BIAS IN SEGMENTED GAMMA SCANS ARISING FROM SIZE DIFFERENCES BETWEEN CALIBRATION STANDARDS AND ASSAY SAMPLES

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ABSTRACT

Recent advances in segmented gamma scanning have emphasized software corrections for gamma-ray self-absorption in particulates or lumps of special nuclear material in the sample. Another feature of this software is an attenuation correction factor formalism that explicitly accounts for differences in sample container size and composition between the calibration standards and the individual items being measured. Software without this container-size correction produces biases when the unknowns are not packaged in the same containers as the calibration standards. This new software allows the use of different size and composition containers for standards and unknowns, an enormous savings considering the expense of multiple calibration standard sets otherwise needed. This report presents calculations of the bias resulting from not using this new formalism. These calculations may be used to estimate bias corrections for segmented gamma scanners that do not incorporate these advanced concepts.

INTRODUCTION

The Segmented Gamma Scanner (SGS) is one of the most widely used nondestructive assay (NDA) instruments. Recent research\(^1\)\-\(^4\) has concentrated on providing more mechanical features, more flexible software, and a partial ability to correct for self-absorption in particulates, or lumps, of special nuclear material (SNM) in the sample. Associated with the so-called “lump correction” in current Los Alamos-developed SGS software is an implementation of a calculation for an enhanced matrix-attenuation-correction factor that is briefly mentioned in Ref. 4. This advanced matrix-attenuation-correction-factor formalism is an important ingredient of modern SGS software. Measurement results will be biased if the unknown sample is packaged in containers of different size and composition than the calibration standards unless this new attenuation-correction-factor formalism is used.

This paper describes this attenuation-correction-factor formalism in more detail and illustrates the magnitude of the biases that may arise if it is not used.

ATTENUATION CORRECTION FACTORS

The standard work in the field of attenuation correction factors [CF\(\text{(AT)}\)] for gamma-ray NDA is that of Parker.\(^5\) I will not attempt to summarize his entire work, only to illustrate some of the main points that are necessary for this discussion. The reader is urged to consult Ref. 5 for a thorough discussion of definitions and methods of calculating CF\(\text{(AT)}\)\(s\). The equation representing the general case of gamma-ray assay is

\[
\text{TCR} = \text{RR} \times \text{CF(RL)} \times \text{CF(AT)}.
\]

where

- TCR = total corrected rate,
- RR = raw rate of data acquisition,
- CF(RL) = correction factor for counting rate-related electronic losses, and
- CF(AT) = correction factor for self-attenuation in the sample.

Quoting from Ref. 5—“If the correction factors are properly defined and computed, TCR is the data acquisition rate that would have been observed if there were no electronic losses and if the sample were changed to a simpler shape (such as a point or line) with the same gamma-ray emission but no self-attenuation. Thus computed, TCR is proportional to the mass of the isotope emitting the gamma ray of interest.” Reference 5 then goes on to discuss the proportionality constant or calibration constant \(K\). When the above corrections are made one can write

\[
\text{TCR} = K \times M
\]

where

- \(K\) = calibration constant, and
- \(M\) = mass of assayed isotope.

The calibration constant is determined by using appropriate standards and includes the effects of detector efficiency, measurement geometry, and gamma-ray emission rates. The CF\(\text{(AT)}\) are determined so that the TCRs for both unknown and standard are those that would have been observed if they had the same nonattenuating spatial configuration in the same position with respect to the detector.

The definition of the CF\(\text{(AT)}\) uses the concept of the Full Energy Interaction Rate (FEIR), which is the rate at which data would be acquired in the full energy peak in the gamma-ray spectrum in the absence of counting-rate-related electronic losses. Thus

\[
\text{FEIR} = \text{RR} \times \text{CF(RL)}.
\]

where the definitions are as given in Eq. 1. Thus Eq. 1 could also be expressed as

\[
\text{TCR} = \text{FEIR} \times \text{CF(AT)}.
\]

The general definition of CF\(\text{(AT)}\) is best described by paraphrasing Ref. 5. We define CF\(\text{(AT)}\) with respect to a specified shape, which is usually not that of the actual sample. The specified shape is usually simpler than the real shape, often a point or a line. If we rearrange Eq. 4 solving for CF\(\text{(AT)}\) and changing the notation somewhat, we have

\[
\text{CF(AT)} = \frac{\text{FEIR}(\mu = 0, \text{Spec \ Shape})}{\text{FEIR}(\mu = 0, \text{Real \ Shape})}
\]

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where

\[ CF(\Delta T) = \text{the correction for self-attenuation with respect to a specified shape}, \]

\[ \text{FEIR}(\mu = 0, \text{Spec Shape}) = \text{the FEIR that would have been measured if the sample were totally nonattenuating (} \mu = 0 \text{) and if it were changed to the specified shape}, \]

\[ \text{FEIR}(\mu \neq 0, \text{Real Shape}) = \text{the actual measured FEIR from the sample}. \]

The CF(\Delta T) is actually determined by calculating the ratio of \[ \text{FEIR}(\mu = 0, \text{Spec Shape}) \] to \[ \text{FEIR}(\mu \neq 0, \text{Real Shape}) \] based on the known sample \( \mu \) (from transmission measurement), the sample-container configuration, and the sample-detector geometry. It is not necessary to know the detector efficiency because only a ratio is calculated. These calculations are typically done by numerical methods for most useful geometries. There are a few elementary cases that can be expressed in an analytical closed form. Again, details of these calculations may be found in Ref. 5.

**CF(\Delta T) FOR A SEGMENTED GAMMA SCANNER**

The SGS provides an example of the most complex correction-factor calculation that is routinely performed. A full three-dimensional sample geometry is considered, including the sample container. "Perfect" vertical collimation is considered explicitly and there is no collimation in the horizontal plane. The detector is modeled as a vertical line at the rear of the collimator to account for gamma rays emitted from sample regions where only a portion of the detector is viewed through the collimator. A more extensive two-dimensional detector model cannot be reasonably calculated. The detector efficiency is considered to be independent of the position or angle of incidence of the gamma ray striking it. The incident gamma ray's finite interaction depth in the detector is also considered in the calculation.

Qualitative arguments for the SGS indicate that if cylindrical samples of different diameter are to be assayed in a common geometry, or if the standards are of different diameter or packaging than the unknowns, then the CF(\Delta T) are best calculated with respect to a nonattenuating line source on the axis of the sample. With this definition, the corrected rates for samples of different diameters and/or packaging can be directly compared and also related to standards of yet other diameters and packaging.

The formal definition for the correction factor used in Los Alamos SGS software is an attenuating cylindrical sample and package with respect to a nonattenuating line source. Implementing this correction-factor formalism in an SGS analysis program requires several steps. A CF(\Delta T) must be calculated as a function of sample transmission for each different combination of measurement geometry and container type. These calculations are lengthy, are carried out off-line, and are not part of the SGS analysis code. They are performed according to the detailed algorithms presented in Ref. 5. Typically we compute CF(\Delta T) at 13 evenly spaced (in log space) values between transmissions of 0.01 and 1.0. The CF(\Delta T) are then parameterized as a function of the sample transmission (T) by fitting the 13 [CF(\Delta T), Transmission] pairs, by least squares techniques, to a power series in \( \ln(T) \).

\[
\text{CF}(\Delta T) = A(1) + A(2)\ln(T) + A(3)\left[\ln(T)\right]^2 + A(4)\left[\ln(T)\right]^3 + A(5)\left[\ln(T)\right]^4 \quad (6)
\]

The five coefficients \([A(1) - A(5)]\) of Eq. 6 are then entered into the SGS analysis code as parameters enabling the code to compute the CF(\Delta T) at any measured transmission value. The typical off-line computational time for 13 [CF(\Delta T), Transmission] pairs is about 1 hour on a MicroVax II. The calculation time of approximately 5 minutes per transmission value clearly makes it impossible to do this portion of the analysis on-line for an assay that may include 15-30 segments or transmission values—thus the above parameterization scheme.

The CF(\Delta T) calculation procedure requires manual data entry for parameters that describe the container-detector geometry. Required data are as follows:

- **Assay energy**
- **Empty container transmission at the assay energy**
- **Distance from the center of the sample to the rear of the collimator**
- **The outer radius of the sample**
- **The inner radius of the container (does not need to be the same as the outer radius of the sample)**
- **The outer radius of the container (to account for the container wall thickness)**
- **The height of the collimator**
- **The depth (or length) of the collimator**
- **The distance from the rear of the collimator to the front of the detector crystal (the interaction depth in the crystal is computed from the input assay energy and germanium absorption coefficients embedded in the software)**
- **Integration parameters (number of radial increments, angular increments, and height increments)**

**TYPICAL CF(\Delta T) RESULTS**

Segmented gamma scanners are typically found in two sizes: a can-sized geometry to measure samples from a few inches diameter to typical 5-gal (19 L) pail sizes, and a barrel or drum-sized system to measure 55-gal (208 L) and 30-gal (113 L) barrels. Examples of these two configurations are shown below in Figs. 1-2, which are drawn to the same scale.

The results of CF(\Delta T) calculations for a 55-gal drum in the above barrel geometry and a 6-in. diam can in the can geometry of Fig. 1 are shown in Fig. 3.
CONTAINER SIZE EFFECTS

To this author's knowledge, SGSs (from any source) installed before about 1989 will not contain the correction factor algorithms discussed above. It may be desirable, for such installations, to estimate bias corrections to allow for the difference in container size between the unknowns and the calibration standards. The main purpose of this report is to illustrate the magnitude of this possible bias.

Figure 4 shows the bias, as a function of the container diameter of the unknown, for the can SGS geometry of Fig. 1 and an assumed calibration standard diameter of 3.75 in. Sample diameters less than the standard produce CF(AT)s that are smaller than the CF(AT) of the standard for a given transmission value. Larger diameter cans (than the standard) produce larger CF(AT)s than the standard does. For most measurements and unknown/standard size differences, this bias may be ~5 ± 3%. Figure 4 illustrates that biases as large as 10% can arise. For cases in which the standard size is different from the 3.75-in. size assumed in Fig. 4, the bias is just the difference between the curves for the two container diameters.

Figure 5 illustrates typical bias at 414 keV for the barrel geometry of Fig. 2. The bias arising from measuring a 30-gal. drum with a 55-gal. drum calibration is quite small, <1% for transmission values >0.01. Even the bias for the 3.75-in. diam can measured in a barrel geometry is not as large as might be inferred from Fig. 4. The effects arising from size differences are relatively smaller for the less compact barrel geometry than they are for the can geometry.

The magnitude of these possible biases is little affected by the energy of the assay gamma ray. Figure 6 shows the difference between CF(AT)s at 414 keV and 186 keV, the two most common assay energies, is about 1% and is essentially independent of transmission for a 55-gal. barrel in a barrel measurement in these geometries. This is a very large correction; the bias that would result without any correction (obviously standard dependent) would be significant.

The vertical dashed line in Fig. 3 at a transmission of 0.01 is meant to represent an approximate dividing line between good measurements (transmissions > 0.01) and less reliable measurements (transmissions < 0.01). The reader should take greatest note of the curves for T > 0.01, to the right of the dashed line. We see the correction factors for these two cases are similar. This is because the relative 1/h^2 differences from extreme parts of the samples do not differ greatly between the two geometries. We also note the magnitude of CF(AT). CF(AT) should not be greater than about 4 or 5 for a valid
SUMMARY

This paper has illustrated the magnitude of typical biases that may result when SGS measurements are made on unknowns with container sizes different from those of the calibration standards. In extreme cases, biases as large as 10% may arise, however, the majority of measurements are likely to be biased at the level of 5% or less. These biases can be avoided completely with the use of SGS analysis software that specifically includes the measurement geometry in the calculation of the attenuation correction factor. This software has been developed and is now in routine field use.

REFERENCES


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