Template Applications for Monitoring Warhead Dismantlement

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Abstract

As further reductions in nuclear weapon stockpiles are planned, it becomes increasingly important to confirm with high confidence that items presented for monitoring and subsequent dismantlement are genuine nuclear weapons. The monitoring approach must make use of sufficient data to provide high assurance of authenticity but must do so without revealing sensitive design information to the monitoring party. Use of an open, secure processor to evaluate measured data and present only the non-sensitive results of the evaluation to the monitoring side is becoming an accepted concept. Technical options for monitoring weapon authenticity presently under discussion are being described as either attribute or template approaches. The fundamental elements of each type of approach are analyzed, misconceptions associated with the definitions are clarified, and complementary aspects are identified. A template is an experimentally determined pattern of characteristics whose measured values describe an item to be monitored. A template approach compares measurements of an unknown object with a template of reference data and reports only the variability of the match. Characteristics of nuclear weapons which might otherwise be unusable because of their sensitivity can be practically incorporated in template approaches. Use in the monitoring process of the quantitative variability parameters resulting from template comparisons is suggested as a means to resolve results that are intermediate between pass and fail. This work explores how increased assurance of weapon/component authenticity might be obtained, with minimal risk to sensitive information, by incorporating expanded classes of weapon characteristics into monitoring procedures, by using data of higher resolution or unrestricted accuracy, and by using variability information to trigger follow-up activities for resolution of anomalous or ambiguous situations.

Introduction and Definitions

Two different approaches have been put forward for the analysis of radiation signature data for monitoring of international arms control agreements such as those related to the safe and secure storage of special nuclear materials as well as in the various stages of dismantlement of nuclear weapons. These are referred to as the *template* approach and the *attribute* approach. This document reviews and categorizes the advantages and disadvantages of using template approaches to complement attribute measurements for specific applications within a given monitoring regime. The following definitions are essential for understanding these approaches.

A *template* is an experimentally determined pattern of characteristics obtained from measurements of known items of the same type; it may be an average of such measurements. The *template method* is a procedure to identify an unknown item by comparison with an established template. A *template element* is one of the independent variables included in the template. A *match* is the result of a comparison in which the unknown object and the template are the same within an agreed variability. *Standard deviation* is a measure of the variability of a statistic used to evaluate template match or attribute threshold. An *attribute* is a characteristic, derivable from measurements, which is relevant to a particular regime or agreement. A *threshold* is an agreed value or range of values to which an attribute should be compared so as to determine acceptance of a test item.

Background

For many years in both the US and Russia, radiation measurements have been compared with stored template data from nominally identical items to confirm the presence, authenticity or completeness of a controlled item. The template method has also been used for monitoring of the Intermediate-Range Nuclear Forces (INF) Treaty, and could potentially be useful in monitoring future international agreements.

Fundamentals of Template and Attribute Methods

The reasoning behind the template method is that the radiation field depends on the mass, composition, physical form, isotopics, and the geometry of radioactive source materials within the item, as well as the dimensions and composition of intervening materials that cause scattering and absorption, in a complex but physically determined way. Thus two objects will generate the same pattern of gamma rays and neutrons (to within some experimental error) if and only if the two objects are physically identical in regards to all the above defining parameters. The intended uses of template measurements are in demonstrating that (a) an object remains unchanged in its storage configuration or (b) it matches a standard object or (c) it matches a statistical average of a population of the same type.

A template scheme requires that the user have some qualitative knowledge of the expected measurement results, but not necessarily quantitative knowledge. A template user does not necessarily have to calculate the comparison pattern from first principles to find the template method useful. Most often the template is experimentally determined from a known standard item or an average of accepted items. However, the user must know that the pattern is adequately complex to distinguish between acceptable and unacceptable types of items that are likely to be encountered. For example, a simple gamma-ray count rate may not distinguish a weapon from a carefully selected radionuclide source. However, the energy spectrum of gamma rays from those two sources will adequately distinguish between them. The user must also know that some characteristic distinguishing between the items will be measured in the pattern chosen as the template. For example, if two items differ *only* in the emission of a low-energy gamma ray, and if the objects are heavily shielded so as to prevent detection of low energy gammas, a conventional template scheme will not distinguish between the items. In general, the greater the number and physical diversity of the characteristics that are included in the template, the greater the assurance the template comparison provides.

One concern about templates for arms control agreements has been the possibility that the measured quantities may not be directly related to the central questions addressed by a monitoring regime. For example, a template can readily address the question ñIs object *"A"* very similar to objects of the type producing the template?ò However, a single template does not readily address the broader question ñDoes object *"A"* contain significant amounts of special nuclear materials in a configuration consistent with its being a nuclear weapon or component?ò That broader question may require a complete set of templates for acceptable items, credibly initialized. Then, a match to any of the comprehensive set of templates could answer the second question without necessarily identifying which type was matched. Assurance provided by template comparison can also be improved by including more numerous and diverse characteristics in the template.

The template algorithm can be designed to derive attribute information for both the unknown and the template and then to compare the derived attribute values with the agreed threshold. It may also be useful for the template algorithm to compare attribute values derived for the unknown to attribute values derived from the template array. In the template mode the derived attribute values for unknown and template could be required to match with much greater precision than when attributes are compared only to the agreed non-sensitive thresholds. An attributes method would encounter difficulty in answering the second question above if the thresholds must be set so broadly that they encompass non-weapon configurations that the regime seeks to distinguish from the controlled items.

The template approach could have difficulties with matching to an indeterminate amount of material in a container, rather than a precisely machined component. This problem could be addressed by setting allowable error limits for the matching procedure, consistent with the expected variance of the population of containers. Thus, the utility of the template approach depends very much on the nature of the questions being asked. Furthermore, as nuclear materials from weapons and components become more removed from the weapons configuration in the course of the dismantlement process, both templates and attributes associated with the material become more similar to bulk nuclear material and less characteristic of the original weapon configuration.

The utility of the template approach also depends very much on the confidence with which one can establish the authenticity of the initial set of objects used for creation of the template. For example, object *"A"* could be a nuclear weapon but fail a template match because the template set did not contain a similar design. It could also fail its intended purpose if a non-weapon were to match a template erroneously accepted as a weapon.

A viable template application occurs when the template consists of a set of averaged measurements obtained from a representative number of items known to be genuine (as a result of independently derived information such as chain of custody from a deployment site). An unknown item can then be measured with the same instrument(s), and the data are compared to the average-value template. If the results of the measurements show that the item is the same (to within experimental error limits and build tolerances), the declaration is confirmed and the item is said to match the template. If the items used to create the template are known to be accountable objects, such as nuclear weapons or components, then the unknown item is also identified as such. By extension, a large number of the same type of items could be tested against the same template.

The alternative way to analyze signatures, called the attribute approach, requires the measurement of only the item to be evaluated. It is then necessary to extract ð from the same sort of radiation data as might be measured for template signatures ð quantitative information about the important attributes of an object under test and to compare the experimentally determined quantities with negotiated threshold values. This approach avoids the step of template initialization with an object known to be genuine (with a high degree of confidence) and allows individual items to be measured against a generic standard that defines a range of non-identical objects fitting some approximate criteria of concern. Attributes can be identified which have high importance for a particular agreement, but the selection and weighting of attributes for monitoring sometimes must be based on policy and negotiation rather than on strictly technical merit. The extraction of quantitative attributes from measurements may require greater experimental and analytical effort than matching the data from two sets of measurements. For example, longer counting times may be needed to acquire better statistical information for weaker or more convoluted components of the attribute signals, and a more detailed analysis must be performed to provide an absolute quantitative result to compare with an agreed threshold.

Examples of Template Radiation Data

Low-Resolution (NaI) Gamma-Ray Spectrum

RIS. The Radiation Identification System (RIS) developed at Sandia National Laboratory is used for rapid identification of types of warheads and components. The data acquired are low resolution gamma spectra from a NaI detector. The elements of the template are count rates in

16 energy bands, including the sum of the photopeaks and the Compton-scattered events, minus background counts obtained in the same room but far from the test object. The counts in all bands are compared to those in the template by calculating the sum of the squares of the differences between test object and template, and dividing the result by the variance expected purely from counting statistics. Regions of the spectra which tend to be variable due to background, age of Pu or minor isotope impurities (such as U-232) are excluded from the analysis. The regions included are sensitive to the mass of Pu-239, U-235 and U-238, but not capable of resolving Pu-240. If other radioactive sources were present in comparable strengths, the spectrum would not match the template. Typical measurement times are of the order of 30 seconds.

Ranger. The Ranger instrument developed by Los Alamos acquires similar gamma spectra to those obtained by RIS, but is programmed to extract attribute information. It also includes a neutron counter, which adds an additional element of information. With appropriate software and a securable storage medium, it could be operated in a template mode similar to that of RIS, with the neutron data incorporated as well.

High Resolution Gamma Spectrum

CIVET Algorithm. The Controlled Intrusiveness Verification Technology (CIVET) measurement system was developed at Brookhaven National Laboratory in the early 1990's for performing template measurements on warheads and components using high-resolution gamma spectroscopy. The system consists of a high purity germanium detector, a spectroscopy amplifier, an analog-to-digital converter, and a custom-built single-board processor designed for ease of authentication. A spectrum of 4096 channels is accumulated by the digital hardware in a volatile memory card. The simple embedded processor has no operating system, but boots up directly into the dedicated application. It performs the functions of a multichannel analyzer (MCA) and also carries out the template-matching statistical calculations.

Selected peaks of special nuclear material isotopes are stripped from the Compton continuum and integrated. The areas of the important peaks are used as independent elements of a template array that is stored in a non-volatile removable memory card. A statistical routine is used to compare the array for an unknown item with the template, and two parameters are calculated: (a) the average ratio $\boldsymbol{R}$ between elements in the test item array and those in the template array (related to source strength, average attenuation and distance to detector); and (b) a quality of fit parameter $\boldsymbol{Q_{fit}}$ which is determined from the relative amplitudes of the peaks in the array (related to isotopic composition and differential attenuation). These quantities are expressed in units of the expected error $\boldsymbol{\sigma}$ (sigma), based on Poisson counting statistics. If an item matches the template, $\boldsymbol{R}$ should be about unity, $\boldsymbol{Q_{fit}}$ should be near zero. The display of these fitting statistics is considered to be non-sensitive. However, the stored templates are expected to contain classified information, and must be protected by the host. One advantage of high-resolution spectra over those obtained with NaI detectors is the reduced sensitivity to changes in the Compton continuum, which might occur in the presence of nearby extraneous radiation sources, such as other weapons.

TRIS method This method is being developed at Sandia. In addition to the areas of the photopeaks in a high-resolution spectrum, information on small-angle scattering by intervening materials is obtained from steps in the continuum at each photopeak. The amplitudes of these steps could also be elements of the template.

Neutron Measurements

Neutron Flux 2-D Matrix. Provisions in the INF treaty allowed monitors to count neutrons at a number of positions on a grid laid out on the ground under a missile positioned horizontally, as well as along the top of the missile. The array of data points was compared to a template array, and a confirmation was defined according to a prescription which allowed for acceptable experimental errors (i.e. ±50%). In this case the data were considered non-sensitive, and the template was shared information. The spacing of the measurement points was of sufficiently fine resolution to distinguish between single and multiple warheads, which was the relevant characteristic to be addressed by the regime.

Neutron Die-Away. The Nuclear Materials Identification System (NMIS) is an active interrogation method developed at Oak Ridge National Laboratory. The time correlation of neutrons and gammas detected after an initiating neutron input provides a unique template of a particular assembly of fissionable materials combined with moderators and absorbers. These die-away data can be transformed to the frequency domain and the template can be created from a number of frequency bands. Alternatively, template elements could be generated from counts occurring in specific intervals of the time domain. Such data have been shown empirically to distinguish between different geometries and masses of special nuclear materials. Compared to gamma spectroscopy, this method is undoubtedly more sensitive in detecting shielded highly enriched uranium (HEU). Deriving actual physical attributes from these data requires complex analysis, which represents an ongoing challenge. However, this technique is clearly successful in the template mode.

Attributes Being Considered

Table 1 shows some attributes and the proposed bases for their corresponding thresholds that are being considered for arms-control and warhead dismantlement regimes. For reasons of sensitivity the thresholds must be set so broadly that even collectively they may fail to confirm the authenticity of a warhead with the desired high level of confidence. It is difficult to exclude all other configurations that might have attributes falling within the same thresholds. Template methods can incorporate additional characteristics in the verification process to complement attribute methods.

Table 1. Some Attributes of Nuclear Weapons

Attribute	**Threshold basis**
Presence of Pu	Significant intensity of ^{239}Pu gamma rays
Minimum mass of Pu	negotiated value (combined gamma and n)
Weapons grade Pu	Pu isotopic ratio, 240/239 10%
Presence of Pu oxide	Oxide identifiers in gamma spectrum
Pu metal (absence of oxide)	Absence of oxide identifiers
Extent of source	Distributed, larger than point source
Age of Pu	Relative intensity of ^{241}Am to ^{241}Pu gammas
Presence of highly enriched uranium	Intensity of ^{235}U and ^{232}U gamma rays

Comparison of Attributes and Templates

Some of the advantages and disadvantages that have been associated with template and attribute methods are summarized in Tables 2 and 3 respectively. Space permits only selective discussion.

Table 2. Characteristics of Template Methods

Advantages	Disadvantages
• Short data-acquisition time • High-resolution data, high-precision matching • Unique ID of each type of item • Thresholds not discussed or negotiated • Dominant characteristics not identified • Template data are protected by host • Confidence depends on extent of data included in template & matching criteria • Can be designed to emphasize critical characteristics, e.g., mass of SNM • Possibility to validate disassembled components by comparison with fully assembled object	• Sensitive stored data requires protection. • Matched characteristics may not be relevant to regime. • Intended characteristics may be unmeasured and contribute nothing to the matching process • Difficult to initialize and authenticate templates

Table 3. Characteristics of Attribute Methods

Advantages	Disadvantages
• No storage of sensitive data • Measured characteristics are relevant to the regime. • Considerable variation between items is tolerated	• Long measurement times may be required • Desired characteristics may not be measurable • Loose criteria / easily deceived • Only non-sensitive thresholds can be negotiated and used

The typical data acquisition time for low-resolution gamma templates is of the order of 30 seconds, while high-resolution templates acquired in 5 to 10 minutes can distinguish between objects. Attribute measurements have been known to take more than an hour in order to acquire sufficient counting statistics to make a quantitative calculation. The short measurement duration of a template may hold false promise. If the only characteristics that distinguish between metallic plutonium and plutonium oxide objects are a few peaks that require a long measurement time to identify, the template measure would require the same measurement duration as the attribute measurement to assure that the oxide related features will have adequate statistics to be significant in the template comparison. However, other features of a template spectrum might serve to distinguish between objects much more rapidly.

The template approach can more readily distinguish between two types of objects because it can set tight tolerances on several correlated parameters. The expected values of the measured characteristics do not have to be declared or observed, so they can be determined with high precision by the trusted computer. The allowed deviation from the template can be chosen to match the population of objects that are supposed to be of the same type. If these are machined metal components with fixed dimensions, the radiation from them should be very reproducible, subject only to variations due to the machining tolerances and changes in the positioning of the detector. Other objects machined to different dimensions, random scraps of metal, or oxide powder cannot easily reproduce the spectrum at all energies, because there are certain to be differences in source strength and self-attenuation. For neutron measurements, there will be similar variations in source term, moderation, absorption and multiplication.

Since quantitative values of characteristic thresholds do not have to be negotiated quantitatively in the template method, sensitive data and derived characteristics can be included in the template and compared with high precision using a secure open-architecture processor. For example, spatial characteristics can be used in a template method. Radiation measurements would be made at several intervals along the axis of an unknown device and the spatial profiles compared with a template. The template algorithm could also derive and compare values of spatial characteristics such as component diameters and source locations relative to physical features on the outside of the test object's container. The quantitative values of sensitive parameters would not be revealed to the template user.

Template methods provide greater assurance for the authenticity of items when they are focused explicitly on the characteristics of the regime. For example, a template that examines specific high-resolution gamma-ray lines specifically related to uranium and plutonium may provide greater assurance of authenticity than a template that simply compares regions of a low-resolution spectrum. Moreover, amounts of special nuclear materials used for weapons are controlled to within narrow tolerances, so templates can be measured precisely and reproducibly as long as the measurement data are not revealed.

A disadvantage of the attributes method is that the thresholds must be set very loosely, since the threshold values must be non-sensitive and negotiable. The actual measured attribute values are assumed to be sensitive, and protected by an information barrier. Of necessity, they must be significantly offset from the threshold values. The attribute approach must be limited to a wide acceptance band about each parameter where the correlation can not be used without revealing more information than intended. Therefore, the pass/fail criteria may be easy to spoof with approximate surrogates.

In the template method the statistical parameters (such the $\boldsymbol{R}$ and $\boldsymbol{Q_{fit}}$ of the CIVET algorithm) used to evaluate the match could be monitored and recorded as comparisons are carried out for each type of weapon. These data could be used to evaluate the variability of the population and assure that the acceptance/rejection criteria were not set too loosely. These statistical parameters could be considered attributes for each type of weapon and could be assigned empirically determined thresholds. Items outside the threshold range would be rejected.

It seems likely that the host will always have custody of the equipment used in the monitoring regime. This ensures that, although the stored template data are highly sensitive, the host can have high confidence that no sensitive information will be revealed. On the other hand, the monitor needs assurance that the template data is a valid representation of a treaty-limited item. This requires carefully crafted procedures in preparing the original templates, and in ensuring that they have not been modified between measurements. Preserving the integrity of template data stored in the host State is a tractable problem for which precedents exist. It is possible to encrypt the template data with dual keys so that they cannot be altered by the host nor read by the monitor.

Combining Features of Template and Attribute Methods

One possibility would be to measure all relevant attributes and use these quantities as elements of a template to compare objects of the same type. Test objects would be required to pass attribute tests using the negotiated non-sensitive thresholds. They would also be required to match templates and other items of the same type at a much higher level of precision. A disadvantage of this approach is that the time required for the most time-consuming attribute measurement would have to be allocated to every measurement.

An alternative would be to use a serial approach. One or more items would be validated to assure that they have the attributes of a weapon. Then the template method would be used to compare other items of the same type to the original set, and these template comparisons might be carried out more rapidly and expeditiously than the initial attribute evaluation. Matches with previously measured templates would provide further assurance and also would serve to reconfirm the integrity of the older templates.

Conclusions

Template methods have the potential for comparing and validating many items of the same types, possibly more rapidly and expeditiously than with pure attribute methods. Template methods can increase the level of assurance by comparing sensitive characteristics with much greater precision than would be possible if the threshold had to be negotiated in an attribute approach. Template methods can increase the level of assurance by incorporating a greater variety of physical characteristics into the validation process.