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Low-Resolution Gamma-Ray Measurements of Process Holdup

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1. Introduction

Nuclear facilities worldwide have deposits of nuclear material remaining in processing equipment. After equipment has been used to process material, it is very difficult to remove all traces of the material. Measurements of these residual deposits containing nuclear material are necessary for accounting, safety, process control, and decommissioning reasons. These measurements must be reliable, yet they are generally requested to be accomplished with insufficient resources and with insufficient time. These measurements are performed with portable tools, often by personnel who are encapsulated in anticontamination clothing and apparatus. A variety of operators with different training creates a need for automation and simplicity of use.

Nuclear facilities need portable, automated tools based on gamma-ray spectroscopy to perform plant wide *insitu* assays of special nuclear materials (SNM) deposited in processing equipment. These tools have requirements to

1. acquire and manage several hundred spectra in an hour;
2. produce prompt and reliable quantitative analyses;
3. be self-powered, easily carried, and operated by one use;
4. accommodate varying degrees of user expertise;
5. correct for the effects of equipment variables;
6. tolerate facility variables such as temperature and equipment accessibility; and
7. accommodate the geometry of each measurement.

A new, integrated holdup measurement system designed to meet these requirements has been evaluated quantitatively for *insitu* assay applications.

The hardware for the integrated holdup measurement system consists of a compact gamma-ray detector with collimation and shielding (Russo, Stephens, and Bourret, 1990), a self-contained portable gamma-ray spectroscopy instrument (Halbig et al., 1993), and a palm-size programmable control and data-storage unit. The application software, called the Holdup Measurement System Two (HMSII; S. E. Smith, 1995), masks the sophistication of the hardware and data analysis with a simple user interface. The heart of the integrated holdup measurement system is the generalized-geometry holdup (GGH) calibration and analysis formalism. The GGH formalism is based on simplifying assumptions that each of hundreds of holdup deposit geometries can be interpreted as one of three simple geometric models (point, line, or area) for the purpose of reducing the calibration and analysis effort to manageable proportions.

HMSII assumes the measurement locations have been selected and the necessary information has been assembled to allow rapid replicate measurements. The initial measurement campaign requires more flexible software, more creative users, and lots of information-collection efforts.

The GGH formalism has been tested and verified quantitatively in exercises (Russo, Sprinkle, Jr., and Elmont, 1987; Russo et al., 1990; Wenz, 1992) that have involved one-time calibration and measurement activities followed by equipment cleanouts or alternative assays.

Variations in the accuracy of individual GGH assays derived from these exercises includes the systematic effects of each unique combination of many hardware- and user-determined variables as well as uncertainties from determination of reference values. The automation provided by the HMSII application software eliminates many of these variations.

2. GGH Formalism/Measurement Technique

This formalism dates from early seventies (NRC Regulatory Guide 5.37, 1973; NRC Regulatory Guide 5.23, 1973; Augustson and Reilly, 1974; Kindle, 1976. The authors first encountered it in NRC regulatory guides (1973) and in reports of Los Alamos measurements performed at Kerr-McGee in 1974. The overall philosophy assumes the operator must make many measurements in a short time with limited resources. Therefore, every measurement location is modeled as a point, line, or area source. The method uses portable equipment, but has relied heavily on specialized training for operators who perform the measurements.

SNM can be distributed throughout process equipment in a wide variety of ways. When measuring SNM holdup, it is necessary to interpret radiation data in the context of an assumed (or known) material distribution in order to convert the measurements to quantitative results. The three basic source distributions are

- a small, localized deposit that can be treated as a **point source**;
- a long, narrow deposit (*e.g.*, in a pipe) that can be treated as a **line source** of uniform mass density per unit length; and
- an extended deposit (*e.g.*, on the floor of a glovebox, over the bottom of a large-area duct, in a concrete spill basin, etc.) that can be treated as an **area source** of uniform mass density per unit area.

It is rare when a holdup deposit conforms strictly to one of these ideal distribution geometries. However, practical measurements and analysis may require the assumption of one or more of these distributions in order to get a usable measurement result in a short amount of time.

In some cases, the holdup deposit may be distributed in such a way that assumption of only one of these distributions introduces unacceptable uncertainty and/or bias to the final results. In those cases, it may be advisable to analyze the measurement data, assuming two or all three of the ideal distributions, and average the results. The scatter in the individual results compared to the average may then serve to indicate the magnitude of the uncertainty on the true result.

Some holdup measurements may not lend themselves even to this hybrid approach. Such cases may require a specially designed measurement procedure with unique analysis algorithms. Every effort should be made, however, to minimize the number of such customized measurement tasks in a holdup measurement campaign, if only in the interests of cost-effectiveness. In many such demanding cases, resorting to the simpler analyses associated with the basic source geometries may provide an equally uncertain—but equally good—result that is more defensible and will be more understandable by others who may be required to deal with the same measurement later.

A single calibration check source can be used to generate calibration constants for the three basic geometries (Russo et al., 1995). This approach is attractive because it requires only a small check source (rather than a large number of SNM standards) to equip the measurement system for a variety of measurement scenarios.

To carry this simpler approach further, applying it to the source geometries encountered (but sometimes not fully known) in real facilities, requires experience and creativity on the part of the measurement team as well as a strong dose of practicality and a sense of proportion.

2.1. The Point Source Geometry

This geometry follows the classic inverse-square-law dependence for count rate as a function of source-to-detector distance. It is applicable when the source is small compared with the diameter of the detector's field of view (see Fig. 1).

Fig. 1. Collimated gamma detector placed at distance r_0 from point source of m_0 grams of SNM.

2.2. The Linear Source Geometry

This geometry follows the classic inverse-law dependence for count rate as a function of source-to-detector distance. It is applicable when the source is small in one dimension, but large in the other when compared with the diameter of the detector's field of view (see Fig. 2).

Figure 3 illustrates how combining several measurements of a point source can be used to simulate a line source. The responses from these measurements can be used to create a profile similar to that in Fig. 4.

Fig. 2. Measurement of unknown linear holdup source with linear mass density, λ . At the same perpendicular distance as that used in the calibration, the detector has the same field of view and effective source length parameter, L .

Fig. 3. Geometry for use of point source to establish linear source calibration. The computed effective source length parameter is also indicated.

Fig. 4. Illustration of the measured radial response of a collimated ("real") detector to a point source placed at several equally spaced positions as described in the text and in Fig. 2. Also depicted is the response of an ideal detector whose on-axis response at distance r_0 to the point source is C_0 counts/s. The ideal detector's response to all source positions in its field of view along the line that is a perpendicular distance r_0 from the detector is C_0 counts/s.

2.3. The Area Source Geometry

The line source calibration data can be used to construct a calibration for area sources of SNM. To see this, we consider Fig. 5, which shows the line-source calibration setup from the area source perspective. Only the "positive" source position indices are used, since each source position corresponds to a full annular region centered on the central source position, and this annulus includes the corresponding negative source positions.

Fig. 5. Line source calibration setup from the areal source perspective. Each position of the calibration source of mass m_0 defines an annular region over which a uniform distribution of such sources is visualized. The detector is still placed at a perpendicular distance r_0 from the central source position, to give the central count rate of C_0 as before.

To construct the calibration for an area source, we visualize (at a given source location along the line) successive placements of the calibration source around the corresponding annular area. In the linear calibration exercise, we considered each source position as a linear segment of unit length s with SNM mass m_0 . In the areal calibration, we consider the source m_0 to be situated on a unit area α , giving an areal SNM mass density (ρ_0) of:

$$\rho_0 = m_0/\alpha \text{ (grams SNM per cm}^2\text{)}.$$

We then visualize the successive placement of m_0 in unit areas α around the annulus as depicted in Fig. 6.

Fig. 6. Illustration of the visualized successive placements of m_0 grams of SNM around one of the annular regions defined by the linear source position to simulate a uniform areal distribution of SNM of areal density m_0/α .

2.4. Summary of Generalized Geometry Calibration Equations

It is possible to calibrate the measurement system for the three basic source geometries (point, line, area) using a single point calibration source and a set of measurements on that source (Russo et al., 1995). In the calibration exercise, the quantities that are recorded prior to measurement are

- m_0 , the mass of the point calibration source;
- r_0 , the perpendicular distance between the point source and the detector face, along the detector axis (also the perpendicular distance between the detector face and the line along which the calibration measurements are made); and
- s , the spacing between successive placements of the calibration source along the line.

The basic count rates that must be measured are

- C_0 , the calibration source net count rate with the calibration source a distance r_0 from the detector face and on the detector axis, and
- C_i , the count rates from the calibration source located at several successive positions along a line transverse to the detector axis and a perpendicular distance r_0 from it.

Finally, two parameters must be calculated from the recorded and measured data

- L , the effective line source length parameter; and
- A , the effective area source area parameter.

From this information, the generalized geometry calibrations can be computed, and these are summarized in Table 1 below.

Table 1. Generalized Geometry Calibration Equations

Geometry	Effective Dimension Parameter	Holdup Relation	Calibration Constant [g-s/cm²]
Point	n/a	$m(\text{grams holdup}) = K_p C(r) r^2$	$K_p = \left[\frac{m_0}{C_0 r_0^2} \right]$
Line	$L = \sum_{i=-\infty}^{i=+\infty} s \frac{C_i}{C_0} = 2s \sum_{i=0}^{i=+\infty} \frac{C_i}{C_0} - s$	$\lambda(\text{grams holdup/cm}) = K_l C(r) r$	$K_l = \left[\frac{m_0}{C_0 r_0 L} \right]$
Area	$A = \sum_{i=1}^{i=\infty} a_i \frac{C_i}{C_0} + a_0 = \pi s^2 \left[2 \sum_{i=1}^{i=\infty} i \frac{C_i}{C_0} + 1/4 \right]$	$\rho(\text{grams holdup/cm}^2) = K_a C$	$K_a = \left[\frac{m_0}{A C_0} \right]$

3. Evaluation of Portable Gamma-Ray Holdup Assay Technologies

The Safeguards Assay Group at Los Alamos National Laboratory conducts an annual training seminar in holdup measurements for DOE personnel. Each year, as many as 24 people attend this seminar, where they calibrate for and measure holdup deposits. As part of the seminar, the students select the measurement geometries, detector-to-sample distances, and the number of measurements for several items with simulated holdup. The students have a variety of pipes, ductwork, glovebox equipment, and simulated spills to measure. We have recorded the results of their measurements for four years (Russo et al., 1995). During these seminars, we have also demonstrated the HMSII system. For the HMSII demonstration, the students perform the holdup measurements at locations and distances that were defined by the HMSII system administrator.

These reported results support the general opinion that holdup measurements have measurement uncertainties of the order of 20–50% at best. It is worth remembering that these measurements are performed in the presence of instructors and with little time pressure, and therefore might be better than those resulting from measurements of unknowns in facilities.

Phyllis Russo (1995) also lists the results obtained by two operators, who each performed five measurements of each item with the automated HMSII system. The standard deviations are much smaller for the automated measurements. We would expect the standard deviations to be smaller for automated measurements because there should be less variation with positioning and with selection of measurement geometry. It seems that measurement precisions can be improved to 15% or better with the help of automation.

4. In-Field Applications

We have now developed prototype software for use in the initial set of measurements. When the first set of holdup measurements are made, the correct application of this technique requires experienced, well-trained users who make many technical decisions in the field, often with inadequate information. The users must also collect as much information as possible from the facility operators and engineering drawings about intervening attenuators and possible sources of background. We plan to use this prototype software in low-enriched uranium and plutonium fuel fabrication plants to make the original measurements. The replicate measurement points will

generally be selected as a subset of the original survey. After the measurement point locations are selected, based on the initial measurements and the collection and analysis of additional information about geometry, attenuation, and backgrounds, we will install HMSII to help the facility keep track of the thousands of measurements needed on a bimonthly basis.

5. Summary

This tool, consisting of software with a compact detector, an M3CA, and an Intermec datalogger

1. acquires and manages several hundred spectra in an hour;
2. produces prompt and reliable quantitative analyses;
3. is self-powered, easily carried and operated by a single user;
4. accommodates varying degrees of user expertise;
5. corrects for the effects of equipment geometry;
6. corrects for the effects of equipment attenuation;
7. tolerates facility variables such as temperature fluctuations and equipment accessibility;
8. has been subjected to quality testing under field conditions; and
9. does not require extensive specialized training for the operators.

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