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Comparison of Gamma-ray Non-Destructive Assay Measurement Techniques

Several techniques based on gamma-ray measurements are commonly available for both Safeguards measurements and Non-Destructive Assay (NDA) of radionuclides including Special Nuclear Material, including plutonium and uranium. The techniques discussed here are referred to as : "ISO-CART", "QED", "SGS" and "TGS"; some include shielded chambers for the lowest activity measurements. This Technical Note compares the measurement characteristics and the range of samples for these techniques. Not all aspects of the technology are covered, but this is a guide to NDA users and those with a general knowledge of gamma-ray measurement technology in the selection of a system for their use.

The measurement techniques are listed in order of increasing accuracy and precision and robustness. Robustness is defined as the reliability of the instrument to produce a successful result. Thus the techniques are in decreasing order of the number of assumptions made in the measurements and analyses performed. Although some specific reference is made to ANTECH and ORTEC products, the notes apply to all similar measurement instruments and techniques.

"ISO-CART Method" (Single, Collimated HPGe Detector)

Description and Characteristics

The ORTEC ISO-CART and other collimated, single High Purity Germanium (HPGe) detector-based systems are the most general and most widely applicable gamma-ray sample and waste measuring instruments. In the simplest of applications, these instruments can be used for far-field measurements of a waste drum, other container, or surface, where a single sample spectrum is analyzed to produce an assay result. The distance to the sample, its dimensions, container materials and container contents (matrix) are used to calculate drum activity.

This method is normally used in conjunction with a mathematical model of the measured sample. The model includes both the geometry and material composition of the sample being measured and any attenuating media between the detector and the sample. In the case of the ORTEC ISO-CART, the mathematical modeling is performed by the program ISOPLUS. (Previously called ISOTOPIC).

Measurement times necessary to achieve specified limits on the contents with such systems depend on a wide variety of factors including HPGe detector efficiency, radioactive background activity levels, activity of the waste item, and the density of the waste material and geometry factors. Counting times range from a few minutes to over an hour. The instrument is the most portable of the gamma-ray assay systems. Typically it uses a portable "Gamma-Gage" style HPGe detector with metal collimator (usually lead or tungsten), digital portable MCA, and laptop computer, all mounted on a mobile, adjustable, wheeled cart. Laser range-finding may be used to facilitate measurement of sample-to-detector distance.

Matrix Attenuation Correction, Shielding and Collimation

Other than the metal collimator surrounding the detector, there is usually no other shielding present. In certain circumstances (e.g., measurements in a drum storage area), additional shielding may be used to shield the object being measured. Occasionally, additional shielding may protect the operator. Gamma-ray transmission sources are not usually used with ISO-CART.

If only a single measurement of a sample is made, the assumption is that the radioactivity and matrix are both relatively homogenous. The field of view of the detector should include the whole sample. If the detector does not "see" the entire sample, the assumption is made that the total sample is the same as the part within the field of view. These homogeneity assumptions can be checked by making repeat measurements from different angles or directions and performing weighted averaging of the results. The ISOPLUS software can be used to plot peak-by-peak differential absorption for selected nuclides to show the inhomogeneities.

Target Sample/Waste Type

The ISO-CART Method and similar instruments are applicable to a very wide range of measurement requirements including hold-up, soil contamination, and waste assay. Virtually any waste object can be measured ranging from small cans to large waste boxes. For low-level waste screening or for the measurement of very low activity waste, additional shielding may be necessary. A turntable may be used to reduce attenuation errors in drum measurements.

Calibration

Every system must be energy and efficiency calibrated. A multi-nuclide (multiple gamma ray lines) source must be used to energy-calibrate the system. The ORTEC ISOPLUS software can use this same source to provide the efficiency calibration if the source activity is certified. The efficiency will be traceable if the source used is traceable to an internationally recognized laboratory. Other systems of this type can provide a simulated efficiency ("sourceless") calibration which will require extra validation steps to be considered traceable.

Measurement Assumptions and Limitations

These measurement methods are based on the largest number of assumptions of all of the gamma-ray waste measurement systems. Both the geometry and characteristics of the sample and the geometry of any intermediate attenuating materials must be correctly represented in the model, which is applied to the measurement situation. The degree of gamma-ray attenuation in the matrix must also be correctly estimated. The system is ideal for replicate sample analysis. Multiple measurements and careful analysis of the differential attenuation plots in the ORTEC ISOPLUS software can produce good results in the hands of a spectroscopist for more complex operations.

Measurement Errors

This measurement method has the largest measurement errors of all of the gamma-ray waste assay techniques because of the extensive assumptions made. With reasonably correct assumptions and good estimates of matrix attenuation, measurement errors are typically 10% to 50%. If the assumptions are not met or if incorrect estimates are used, errors can be much larger, perhaps as large as 500%. This range of errors applies to the ISO-CART as well as similar assay systems using "source-less calibration".

Summary of the "ISO-CART" Method

The ISO-CART Method for waste assay is the most versatile in its ability to measure a wide range of waste containers including large containers and objects that can only be measured in situ. At the same time, the ISO-CART method may be the least precise with the largest errors, due to the many assumptions that must be made, if the sample is highly inhomogenous, or has very low levels of activity. It is the gamma-ray assay method with the lowest instrument cost.

Unlike some similar systems of this type, the ORTEC ISO-CART has diagnostic features that indicate to the user when assumptions are wrong and that the result has large errors. This diagnostic information may often be deduced from the relative intensities of different gamma-ray lines from the same nuclide. However, the method can be considered as the least robust waste assay technique requiring the supervision of a gamma-ray spectroscopy expert for the purposes of data review.

QED – Low-Level, Low-Density Waste Assay System

Description and Characteristics

The ORTEC-ANTECH QED is a shielded waste assay instrument intended for the measurement of low-density waste in 200 litre (55 gal US) drums or similar packages or bags. Other systems of the same general type exist. It is particularly suited for the measurement of low-level waste. Shielding is used to reduce the gamma-ray background, so the QED can be used to sentence or consign waste that may be suitable for free release. The instrument includes an integrated load cell to weigh the waste item and to eliminate manual data entry operations and errors. The measured sample weight is needed to determine sample density and estimate the average gamma-ray attenuation.

The QED consists of three uncollimated HPGe coaxial detectors in a fixed, vertical array. One detector is located next to the mid-plane of the bottom third of the drum, one next to the mid-plane of the middle third and one next to the mid-plane of the top third of the drum. The detectors are most sensitive to gamma rays emanating from the closest third of the drum, but the detectors record gamma rays from the whole drum or package volume, increasing the total detection efficiency. The drum is rotated during the QED measurement. In its basic analysis mode, the QED sums the individual gamma-ray spectra from the three uncollimated HPGe detectors to produce the assay result. In addition, the QED implements a more sophisticated analysis to produce much smaller errors and contains a diagnostic function to identify inhomogeneity in the measured sample.

Matrix Attenuation Correction, Shielding and Collimation

Both the instrument and the sample being measured are shielded, as they are contained inside a steel shield which is typically 100 mm (4 in.) thick. The HPGe coaxial detectors do not have separate shields or collimators. No transmission sources are employed. The attenuation correction is based on the measured drum weight and calculated density or user-supplied matrix material information.

Target Sample/Waste Type

The QED is used to measure low density waste in 200 litre (55 gal US) drums or similar packages or bags. In practice, the maximum waste density for which the QED is suitable is about 1.5 g/cm^3. It can be used up to 2 g/cm^3 with larger errors. The waste should be homogeneous and have a relatively uniform distribution of activity. QED can be used to measure non-homogeneous waste but with larger errors, which cannot be easily quantified.

Calibration

The system is calibrated by placing gamma-ray point sources at different positions in the measurement drum and performing several measurements with different matrix materials. A set of calibration functions (curves) are generated for the efficiency of the system. Each specific calibration function corresponds to a specific matrix density (i.e., gamma-ray attenuation) which is correlated to measured drum weight (or known matrix composition). The result is a volume weighted response function for each matrix. The choice of which calibration function to use on a particular drum is based on the load cell determination of drum weight (density) and any operator knowledge of material type. Measurement errors and hence precision and accuracy are established as a result of replicated calibration drum measurements.

Measurement Assumptions and Limitations

The waste must be of relatively low density, and is assumed to be homogeneous with a uniform distribution of activity. It is also assumed that drum weight is correlated with the average attenuation coefficient of the waste item and that the drum weight can be used to select the appropriate calibration function.

Measurement Errors

Measurement errors are strongly dependent on counting statistics and hence the activity of the waste item and the degree of attenuation of the waste matrix as well as measurement time. For waste items with reasonable counting statistics (relatively high activity and low matrix density) measurement errors (accuracy) are typically 15% to 25%. If the waste item is not homogeneous, for example, the matrix contains regions of strong self-absorption or the activity distribution is very non-uniform, measurement errors can be very large, perhaps greater than 500%.

Summary of the QED Method

The ORTEC-ANTECH QED and similar HPGe multi-detector shielded systems are the most sensitive gamma-ray instruments for the assay of low-level, low-density, low-activity waste. It has the lowest detection limits or minimum detectable activity (MDA) for gamma-ray assay of waste. It can be certified for use to sentence or consign low-level waste for free release. Compared to similar systems, the ORTEC-ANTECH QED provides enhanced performance and smaller measurement errors due to a more sophisticated algorithm for combining the results of the three detectors.

Segmented Gamma Scanner (SGS)

Description and Characteristics

The Segmented Gamma Scanner (SGS) is the most commonly employed technique for gamma-ray assay of nuclear waste. It has an advantage over less sophisticated instruments in that it employs a transmission correction to estimate the average attenuation of the waste item. The SGS is usually employed to measure waste drums, typically 200 litre (55 gal. US) or smaller cylindrical waste containers (cans). An SGS uses one or more shielded and collimated HPGe coaxial detectors and typically a transmission source, either one or one per detector, to determine attenuation.

Most SGS systems employ a single shielded HPGe detector and single transmission source. The transmission source is positioned on the opposite side of the drum to the detector such that gamma-rays from the transmission source pass through the central axis of the drum and are counted by the detector when they emerge from the opposite side of the drum. The drum or waste package is rotated during the measurement.

Typically a drum is divided into 16 vertical segments (smaller containers typically have 13 vertical segments). Each segment is measured separately and the assay result is the sum of the results from the measurement of each segment.

Two measurements are made (two gamma-ray spectra are obtained) for each segment of the drum or waste package. The first is the transmission measurement with the gamma-ray transmission source exposed. The measured transmission gamma-ray spectrum is used to obtain an averaged attenuation correction for the segment. The second measurement is the emission spectrum from the sample for the segment with the transmission source shielded from view.

Gamma-ray peak areas from the sample emission spectrum are used to determine the activity of radionuclides in the segment. The peak areas are corrected for attenuation using the data obtained during the transmission measurement. Alternatively, if no transmission source is used, the activity is determined by comparing the peak areas to the equivalent peak areas obtained from calibration measurements for an assumed equivalent matrix.

In some applications of the SGS, it is possible to combine the transmission and emission measurements for each segment into one measurement.

Matrix Attenuation Correction, Shielding and Collimation

The SGS employs a shielded transmission source with shutter mechanism and a collimated HPGe detector. The detector has a collimator shaped so the detector sees only one segment in height but the width of the drum. Multiple segments can be measured simultaneously using multiple shielded HPGe detectors and transmission sources in order to reduce measurement times.

Some SGS systems have used differential attenuation to determine the attenuation correction in place of a transmission source. This attenuation correction method requires that appropriate gamma ray lines of different energy are available from radionuclides in the waste. This method is the same as that employed in the ORTEC ISO-CART system.

Target Sample/Waste Type

The SGS is suitable for the assay of waste items of low to intermediate density, which are homogeneous within each segment. In practice, the maximum waste density for which a SGS is suitable depends on the diameter of the waste container, the energy of the measured gamma-ray line, and the transmission source energy. For a 200 litre (55 gal. US), this is about 3 g/cm^3.

Calibration

Calibration of the SGS is based on the use of a matrix specific calibration procedure. The calibration involves performing replicated measurements for a given matrix type with small sources typically distributed in re-entrant tubes in the matrix. A separate calibration is performed for each different matrix to be measured. A small degree of inhomogeneity can be included using matrix specific calibrations as the calibration can include some component of the attenuation correction. Alternatively, SGS calibrations may be performed using several specially prepared drum samples, each of which has a uniform distribution of the target radionuclide.

Measurement Assumptions and Limitations

The most important assumption in SGS measurements is that both the gamma-ray attenuation (matrix density) and source distribution are uniform within each segment. This is because the attenuation correction is based on averaging the transmission measurement over the segment as the segment is rotated. As each segment is measured separately, the SGS does not assume homogeneity between the different segments.

Measurement Errors

Because of the effective transmission source correction for gamma-ray attenuation, systematic measurement errors can be smaller than for ISO-CART and QED. For homogeneous samples with relatively low attenuation, errors range from 10% to 30%, although they increase for samples with higher attenuation due to poorer counting statistics. Very large errors of greater than 500% can occur if waste items exhibit gross heterogeneity of gamma-ray attenuation and these errors are not detected by the method. Hot spots (concentrations of activity) also cause large measurement errors. This is because the SGS method assumes that the activity is uniformly distributed and therefore the attenuation correction will be wrongly applied to the measured hot spot. This error will be less significant if the hot spot is on the central axis of the drum. If it is off axis or near the periphery of the drum the resulting errors can be very large.

Summary of the SGS Method

The SGS is the most commonly implemented gamma-ray assay method covering waste from low to intermediate density. It requires matrix specific calibration (a separate calibration for each separate matrix type) and the method is not accurate if the waste matrix or source distribution is not relatively homogenous over each segment. Some allowance for inhomogeneity is provided by the use of matrix specific calibrations. Because of an inability to measure waste with gross heterogeneity, and for improved accuracy and robustness, the SGS technique is being replaced by the use of the TGS.

Shielded Segmented Gamma Scanner

Description and Characteristics

The Shielded Segmented Gamma Scanner is identical to the SGS except that it is contained in shielding, typically 100 mm (4 in.) of steel, around both the sample and the measuring instrument, similar to the shield used in QED. The instrument performs in exactly the same way as the normal SGS but with lower minimum detectable activity (MDA) as the gamma-ray background is greatly reduced.

A common configuration of the Shielded SGS is to use three HPGe detectors in fixed positions so that a drum or waste item is scanned in a short time using only three large segments instead of the normal 16 segments. The detector configuration is similar to that used in QED, but differs in that the detectors are collimated.

Matrix Attenuation Correction, Shielding and Collimation

Both the instrument and the sample being measured are shielded, as they are contained inside a steel shield which is typically 100 mm (4 in.) thick. As a result the HPGe coaxial detector does not have a separate shield, however, the detector does use an SGS collimator. The transmission correction method is the same as used in the SGS.

Target Sample/Waste Type

As for the SGS, the Shielded SGS is suitable for the assay of waste items of low to intermediate density. The waste item is assumed to be relatively homogeneous and have a relatively uniform distribution of activity within each segment. As a result of the shielding, the instrument is also capable of low-level measurements of activity, as for the QED, but now for higher density homogeneous matrices. Due to the collimation, the Shielded SGS is not as sensitive as QED for low density waste assay.

Calibration

Calibration of the Shielded SGS is performed in the same manner as for the normal, unshielded SGS.

Measurement Assumptions and Limitations

As for SGS, the important assumption in Shielded SGS measurements is that both the gamma-ray attenuation and source distribution are relatively uniform over each segment. For the fixed three HPGe detector, three segment implementation, less vertical inhomogeneity is permitted because there are only three segments and each one is assumed to be relatively homogeneous. The other limitation is to do with counting statistics. Poor counting statistics can arise either because of low activity in the sample or high attenuation due to high matrix density.

Measurement Errors

Measurement errors are similar to those for SGS and the minimum detectable activity is lower as the shielding greatly reduces the gamma-ray background, which contributes to the error. For the Shielded SGS, very large errors (greater than 500%) can occur if waste items exhibit gross heterogeneity of gamma-ray attenuation and these errors are not detected by the method. The method suffers from errors due to activity hot spots as for the conventional SGS. Large errors will also arise if a high density object, such as a metal tool, is located in what would otherwise be a uniform low density matrix such as plastic material. If some of the activity is locally shielded by the high density object, the instrument will seriously underestimate the drum total activity and the method does not provide any diagnostic indication that this large error has occurred.

Summary of the Shielded SGS

Like the SGS, the Shielded SGS requires matrix specific calibration (a separate calibration for each separate matrix type) and the method can fail if the waste matrix or source distribution is not relatively homogenous over each segment. Some allowance for inhomogeneity is provided by the use of matrix specific calibrations. Due to the instrument shielding, the device is capable of measuring homogeneous low-level waste with low activity, although with less sensitivity than QED. It is capable of sentencing homogeneous low-level waste for free release. Because of an inability to measure waste with gross heterogeneity, and for improved accuracy and robustness, the Shielded SGS technique is being largely replaced by the use of the Shielded TGS.

Tomographic Gamma Scanner

Description and Characteristics

The Tomographic Gamma Scanner (TGS) is a further extension of the SGS technique, extending the range of applicability permiting the measurement of heterogeneous waste items. For a given matrix, a TGS measurement will result in a lower error than an SGS measurement.

The TGS obtains 150 spectra for transmission and 150 spectra for emission for each segment. The movement of the waste item is also different. Instead of simply rotating the item, it is simultaneously rotated and translated horizontally. In particular, a waste drum travels through 2.5 revolutions while it is translated through a drum radius.

Like the SGS method, the TGS method involves measuring a waste item in vertical segments. ANTECH has implemented the TGS method in an instrument designated the TSGS, so named because it incorporates both SGS and TGS measurement methods. The user can choose to operate the instrument as an SGS or as a TGS. When implemented with a high-resolution safeguards quality HPGe detector, the TSGS can incorporate the PC/FRAM code (developed at LANL), which uses the gamma-ray spectra data to determine plutonium isotopic ratios and uranium/plutonium ratio if appropriate.

The transmission data is analyzed using a maximum likelihood algorithm, which results in a rectangular map in two dimensions (2-D) of the distribution of density or gamma-ray attenuation for each segment.[1] The attenuation map information is then used in the analysis of the distribution of activity in the segment. As in the TGS transmission correction measurement, the TGS emission measurement generates a map or 2-D picture of the activity distribution in the segment. The TGS analysis, combining the data from the transmission and emission maps, results in a very accurate transmission correction for the determination of the activity distribution in the segment. In addition to providing an improved accuracy attenuation correction, the TGS method overcomes the large errors which arise in waste measurement when an off axis activity hot spot is present in the waste. The TGS method is therefore appropriate for the measurement of waste with strong heterogeneity in the distribution of both density (gamma ray attenuation) and activity (hot spots). Both of these situations cause the SGS method to fail.

In addition to the more accurate assay, the TGS method also produces 2-D images or maps of both the distribution of attenuation or density and the distribution of activity in each segment. These are combined in the instrument to produce 3-D images of both attenuation (density variation) and activity distribution for a range of radionuclides in the drum or waste package. These images are useful as part of non-destructive examination (NDE) of waste items.

Matrix Attenuation Correction, Shielding and Collimation

The TGS normally employs a shielded transmission source with shutter mechanism and a shielded and collimated HPGe detector. The detector collimator has a diamond shaped aperture, such that the detector "sees" a relatively narrow "beam" through the waste item. Multiple segments can be measured simultaneously using multiple shielded HPGe detectors and transmission sources in order to reduce measurement times.

Target Sample/Waste Type

The TGS is suitable for the assay of waste items of low to intermediate density. A major advantage of the TGS is that the waste items can be homogeneous or heterogeneous and there is no restriction on the distribution of activity in the sample. Like the SGS, the maximum practical waste density for which TGS is suitable depends on the diameter of the waste container, the energy of the measured gamma-ray line and the transmission source energy, and for a 200 litre (55 gal. US) drum is about 3 g/cm^3. Higher density waste can be measured with larger errors and these errors are always less for TGS than for SGS.

Calibration

Using the TGS data collection and analysis method, a very accurate transmission correction is performed using information from the gamma-ray attenuation map and the source distribution map for each segment of the sample. Normally, calibration is performed by placing samples in an empty matrix. Since all of the attenuation correction is done using the TGS method, matrix specific calibrations are not required. In other words, only one calibration is required for a range of different matrices and matrix specific calibration is not required.

Measurement Assumptions and Limitations

Because of the accuracy of the tomography based transmission (attenuation) correction, no assumptions about the waste matrix are necessary. The TGS method is the most robust gamma-ray assay method requiring no assumptions about the sample.

Measurement Errors

As with SGS, the presence of an effective transmission source correction for gamma-ray attenuation means that measurement errors are small. More importantly, since the TGS method is effectively a point-wise attenuation correction (as opposed to an average over the segment), the correction is much more accurate (and precise) than for all other gamma-ray analysis methods. Unlike the SGS where very large undetected measurement errors can occur, the TGS will always report realistic errors which are typically in the range 5% to 20% depending on the activity of the item and the matrix. Also, the TGS will detect anomalies such as shielding material in a light matrix. It will also identify hot spots (activity concentrations) in a waste drum.

Summary of the TGS

The TGS is the most robust and the most accurate measurement method for low to intermediate density homogeneous or heterogeneous waste using unshielded systems. It makes no assumptions about the waste type or the waste matrix. The method produces realistic measurement errors and is able to correctly identify anomalies that defeat all other gamma-ray assay methods. The 3-D images of the density variation and source distribution inside the waste item are a useful tool for non-destructive examination (NDE).

[1]By comparison, the SGS provides only an average attenuation for the segment, which can lead to large errors when performing the attenuation correction.

Shielded Tomographic Gamma Scanner

Description and Characteristics

The Shielded TGS is basically the same as the TGS but includes shielding, typically 100 mm (4 in.) or more of steel, around both the sample and the measuring instrument, similar to the shield used in QED. The instrument performs in exactly the same way as the normal TGS but with lower errors and lower minimum detectable activity (MDA) as the gamma-ray background is greatly reduced due to the shielding.

Matrix Attenuation Correction, Shielding and Collimation

Both the instrument and the sample being measured are shielded, as they are contained inside a steel box which is typically 100 mm (4 in.) thick. As a result the HPGe coaxial detector does not have a separate shield, however, it does use a TGS diamond collimator. The transmission correction method is the same as used in the TGS.

Target Sample/Waste Type

As for the TGS, the Shielded TGS is suitable for the assay of waste items of low to intermediate density. The waste items can be homogeneous or heterogeneous and there is no restriction on the distribution of activity in the sample. As a result of the shielding, the instrument is also capable of low-level measurements of activity, as for the QED, for heterogeneous as well as homogeneous matrices.

Calibration

As for the TGS, matrix specific calibrations are not required. The calibration is performed by placing relevant radionuclide sources in an empty matrix. The resulting wide ranging calibration is applicable to many matrices.

Measurement Assumptions and Limitations

As for the TGS, no assumptions need to be made about the waste composition or the matrix. The only limitation is due to counting statistics. Poor counting statistics can arise either because of low activity in the sample or high attenuation due to high matrix density, and this is the case with all other gamma-ray assay methods.

Measurement Errors

Measurement errors are smaller than for TGS (typically 5% to 15%) as the shielding greatly reduces the gamma-ray background, which contributes to the error.

Summary of the Shielded TGS

The Shielded TSGS is the most accurate and the most broadly applicable gamma-ray assay instrument for the measurement of radionuclide waste in drums. It has the lowest MDA of any gamma ray instrument, except for the QED measuring low density homogeneous waste. Although slightly less sensitive than QED (due to fewer detectors and collimation), it is capable of sentencing heterogeneous low-level waste for free release. No assumptions are necessary about the characteristics of the waste and the technique has the lowest errors of all gamma-ray assay methods. The Shielded TSGS, combining SGS and TGS operation, is therefore the most robust gamma-ray NDA technique.

Comparison of Gamma-ray Non-Destructive Assay Measurement Techniques

Unshielded Assay Instrument	Shielded Assay Instrument	Uncertainty Range	Worst Case Errors	Applicable Waste Type	Transmission Source	Measure Time (200 L drum)	Maximum Sample Size (typical)
ISO-CART		10% – 50%	>500%	Low density, homogeneous geometry and material types well known.	NO	10 min. typical	Large boxes (e.g., 4'x4'x8') via multiple measurements
	QED	15% – 25%	>500%	Low density, homogeneous. Suitable for free release screening.	NO	10 min. typical	208 Liter Drum
SGS		10% – 30%	>500%	Low/Intermediate density, relatively homogeneous.	Yes or Differential Attenuation	20–30 min.**	208–400 Liter Drum
	Shielded SGS	10% – 30%	>500%	Low/Intermediate density, relatively homogeneous. Suitable for free release screening.	Yes	20–30 min.**	208 Liter Drum
TGS		5% – 20%	50%*	Low/Intermediate density, hetergeneous.	Yes	40–60 min.**	208 Liter Drum
	Shielded TGS	5% – 15%	50%*	Low/Intermediate density, hetergeneous. Suitable for free release screening.	Yes	40–60 min.**	208 Liter Drum

*Larger errors result only from poor counting statistics.
**For a single detector system.

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