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Report No.: **Y/LB-16,015, R1**

ESTIMATING ATTRIBUTES OF NUCLEAR WEAPON AND OTHER FISSILE MATERIAL CONFIGURATION USING FEATURES OF NUCLEAR MATERIALS IDENTIFICATION SIGNATURES

J. T. Mihalczo
J. K. Mattingly
J. A. Mullens
T. E. Valentine
R. B. Perez

Nuclear Materials Management and
Storage Program Office

August 24, 1999

Prepared by the
Oak Ridge Y-12 Plant
Oak Ridge, Tennessee 37831
managed by
Lockheed Martin Energy Systems, Inc.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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DEPARTMENT OF ENERGY

DISCLAIMER

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J. T. Mihalczo, J. K. Mattingly, J. A. Mullens, T. E. Valentine, R. B. Perez

Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee, 37831 USA
(423) 574-5577

ABSTRACT

This brief describes a strategy that, when implemented, will allow the attributes, i.e., the physical properties, of nuclear weapon and other configurations of fissile material to be estimated from Nuclear Material Identification System (NMIS) signatures for arms control, treaty verification, and transparency purposes. Attributes are estimated by condensing measured NMIS signatures into "features" that approximately represent physical characteristics of the measurement such as gamma-ray transmission, induced fission, etc. The features are obtained from NMIS signatures to estimate quantities related to gamma and neutron transmission through the inspected item and gamma and neutron scattering and production via induced fission within the inspected item. Multivariate, i.e., multiple-feature, linear models have been successfully employed to estimate attributes, and multivariate nonlinear models are currently under investigation. Attributes estimated employing this strategy can then be examined to test the supposition that the inspected item is in fact a nuclear weapon.

INTRODUCTION

Most previous implementations of NMIS verified the declared identity of an inspected nuclear weapon component by comparing the signatures measured from the inspected component to a prototypical template of signatures measured from a component whose identity is already known. Although this "template-matching" technique has been widely successful in domestic nuclear materials control and accountability (NMC&A) applications, it suffers from an obvious difficulty when applied in support of a transparency agreement between nations or parties who do not wish to share any classified information. How can one be certain that the measured signatures are those of a nuclear weapon? That is, how can each prototypical signature be *verified* to be legitimate? There must be some assurance that each set of measured signatures was indeed acquired from a nuclear weapon component.

This brief describes a strategy to estimate from NMIS signatures the attributes of an inspected item to support methods to verify that it is in fact a nuclear weapon component. In this context, "attribute" denotes a physical property of a particular weapon or component. Attributes of interest for transparency typically include the relative size and shape of the component, and the relative mass and thickness of the component's principal constituents. The composition (e.g., the average enrichment) of the component's constituents can be subsequently inferred from the masses of the constituents.

ATTRIBUTE ESTIMATION FROM FEATURES OF NMIS SIGNATURES

Attribute estimation has been accomplished by condensing measured NMIS signatures into "features" that approximately represent physical characteristics of the measurement. These features were obtained from NMIS signatures to estimate quantities related to gamma and neutron transmission through the inspected item and gamma and neutron scattering and production within the inspected item. These features do not only significantly condense the NMIS signatures; they also tend to be very robust to perturbations in positioning and instrumentation response.

Figures 1a and 1b illustrate the concept of NMIS signature features. Both signatures shown were acquired from an active measurement of a uranium-metal casting. The first signature is the covariance between the ^{252}Cf-source signal and a detector signal. It represents the time-distribution of detector counts following a ^{252}Cf-fission event and depends on gamma-ray transmission, neutron transmission, and Cf induced fission production. Obviously, this signature can be measured only during an active measurement. The second signature is the covariance between two detector signals; it represents the time-distribution of counts in one detector following a count in the other detector. It depends on gamma-gamma coincidences, neutron-neutron coincidences, and neutron-gamma coincidences. This signature may be measured during both active and passive measurements.

Table 1 lists several features that have been successfully used to approximately predict attributes in recent measurements. Observe that the features are defined as a ratio to a relevant "calibration" measurement. For active measurements, the calibration is obtained by performing the measurement with the inspected component absent and the source and detectors located as they were during the measurement of the component. For passive measurements, the calibration is obtained by passively measuring a ^{252}Cf-source in air at the location of the component and the detectors located as they were during the measurement of the component. By defining the features in terms of ratios to relevant calibrations, the effect of variations in solid angle and detection efficiency are partially mitigated.

Shape recognition and size estimation can be accomplished via active gamma/neutron axial (and perhaps transverse) scans of the inspected item. It has been ascertained that the shape of the inspected object can be correctly recognized from the gamma and neutron transmission profile acquired during such a scan. Furthermore, a recently developed technique that analyzes the gamma transmission profile acquired during a scan was capable of estimating the size of inspected objects to within ~20% of its actual size.

Mass, thickness, and composition estimation can be accomplished by first testing individual and combined features for correlation with known attributes of a collection (hereafter referred to as the "training set") of weapon components and unclassified objects (e.g., uranium-metal castings). This identifies those features relevant to the estimation of each individual attribute. Subsequently, a variety of modeling techniques can be applied to estimate each attribute from the relevant features to identify the model that yields the minimum relative error and uncertainty.

Finally, the resulting models can be applied to "unknown" objects, i.e., weapon components and unclassified parts that were not members of the original training set, to test the models for accuracy and generality.

Recent experimentation with this technique was successful in measurements performed at the Oak Ridge Y-12 Plant.* By using a relatively small training set, five or fewer signature features, and multivariate linear models, the mass and thickness of constituents were correctly predicted to within ~25% of the actual attribute. There has not yet been an opportunity to test the models for generality by applying them to items outside the training set.

STRATEGY TO DEVELOP MODELS TO ESTIMATE ATTRIBUTES

The strategy to develop a general method to estimate attributes may be partitioned into three equally important tasks.

1. Collect the training set. The training set of fissile materials should encompass as broad a range of shape, size, mass, thickness, and composition attributes as is feasible. Therefore a greater variety of weapon components should be measured, and a variety of unclassified fissile material configurations should be measured. This will help ensure that the subsequent models are general, i.e., that they are capable of correctly estimating attributes regardless of the inspected item's configuration

2. Develop the predictive models. Although multivariate linear models have been successful at predicting mass and thickness attributes from signature features, the models are non-optimal in a number of respects. First, only a few signature features have been tried; several other potentially useful features have been identified but are as yet are untried. Second, the predictive features were selected by trial-and-error to minimize the relative error; the predictive features used are not necessarily the best ones. An exhaustive search of all possible feature combinations should be initiated to identify the optimal linear model (this can be automated relatively easily and can be accomplished fairly rapidly). Third, the predictive features used are correlated with one another such that the resultant models yield unrealistically large uncertainties in the estimates. This problem can be mitigated by standard techniques including singular value decomposition. Fourth, only multivariate linear models were used. There is strong evidence that multivariate nonlinear models should be evaluated. Nonlinear models should be developed using genetic programming techniques to select the best nonlinear algebraic (and perhaps transcendental) combinations of features.

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* This NMIS methodology has been used to characterize the shape, mass, and hydration of a large (estimated to be 1300 kg from gamma ray spectrometry) uranyl fluoride deposit in a large pipe at the former Oak Ridge Gaseous Diffusion Plant that alleviated nuclear criticality safety concerns and led to the safe removal of the deposit. NMIS also has application in general in nuclear material control and accountability. This methodology has had a wide variety of nuclear criticality safety applications since 1968 at many U.S. DOE sites.

3. Test the models on unknowns. The models developed in the previous subtask should be tested using measurements on a variety of weapon components and unclassified objects that do not belong to the original training set. These “unknown” items should span the range of attributes present in the original training set. This will establish the generality of the models. Furthermore, some of these items should have attributes outside the range of the original training set. This will establish the limits of extrapolative estimation using the models

CONCLUSIONS

Given the recent successes in predicting attributes from NMIS signature features, it is expected that this strategy will produce a sufficiently accurate, robust algorithm for estimating the attributes of nuclear weapon components and unclassified objects for arms control monitoring purposes. It must be noted however that such a method will not produce estimates of attributes with accuracies that would be required for nuclear weapon stock pile maintenance, life extension programs, or assist in new weapons production activities. These attributes can be subsequently examined to test the supposition that the item is in fact a nuclear weapon component. In other words, if the inspected item is declared to be a weapon component and has the attributes of a weapon component, then the declaration may be presumed legitimate with a fair degree of certainty. Methods to partition “attribute-space” (i.e., given set of attributes that distinguish a weapon from an unclassified configuration) in order to categorize an inspected item as “weapon component” or “other” are not proposed as part of this strategy, although a preliminary partitioning will probably become evident during the development of the models. Such a task should probably be undertaken subsequently to successful completion of the strategy.

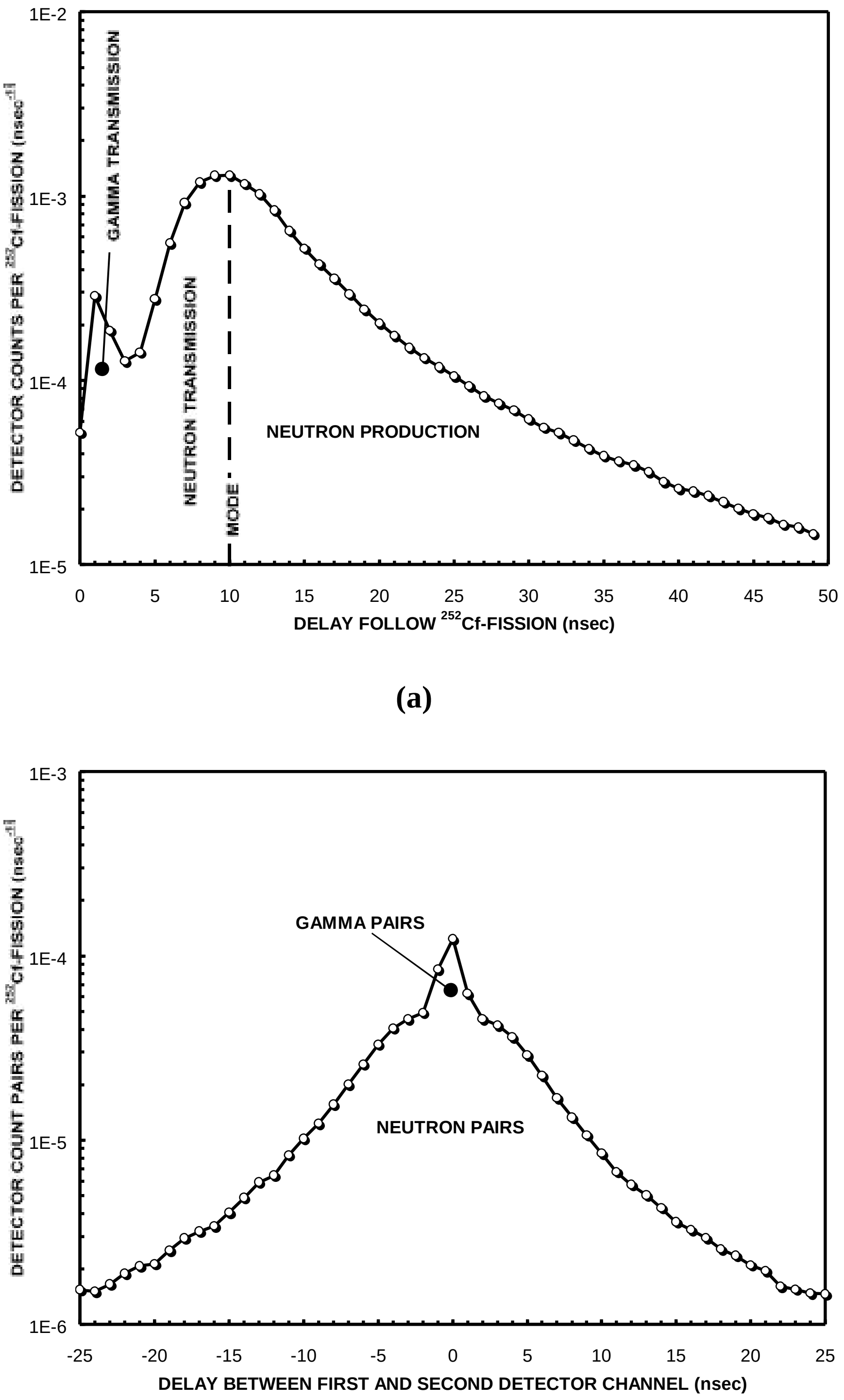

Figure 1. Covariance between the ^{252}Cf-source and one detector (a) and covariance between two detectors (b) acquired during an active measurement of a uranium-metal casting.

Table 1. Definition of NMIS signature features used to estimate mass and thickness attributes

Feature	Definition
Gamma transmission[a]	Ratio of area under component transmitted gamma peak to area under calibration transmitted gamma peak
Neutron transmission[a]	Ratio of area under component neutron peak before mode to area under calibration neutron peak before mode in component neutron peak
Neutron production[a]	Ratio of area under component neutron peak after mode to area under calibration neutron peak after mode in component neutron peak
Gamma pairs[b]	Ratio of area under component gamma pairs peak to area under calibration gamma pairs peak
Neutron pairs[b]	Ratio of area under component neutron pairs peak to area under calibration neutron pairs peak
Log gamma attenuation	$\log_{10}$ inverse of gamma transmission
Log neutron attenuation	$\log_{10}$ inverse of neutron transmission
Log neutron production	$\log_{10}$ of neutron production
Neutron transmission over gamma transmission	Neutron transmission divided by gamma transmission
Neutron production over gamma transmission	Neutron production divided by gamma transmission
Neutron production over neutron transmission	Neutron production divided by neutron transmission
Gamma pairs over gamma transmission	Gamma pairs divided by gamma transmission
Gamma pairs over neutron transmission	Gamma pairs divided by neutron transmission
Neutron pairs over gamma transmission	Neutron pairs divided by gamma transmission
Neutron pairs over neutron transmission	Neutron pairs divided by neutron transmission

[a] From covariance between source and detector.

[b] From covariance between two detectors.