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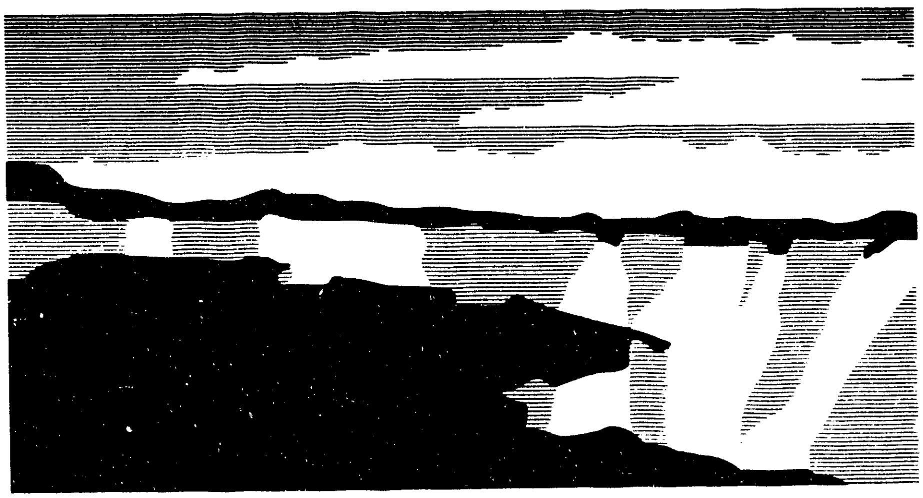

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DEVELOPMENT OF A TOMOGRAPHIC INSTRUMENT FOR GAMMA-RAY NONDESTRUCTIVE ASSAY*

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Transmission-corrected gamma-ray nondestructive assay (NDA) instruments are used routinely throughout the Department of Energy complex for safeguards and waste measurements. The most widely used of these instruments is the Segmented Gamma Scanner (SGS) that was developed by the Los Alamos Nuclear Safeguards program in the early 1970s to determine the radioisotopic content of waste.[1] The SGS is an axial scanner that utilizes a collimated HPGe detector to measure the emission of gamma rays from axial segments over which the sample is assumed to be uniform and homogeneous. The transmission of gamma rays through each segment is also measured at several energies to provide a correction for sample self-attenuation. During the measurement, the sample is rotated to minimize bias caused by heterogeneities in the emitting material and matrix.

SGS assays are accurate for low-density samples and also for high-density samples that are known to be uniform and homogeneous. However, for dense, heterogeneous samples, substantial bias is observed in SGS assays. To assay heterogeneous samples, knowledge of the distribution of emitting and attenuating materials is required. As a result, we are developing a tomographic instrument to assay samples for which the assumptions of the SGS analysis are grossly violated.

This instrument, known as the Tomographic Gamma Scanner (TGS), has the same basic components as the SGS, including a HPGe detector, a transmission source, and a mechanism to rotate and elevate the sample. However, an additional mechanical motion has been added that allows the detector to move in the direction transverse to the sample axis. This additional motion in combination with more stringent detector collimation enables the TGS to acquire three-dimensional transmission and emission tomographic projection data from which the distributions of emitting

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and attenuating material can be determined. This spatial information provides a detailed correction for sample heterogeneities that results in more accurate assays.

Our work on the development of the TGS has emphasized the role of the TGS as an NDA instrument. Accurate determination of the quantity of emitting material is the primary goal. Precise determination of the distribution of emitting materials is a secondary and potentially conflicting objective. Consequently, design considerations and analysis techniques differ from those of computerized tomography applied to medicine and nondestructive testing.

An experimental TGS developed by the Los Alamos Nuclear Safeguards program has been used to assay 208-ℓ drums containing plutonium.[2,3] In the analysis of TGS data, the waste container is coarsely divided into rectilinear volume elements (voxels). Typically, the drum is divided into 16 layers, each containing 100 voxels. Using a continuous scanning protocol, 100 to 150 transmission and emission projections are measured per layer. Results of assays of 208-ℓ drums with dense and highly heterogeneous matrices indicate that accurate assays of difficult samples can be obtained with precision and throughput approaching that of the SGS.[4] The use of a continuous scanning protocol was found to considerably improve throughput over discrete protocols (for example, conventional translate-rotate) in which considerable overhead is incurred while the scanner moves to the next measurement point.

The analysis and modeling package (TGS-FIT) used with the experimental TGS includes a rectilinear discretization of the sample volume, a constrained least squares approach to reconstruct linear attenuation coefficient images from transmission data, and a maximum-likelihood expectation-maximization (ML-EM) algorithm for reconstructing emission images.[5] A "full Beer's law" attenuation model that utilizes interpolated attenuation coefficient images is used to modify the emission transition-matrix for sample self-attenuation at each energy. TGS-FIT has been implemented in C on an IBM-PC equipped with an I860 array processor.

An advanced modeling and analysis code system called TCNDA for general transmission-corrected gamma-ray NDA has also been developed and applied to study the TGS, the SGS, and intermediate scanning modes. TCNDA features include:

1. a finite elements model of the sample with arbitrarily shaped voxels to accurately model sample shape and contents,

2. a conformal mapping procedure to generate grid points for the finite elements model based on transmission images and *a priori* information about sample shape,

3. a general-geometry Monte Carlo model of the spatial response for general collimator/detector designs,

4. a maximum likelihood reconstruction algorithm that accounts for both the error structure in the primary signal and in the measured background,

5. an algorithm to correct assay results for bias caused by self-attenuating particles (lumps) of emitting material, and

6. and an algorithm to determine assay precision that includes the effect of lumps.

Time-consuming modules of TCNDA, including the spatial response modeler, have been implemented in parallel with dynamic load balancing on a heterogeneous network of workstations using Parallel Virtual Machine.[6] TCNDA has been validated with data from the experimental TGS (Fig. 1). We are using TCNDA to study the effect of collimator design and scanning protocol on TGS performance, to identify sources of systematic errors associated with sample discretization, and to investigate grid-refinement schemes for optimal reconstructions.

Bias in TGS assays of transuranic waste (TRU) waste occurs when the emitting material is distributed within the sample as highly attenuating particles (lumps). The bias occurs because the transmission correction accounts only for bulk attenuation by the sample. However, gamma rays produced within the sample are attenuated by both the lumps and the bulk of the sample. This causes assay results to vary with energy. For plutonium, the bias is severe for lumps on the order of 1 mm in diameter. Increasing the transmission-mode resolution to resolve the lumps is probably impractical, even if an x-ray source is utilized.

Instead, we have developed a weighted least-squares technique that uses assay results for several gamma-ray energies to correct for bias because of lumps.[7] The fitted model features a parameterization of the energy variation of effective lump size that allows the correction to be performed for a wide range of lump-size distributions. The correction has been found to significantly reduce the bias in assays of plutonium-bearing samples, usually to within 5% of the known value. The correction can be applied to any volume within a sample, provided the energy variation observed is not the result of other phenomena (for example, matrix effects). Because the bias due to matrix heterogeneities is small for the TGS, the correction can be applied to the entire sample volume. Because the correction does not have to be applied on a voxel-by-voxel basis, the determination of assay precision is greatly simplified.

The next step in TGS development is the construction of a prototype scanner, scheduled for completion in the summer of 1993. The prototype TGS is a flexible research platform that will provide further information on the capabilities and limitations of gamma-ray NDA. The prototype has a generalized scanning protocol to perform discrete and continuous scans of a variety of container geometries. A 70%-efficiency HPGe detector along with a flexible collimator geometry has also been included in the design. The transmission source (^{75}Se) was selected to allow simultaneous acquisition of transmission and emission projections for TRU waste. Analysis of TGS data will occur on a 66-MHz 80486-PC equipped with an I860 array processor. Features of both TGS-FIT and TCNDA, including the ability to assay multiple isotopes, will be incorporated into the analysis software.

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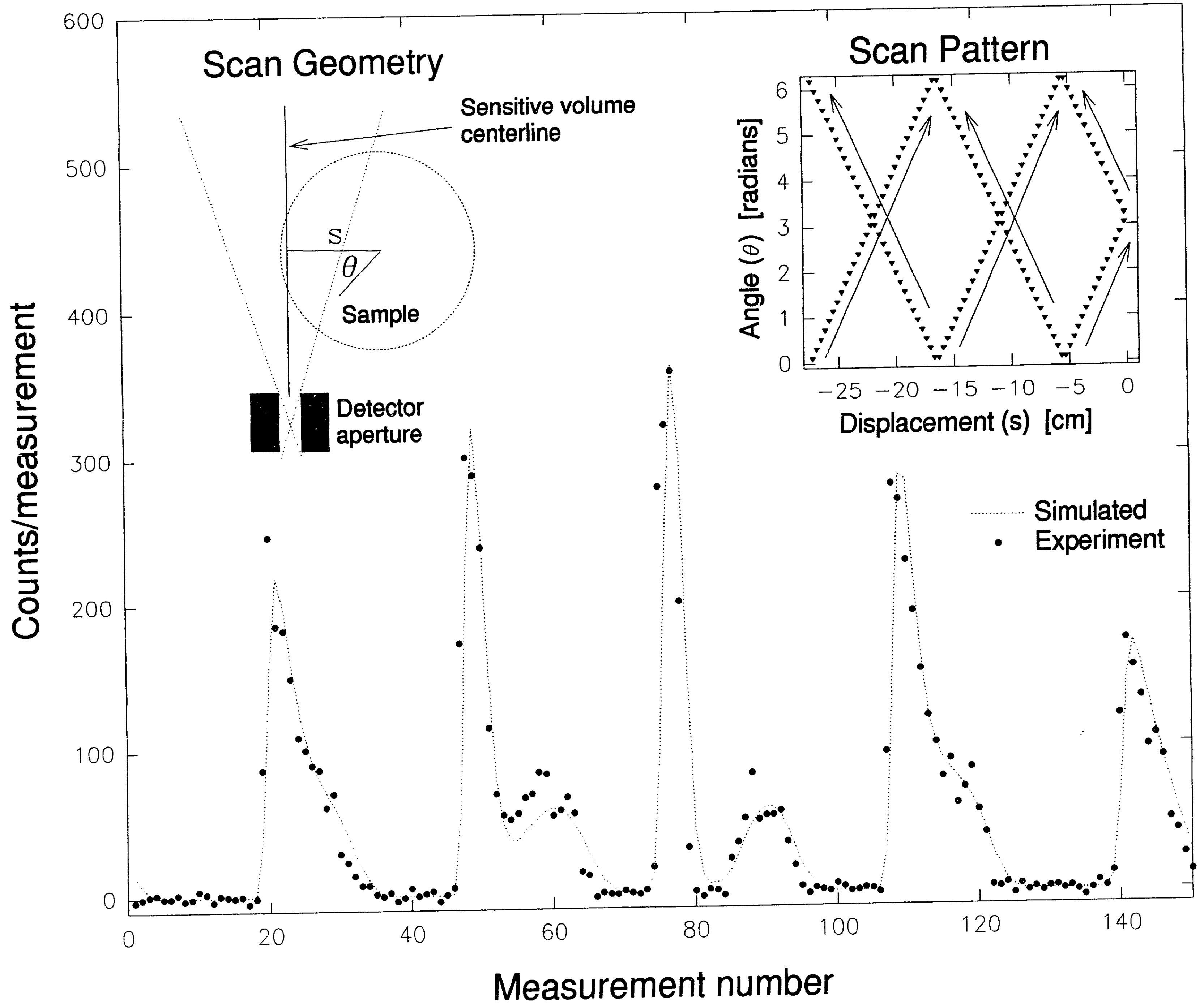
Fig. 1. Simulated (TCNDA) and experimental emission measurements of a layer of a 208-ℓ drum containing a 50-g plutonium source. The measurements were obtained using a scanning protocol in which the sample was translated and rotated continuously. The distribution of measurement points in displacement-angle space corresponds roughly to a 15 translation by 10 rotation discrete first-generation scan.



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Angle (θ) [radians]
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