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SIMULATED NEUTRON TOMOGRAPHY FOR NONDESTRUCTIVE ASSAYS*

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Abstract

The results of an on-going research project to assess the use of resonance-neutron computed-tomography for the assay of fissile materials will be discussed. A simulation study has indicated the potential value of this technique for the nondestructive inspection of a standard to be fabricated by the National Bureau of Standards.

Introduction

The National Bureau of Standards (NBS) has begun a project at the Los Alamos Scientific Laboratory (LASL) for simulation of neutron computed-tomography. It is the goal of this research to provide investigators at NBS with realistic simulations of expected tomographic reconstruction quality given the expected size of objects to be reconstructed, the resolution of the reconstruction, and the nature of the detectors to be used. These have been taken into consideration in the simulations that follow.

The simulations to be presented were used to assess the feasibility of using resonance-energy neutron beams to generate tomographic images of fissile materials. Since tomographic images are quantitative, the hypothesis to be tested was that of matching the detector to the material to be detected so that fissile material inside a closed container could be identified. For example, a ^{235}U fission detector would be used to locate and identify the presence of all ^{235}U in the container. The same procedure would be repeated for ^{239}Pu and ^{233}U .

Proposed Neutron Tomography Experimental Configuration

A possible future NBS experimental apparatus is shown in Fig. 1. It consists of a neutron source and a thick variable-width source collimator designed to produce a pencil beam of primary neutrons for irradiation of a standard. The standard may consist of a 23.6-cm-diameter iron cylinder with various 1-cm-diameter cylinders of fissile isotopes inside. The large cylinder will be mechanically moved and rotated to produce projection data for a conventional filtered back-projection reconstruction algorithm¹ with a parallel rather than fan beam radiation pattern. The detector collimator would be similar in design to that of the source collimator. The initial detectors would be sensitive to the fission cross sections for ^{235}U , ^{233}U , and ^{239}Pu . The projection data acquisition and mechanical aspects of the system will be controlled by a minicomputer. Projection data would then be reconstructed.

Initial reconstructions will be undertaken at a 128 by 128 resolution over the proposed standard. This corresponds to a pixel size of 1.85 mm. It was this experimental configuration which we simulated in our study.

Neutron Tomography Simulation

The simulation that was performed was based on the following assumptions:

1. The materials were homogeneous and contained only a single nuclide.
2. The exponential absorption law holds.
3. The detectors were fission chambers and their response was proportional to the number of incident neutrons that underwent a fission reaction.

A multigroup approach was taken in which the incident neutron spectra were assumed to be divided into a number of almost equal lethargy intervals. The basic cross section and group structure was derived from the 240-group MINX (Multigroup Interpretation of Neutron Cross Sections) library used at LASL for neutron transport calculations.² From the MINX library, a 38-group structure was defined over a range from thermal (less than 0.025 eV) to 2 keV. This range was determined by experimentation to provide the maximum in sensitivity for the fissile materials to be differentiated. A uniform weight was used whenever two or more groups had to be averaged to produce a cross section for the simulation groups. The standard being simulated was generated from a combination of appropriately sized circles placed at specified locations relative to each other. The regions so defined were assumed to consist of a uniform distribution of known density and total neutron cross section. The tomographic detector(s) consisted of fissile material(s) with known fission cross section(s).

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The detector recorded a number proportional to the number of transmitted neutrons that underwent a fission reaction in the detector. No allowances for (n,2n) or (n,n) interactions within the standard or the detector were made. The simulation program assumed a monoenergetic neutron flux with an energy equal to the average energy in the group and an intensity equal to the value of the normalized spectra at that energy. Each projection used in the reconstruction consisted of 128 points, and the projections were gathered over 180 degrees ($\theta = 1, 180$). Each projection point was computed in the following manner. At each projection point, J, the neutron flux passing through the phantom was computed. The total neutron signal $TOT_{\theta}(J)$ was recorded with different neutron detectors for each of the isotopes previously described.

The following formula summarizes this accumulation:

$$TOT_{\theta}(J) = \sum_{L=1}^{38} SN(L) \cdot D_K(L) \cdot e^{(-PL_{\theta}(L,J))} \quad (1)$$

for $J = 1, 128$

where $\theta = 1, 180$ $K = 1, 3$

SN is the number of neutrons emitted by the source per energy group L.

D_K is the fission detector sensitivity to a specific isotope (K) as a function of energy bin L.

PL_{θ} is the integrated neutron pathlength through the phantom at projection point J, angle θ , and energy group L. The total neutron cross sections used to compute these PL are shown in Fig. 2.

Each of three detector responses D was computed as a function of energy group L as follows:

$$D_K(L) = 1 - e^{-F_K(L) \cdot x} \quad \begin{matrix} L = 1, 38 \\ K = 1, 3 \end{matrix} \quad (2)$$

where $F_K(L)$ is the fission cross section of each isotope (K) as shown in Fig. 3, and x is the assumed fission detector thickness (1 mm). Each total detected signal $TOT_{\theta}(J)$ was then converted to total neutron pathlength $TPL_{\theta}(J)$ by the following equation:

$$TPL_{\theta}(J) = \ln(SUM/TOT_{\theta}(J)) \quad (3)$$

for $J = 1, 128$; $\theta = 1, 180$,

where SUM represents the sum of all source neutrons $SN(L)$ over the total energy spectrum.

Poisson noise was added to each projection point $TOT_{\theta}(J)$ prior to the use of Eq. (3) to simulate neutron noise characteristics.³ These operations were repeated for each of the 180 projections mentioned earlier. In order to determine the sensitivity of the phantom to each of three separate fission detectors, $D_K(L)$ was successively replaced, and the projection formation repeated.

The reconstruction of the noisy projections $TPL_{\theta}(J)$ was then undertaken for each detector. Each projection was filtered using a filter with the following frequency domain response prior to back projection:

$$H(f) = f \quad ; \quad 0 \leq f \leq f_n/4 \quad (4)$$

$$= \frac{f_n}{8} \left[1 + \cos \left(8\pi(f - f_n/4) / 3f_n \right) \right] \quad ; \quad f_n/4 \leq f \leq f_n$$

The Nyquist frequency f_n is 0.27 pixels/mm in these simulations. The first half of Eq. (4) is the analytically exact phaseless differentiator used in the original back projection algorithm first derived by Radon. The modification represented by a Hanning roll-off in the second half of the equation is necessary to reduce ringing artifacts and the effects of

noise. The ringing artifacts are present in the reconstructions at material boundaries of high contrast such as exist between these dense fissile materials and air. These filtered projections $\overline{TPL}_\theta(J)$ were used to reconstruct the tomographic cross section $TM(x,y)$ using the back projection algorithm:

$$TM(x,y) = \frac{\pi}{180} \sum_{\theta=1}^{180} \overline{TPL}_\theta(x \cos \theta + y \sin \theta) \quad , \quad \begin{array}{l} x = 1,128 \\ y = 1,128 \end{array} \quad (5)$$

where θ s are 180 equally spaced angles over 180° . x and y are indices of the discrete reconstruction plane.

Reconstruction Results

Figures 4a, 4b, and 4c show typical reconstructions. These reconstructions were created with the fission detectors sensitive to each of the fissionable materials as described earlier. Figures 5a and 5b show single lines along the x- and y-axes of the reconstruction using the ^{235}U fission detector. In each figure, the ^{235}U cylinder is shown centered at pixel (64,64) in the 128 by 128 reconstruction plane. Each pixel represents a 1.85-mm-square area. Figures 5c through 5f show similar plots for the fission detectors sensitive to ^{235}U and ^{239}Pu , respectively. Table 1 is a matrix which shows the peak amplitude of the responses of each cylinder as a function of the chosen detector.

Table 1
Various Response Peaks

Detector Type	Peak Response		
	^{233}U	^{235}U	^{239}Pu
^{233}U	.312	.240	.193
^{235}U	.264	.264	.201
^{239}Pu	.288	.264	.265

Conclusions

The following conclusions can be drawn. The cylinder simulating ^{235}U always exhibits the highest response irregardless of the detector chosen. However, the response markedly decreases for this cylinder when the other fission detectors are used. When the detector sensitive to ^{239}Pu is used, there is a definite increase in the corresponding cylinder's peak amplitude over levels present when the other detectors are used. These results are encouraging. In no case does the response of the iron container approach that of the isotopes present inside the container.

An *a-priori* hope might have been that the major diagonal of Table 1 always yielded a peak response. While this was not quite the case, the changes in response with each detector were significant.

These simulations indicate that differentiation of fissionable materials by neutron tomography can be successful. Nondestructive quantitative assays of sealed radioactive containers may be possible using this technique. Also the simulation code developed in this research can be used in future work where it is desirable to model broadband spectral source and detector configurations.

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Fig. 1. Proposed NBS Tomography System

Fig. 2. Total neutron cross sections

Fig. 3. Neutron fission cross sections

Fig. 4a. Tomographic reconstruction using fission detector sensitive to ^{233}U .

Fig. 4b. Tomographic reconstruction using fission detector sensitive to ^{235}U .

Fig. 4c. Tomographic reconstruction using fission detector sensitive to ^{239}Pu .

Fig. 5a. Reconstruction along x-axis using fission detector for ^{233}U .

Fig. 5b. Reconstruction along y-axis using fission detector for ^{233}U .

Fig. 5c. Reconstruction along x-axis using fission detector for ^{235}U .

Fig. 5d. Reconstruction along y-axis using fission detector for ^{235}U .

Fig. 5e. Reconstruction along x-axis using fission detector for ^{239}Pu .

Fig. 5f. Reconstruction along y-axis using fission detector for ^{239}Pu .