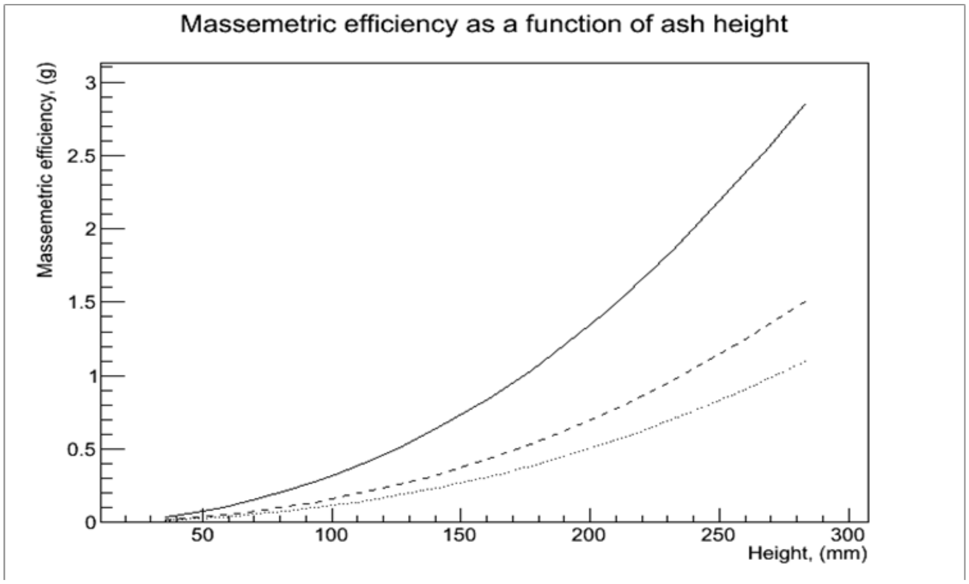

Figure 6, the efficiency as a function of ash height

The massemetric efficiency varies by a factor of 75 for 660 keV for fill heights from 35 to 280 mm. This implies that it is critical to control the fill height of the ash. The fill height can be controlled by adding a scraper at some distance from the conveyor belt and therefore limiting the maximum fill height

Transmission source

The density of the ash can be determined by weighting a section of the conveyor belt and the ash. This may not be a feasible solution and an alternative is to use a transmission source to determine the activity. The transmission source would be placed on the opposite side of the ash from the detector and the source would be measured at the same time as the ash. If the fill height is known and the attenuation is measured the density can be calculated and an efficiency which corresponds to that density can be chosen. With the high expected activity of Cs-137 and Cs-134 the transmission source should have at least one line with higher energy than the 796 keV line of Cs-134. Two sources were considered, Mn-54 and Eu-152, they both have significant lines with energy higher than 796 keV, 835 keV for Mn-54 and 1408 for Eu-152. The source strength should be high enough to be able to determine the density accurately enough so that the uncertainty in the density does not significantly influence the measurement uncertainty. A change in density of 5% will result in an efficiency change of less than 1% for Cs-137 and therefore a change in massemetric efficiency of less than 5% which is low enough so that the uncertainty in the density will not influence the total measurement uncertainty.

The source needs to have high enough activity to observe a statistically significant change in count rate for the 5% change in density. The difference in peak counts for a 5% change in density in units of σ for a 37MBq Mn-54 and a Eu-152 source positioned under the belt 1 m from the detector with a count time of 60 seconds at densities 01.5, 0.2 and 0.25 g/cm3 is shown in Table II and Table III.

Table II, the change in peak counts when the density is changed by 5% for a 37 MBq Mn-54 source for a count time of 60 seconds.

Density (g/cm3)	Peak counts	1 σ statistical uncertainty	Difference in peak counts when density is changed 5%	Difference in peak counts in units of σ when density is changed 5 %
0.15	140171	374	1320	3.5
0.20	131602	363	1648	4.5
0.25	132560	352	1932	5.5

Table III, the change in peak counts for the 1408 keV line when the density is changed by 5% for a 37 MBq Eu-152 source for a count time of 60 seconds.

Density (g/cm3)	Peak counts	1 σ statistical uncertainty	Difference in peak counts when density is changed 5%	Difference in peak counts in units of σ when density is changed 5 %
0.15	21595	147	157	1.1
0.20	20568	143	199	1.4
0.25	19590	140	237	1.7

For the Mn-54 source the difference in peak counts when changing the density ±5% is statistically significant and it would be possible to determine the density with enough precision for it to not influence the total measurement uncertainty. The difference for Eu-152 is not large enough to reliably determine the density not to influence the total measurement uncertainty, the count rate needs to be increased by either using a stronger source or move it closer to the detector. The Compton edge from the 835 keV line from Mn-54 is below the 662 keV line from Cs-137 making the addition to the continuum under the Cs-137 peak smaller than for peaks that have the Compton edge at higher energy than 662 keV as is the case for Eu-152.

CONCLUSION

Both the proposed detectors will meet the statistical uncertainty requirement for the proposed system and they will be able to cover the required dynamical range from 800 Bq/kg to 4000000 Bq/kg at a distance of 400 mm from the conveyor belt. The 60% relative detector has smaller statistical uncertainty and can be located further away from the conveyor belt if needed. The influence on the matrix composition is low enough so that it can be safely ignored and it is not necessary to try to determine it. The density and ash height on the belt has a large influence on the results and needs to be controlled. The height of the ash can be controlled with a mechanical scraper and the density can be measured with a scale or a transmission source.

Mathematical efficiency calculations are a valuable tool for estimating the performance for a measurement system in the design phase. The calculations can be used to help to choose the correct detector and counting geometry to ensure that the required precision is met and the required counting statistics can be reached as well as the total count rate is not too high to give unreliable results. Furthermore it can give information about which parameters that are necessary to control in order for the uncertainty in the efficiency determination not to be higher than the acceptable precision of the measurement system.

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