On Attributes and Templates for Identification of Nuclear Weapons in Arms Control

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ABSTRACT
Two approaches have been proposed for arms-control transparency measurements: *attributes* and *template* comparisons. Characteristics distinguishing the two approaches are, first, that in an attribute approach measured characteristics of only a single item are evaluated whereas in a template approach measurements of items are compared with data for reference item(s). Second, the template approach necessarily requires storage of the reference data. The same measured data (radiation spectra, mass, etc.) could be used in both approaches. In applications involving nuclear weapons or related materials, both approaches require a trusted information barrier to prevent unintended transfer of sensitive information while simultaneously assuring reliable verification.

Parties to an attribute-based agreement must specify the quantitative value and acceptable deviation, or range of values, for each attribute to be evaluated. Because of the diversity and sensitivity of design information, the list of attributes selected for comparison tends to be restricted, and ranges of acceptable values might have to be so wide that real weapons could not be uniquely distinguished from non-weapon configurations of nuclear material. In a template approach the precise quantitative values are contained in the template and, with a reliable information barrier, remain unknown to the inspecting party. Measured characteristics can be compared far more precisely in the template mode than would be acceptable if the parties must negotiate and agree on allowable values and ranges. If the authenticity of the template can be assured, the template approach may provide higher-confidence verification through comparison of sensitive characteristics with sufficient precision to detect, and thereby deter, deception.

Attribute and template procedures could be combined in the same inspection. Analogous to the two-level attributes/variables measurement approach used by the IAEA in safeguards inspections, some items would be evaluated quickly and simply for gross consistency of measured characteristics with agreed values. Additionally, incorporation of potentially more precise comparisons with templates, measured under conditions that support their authenticity, would allow for anomaly resolution and provide further assurance and deterrence against deception.

Spatial features of radiation from nuclear weapons can be exploited in a template approach, but their use would be problematic in an attributes approach. Passive neutron time-of-flight can improve assurance regarding weapon authenticity by introducing signatures that cannot be measured by other techniques currently being considered for verification of weapon dismantlement.

INTRODUCTION

As the numbers of nuclear weapons retained by the nuclear weapon states (NWS) are reduced by treaty, assurance that each device presented for credit against dismantlement quotas is a real nuclear weapon becomes increasingly crucial. Since direct observation of the disassembly process by other treaty partners is unlikely to be acceptable, assurance must be obtained through measurements on the weapons before and after they are dismantled. The two basic assurance approaches that have emerged have been called *attribute* and *template* measurement approaches. Both approaches require a trusted information barrier so that data with sufficient information content to provide high assurance can be used in the evaluation process while simultaneously preventing unintended transfer of sensitive information.[1] In this paper, the fundamental characteristics and limitations of these approaches are reviewed, use of spatial signatures is analyzed, and the passive neutron time-of-flight (NTOF) technique to measure nuclear-weapon characteristics is proposed.

ATTRIBUTES METHOD

The fundamental characteristics of the attributes approach are that 1) measurements are made on a single weapon and 2) evaluated by comparison with values, or ranges of values, for each attribute that have been agreed upon with the opposite side. Furthermore, 3) an acceptance-rejection algorithm must be defined and accepted by both sides to conclude whether the weapon is genuine based on the set of measured attributes. A trusted information barrier can be used to prevent the inspecting side from knowing where in the agreed ranges the measured value of each attribute falls.

Originally the attribute concept was based on the naïve hope for the existence of a set of characteristics for which non-sensitive, unclassified, measured values would be sufficient to distinguish nuclear weapons from non-weapon configurations of nuclear materials, including potential mock assemblies specially designed to deceive the assurance process. The assurance measurements would be made at sufficiently low resolution that the measurement data would be non-sensitive and unclassified. Table 1 shows attributes that have been suggested for transparency or confidence-building applications.[2]

Table 1. Attributes for Identification of Nuclear Weapons (Ref. 2)

1. Presence of Plutonium
2. Plutonium Isotopic Ratio [$^{240}Pu/^{239}Pu$] ("weapons-grade" plutonium)
3. Plutonium Mass above Threshold
4. Plutonium Age (last separation from ^{241}Am)
5. Presence/Absence of Plutonium Oxide
6. Symmetry of Plutonium in Container (neither point source nor widely distributed)

The set of attributes shown in Table 1 can provide only limited assurance that a weapon is genuine for two reasons. First, nuclear-weapon designs are sufficiently diverse that the ranges of attribute values encompassing designs of existing weapons are so wide that they would fail to exclude non-weapon configurations or could be easily spoofed. Second, for some of the attributes listed in Table 1 the measurement technique being considered is low resolution, of limited energy range, or otherwise restricted so that only limited assurance would be obtained. Less restrictive application of proposed methods or alternative measurement techniques would provide more credible assurance. Analysis is showing that the best possible measurement data are required to assure the authenticity of treaty-limited items, exclude non-weapon configurations, and detect spoofing if it were to occur.

In an attributes approach, measurements on each device are evaluated by determining whether the measured data fall within valid ranges. The ranges of validity for each attribute must be agreed upon with the opposite side. When more than one attribute is measured, the sides must negotiate an algorithm that will determine whether an item presented for authentication should be accepted or rejected. Very likely, an algorithm combining a number of attribute measurements would have to be executed through a trusted information barrier in order to protect sensitive information. Even with a trusted information barrier, some very distinguishing weapon characteristics could not be used in an attributes approach because a usefully precise acceptance value, or range of values, would be sensitive classified information. For example, spatial signatures, which are related to the dimensions of weapon components, cannot be used effectively in an attributes approach but can increase assurance substantially in a template approach. Also, the absence of attributes of high-enriched uranium (HEU) in Table 1 suggests that their use in an attributes approach is problematic.

TEMPLATE METHOD

The template method has two distinguishing characteristics. 1) Data for an object measured during an inspection are compared with a set of reference data. As discussed in the next paragraph, the reference data are generally measured data for similar object(s) preferably obtained under conditions that support their authenticity. 2) The reference data must be stored between inspections in a manner that will assure its integrity. Assurance from a template approach is critically dependent on the authenticity of the reference data and on preserving its integrity during storage between inspections.

The following methods might be used to obtain valid reference data. In one method, deployed weapons could be measured in the field or as they are removed from deployment. Authenticity is supported by the presumption that some of the devices found at deployment sites would be working weapons. In an alternative method, the reference data could be derived statistically from measurements, e.g., at a weapons repository, of many items that have been declared to be the same type and are identical in appearance. Between inspections the integrity of reference data could be preserved by using the so-called "dual key" storage concept.

An important advantage of the template approach, compared to the attributes approach, is that acceptable values for the measured characteristics do not have to be agreed upon with the opposite side. Only the algorithm used to compare template features (attributes) would be negotiated. Statistical properties for establishment of acceptance/rejection criteria and follow-up procedures for apparently anomalous results could be negotiated but might also be established empirically.

The tolerances with which inspection data must match reference data can be made very tight for two reasons. First, inspection measurements and reference data would be compared through a trusted information barrier, and the actual values of characteristics being measured would not have to be known to the inspecting side. Second, separate reference data would be used for each type of item being examined, so there would be no need to define a range of values that would be wide enough to fit different types of items.

SPATIAL SIGNATURES

As an example of a spatial signature, the dimensions of a plutonium-containing component of a nuclear weapon would obviously have to be larger than a point source but smaller than the dimensions of its container. As shown in Figure 1, a collimated gamma-ray detector placed at a number of positions along the axis of the device could be used to measure the dimensions of internal components and to locate their positions relative to the container ends or other exterior structural features.

It would be problematic to use the measured dimensions of weapon components in a simple attribute test. First, weapons come in a variety of sizes so that the component dimension might have to be specified for each type of weapon if it were to be helpful in distinguishing real weapons from non-weapon configurations. Second, it would be difficult to agree on useful limits for component dimensions in an unclassified context. However, in the template mode using a

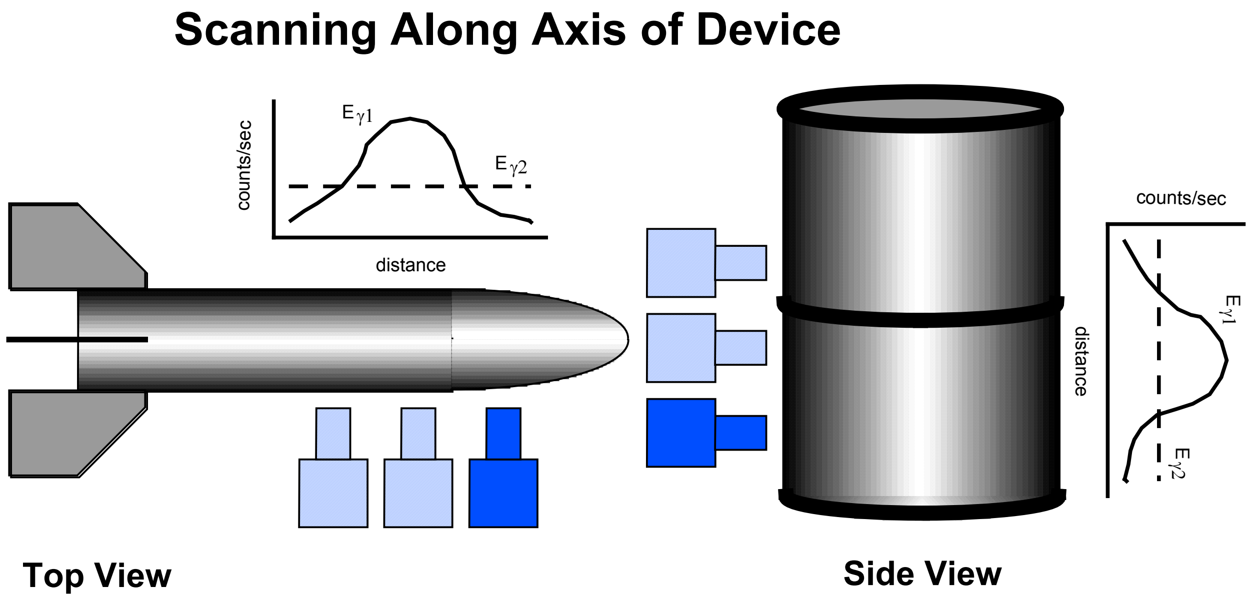

Figure 1. Measurements at multiple locations with a collimated high-resolution gamma-ray detector generate spatial signatures.

trusted information barrier, measured component dimensions could be compared to the template with high precision and without revealing the actual measured dimension.

Figure 1 suggests a number of signature elements that could be measured by high-resolution gamma-ray spectrometry (HRGS) and compared with the template. Profiles of gamma-ray intensities at various energies could be measured along the axis of a device in a container. The widths of gamma-profile features that are related to the dimensions of internal components could be compared to the template data through a trusted information barrier. Gamma-ray peak areas at a number of energies, or their ratios, could also be compared with the template. Different peaks will have unique spatial profiles that depend on the distribution of source materials and shielding in the object. Furthermore, the gamma-intensity maxima should occur at the same positions relative to external features of the container as in the template. Evaluation of spatial signatures in a verification approach would greatly increase assurance against spoofing because it would be necessary to simulate simultaneously the spatial as well as the spectral HRGS features. Figure 1 also suggests that comparison of spatial signatures related to the dimensions of weapon components could provide confidence that a component was obtained from disassembly of a particular weapon.

Use of spatial signatures would be acceptable only in the template mode. Of course, multiple detectors could be used to make measurements at several positions concurrently thereby reducing total measurement time per object.

NEUTRON TIME-OF-FLIGHT (NTOF)

Passive NTOF can be used to measure the spectrum of neutron energies emitted primarily by spontaneous fission of ^{240}Pu in the pit of a nuclear weapon. Gamma rays associated with fission generate the start signal in a scintillation detector, such as BaF_2, which is relatively insensitive to neutrons. A neutron detector at the end of a known (approximately 1-m) flight path generates the stop signal. (Since gamma rays from all sources are more numerous than neutrons, deadtime is reduced by using neutron events as the start signal and gamma-ray events, through a delay line, as the stop signal.) The neutron energy is determined from the measured flight time.

A NTOF system has been built at BNL and tests have been performed with a ^{252}Cf source and various high-explosive surrogates. The data measured at BNL show unequivocally that plutonium oxide can be differentiated from plutonium metal.

Figure 2 shows NTOF data measured by Forman, et al. from underground nuclear explosions.[3] A number of attributes useful in confirming the authenticity of nuclear weapons and components can be derived from NTOF data (number of neutrons vs. energy or time). Some of these attributes cannot be measured by methods currently under consideration for dismantlement verification. We discuss two attributes, the presence of chemical high explosive and the presence and mass of ^{240}Pu, about which NTOF may provide useful information. A trusted information barrier would be needed since sensitive design parameters can be derived from NTOF data.

The constituents of chemical high explosive are carbon, hydrogen, nitrogen, and oxygen; all except hydrogen have resonance features in the MeV range. In Figure 2, oxygen can be identified through resonances at 0.44 and 1.0 MeV and a multiplet in the range 3.2 to 4.0 MeV.

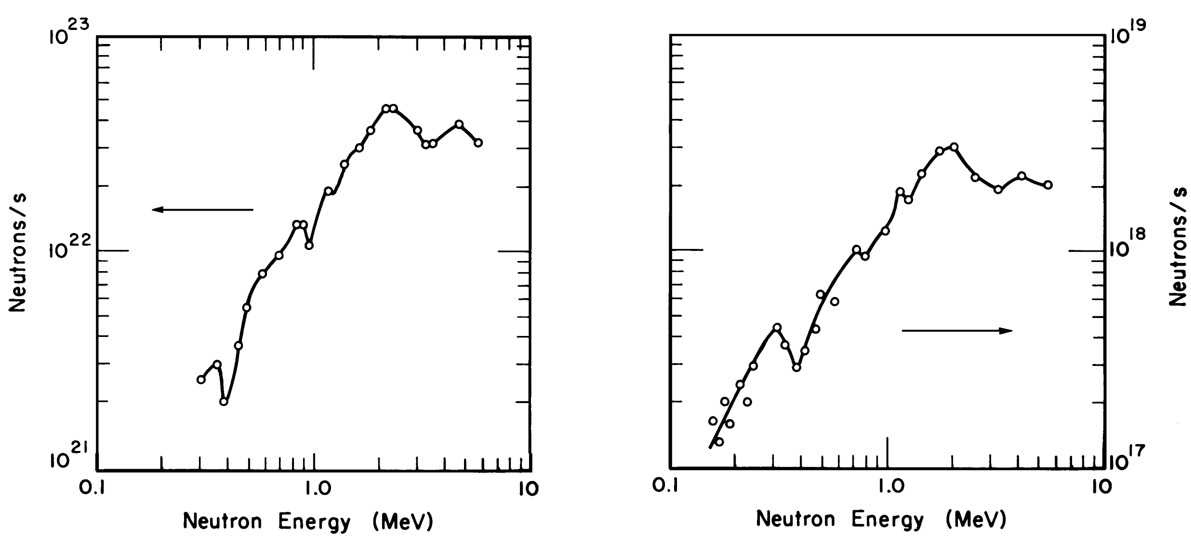

Figure 2. Neutron time-of- flight data by Forman et. al.[2] of underground nuclear detonations. Transmission features show resonance structure of oxygen and nitrogen.

Nitrogen causes an interference window at 4.8 MeV although it is not obvious in Figure 2 because the data end and the resolution is limited (about 0.25 MeV), and carbon has a strong resonance at 8 MeV. With sufficient measurement resolution, analysis of the NTOF spectra can identify the elements in high explosive and provide estimates of the relative elemental concentrations, the high-explosive thickness and areal density. The measured number of neutrons can then be corrected using the calculated thickness of high explosive to obtain the ^{240}Pu content. This, combined with the ^{240}Pu /^{239}Pu ratio data from gamma spectrometry, can be used to estimate the ^{239}Pu mass, just as the plutonium isotopic composition determined by gamma-ray spectroscopy is used to calculate the ^{239}Pu mass from neutron multiplicity counting data.

The high-energy portion of the neutron spectrum can be fitted with a Maxwellian formalism to determine the kinetic temperature of the fissioning nucleus. This temperature is unique for a particular isotope and should allow plutonium to be distinguished from ^{252}Cf, which could potentially be used to simulate the neutron-emission characteristics of a nuclear weapon for the purpose of deceiving the verification process.

CONCLUSIONS

Some characteristics of nuclear weapons cannot be evaluated in an attributes mode because an acceptable range for measured values could not be established through unclassified discussions. Examples include the dimensions of weapon components and other spatial features derived from measurements with a collimated gamma-ray detector close to the weapon at several positions along its axis. HEU signature elements may also be difficult to incorporate in an attributes approach. However, characteristics related to the dimensions of weapon components could add a high level of assurance to the authentication process if they were compared with high precision to a template spectrum, and spatial characteristics could be used to validate the dismantlement process by confirming that the size of the dismantled component was consistent with its size in the full-up weapon. A trusted information barrier is required regardless of whether authentication is based on attributes or template comparisons. Passive NTOF is suggested as a method for measuring additional characteristics that would strengthen assurance of authenticity when nuclear weapons are presented for credit against dismantlement quotas. NTOF would both complement other measurement techniques and exploit additional characteristics that could not be measured by other methods being considered for verification of weapons dismantlement. An optimum approach might combine both attribute and template approaches. The best assurance that a treaty limited item is authentic would be provided by using all possible signature elements in high-quality, unrestricted data measured with a variety of techniques . Of course, a trusted information barrier would be essential.

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