Introduction to Attributes Information Barrier for Nuclear Warhead Authentication

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Abstract:

Part of a chain-of-custody approach to warhead dismantlement verification is the authentication process, where nuclear measurements such as gamma spectroscopy and neutron counting are undertaken to confirm the identity of a warhead. Direct measurements could reveal sensitive data. Information barriers can be used to deliver an unclassified output of classified data measurements. This paper introduces a project which develops an information barrier using an attribute approach.

It analyzes what information could be revealed during direct measurements, explores different information barrier concepts and information barriers built in the past to prevent leakage of sensitive information, suggests a warhead authentication procedure, introduces attributes that could be defined to authenticate a weapon and suggests measurement techniques for each. This paper is an introduction of the project; results are preliminary as the project will be carried out in the future.

Keywords: disarmament verification**;** information barrier; attributes; warhead authentication

1. Introduction

One measure that builds confidence in nuclear dismantlement is the so-called chain-of-custody approach. This chain-of-custody “demonstrates that an unaltered or uninterrupted custody or control of an item has been maintained by the owner or inspector, [...] that provides confidence that deceptions have not been introduced” [1]. This means that a verification regime must provide confidence that from the very beginning of the dismantlement process of a nuclear weapon to the very end no cheating has taken place. While some verification measures have been implemented in previous treaties, a verification system that enables a complete chain-of-custody approach is not available today. A very important part is the actual dismantlement of the warhead - the moment where the warhead itself is taken apart. In order to guarantee a complete chain-of-custody, it must be assured that the device that is being dismantled is in fact a nuclear warhead, the so-called warhead authentication: “Successful authentication will ensure the monitor that accurate and reliable information is provided by a measurement system and that irregularities, including hidden features, are detected” [2]. During the warhead authentication process, it will be assessed whether the warhead is a true warhead or rather a dummy. Such a system is not used today and technology development has been limited so far.

A warhead authentication system can more readily be agreed on if the measurement system does not reveal sensitive information on specific warhead design features as nuclear weapon states consider this information to be highly classified. Therefore, an information barrier (IB) could be used that would analyze measurement results in an automated manner and produce an unclassified output.

The project introduced here tries to develop a warhead authentication system using such an information barrier. This paper is merely an introduction into the topic as the project is still in progress – it presents a number of concepts and measurement tools that could be useful.

2. Revealing sensitive information during dismantlement verification

It must be identified what information could possibly be leaked during the verification process. The verification system developed in this research uses gamma spectroscopy and neutron counting. However, the gamma spectrum will give experienced people, for example (former) weapon designers, the possibility of reverse-engineering - at least to some extent. Most obviously, the isotopic composition of the fissile material can be deduced. From this, it can be determined if plutonium, uranium or a mix of both is used in the fissile core. Also, information regarding enrichment, age (e.g. date of plutonium separation) and further properties of the material (e.g. presence of other isotopes such as U-232 which would indicate that the uranium was used in reactors before) can be deduced from the isotopic composition. This list is by no means exhausting. Neutron counting might give more quantitative information. Under special circumstances where some information regarding the warhead design is initially available to inspectors, a rough assessment of the fissile material mass might be possible. However, information regarding shielding of radiation emitted from the core (see below) is required as well as the isotopic composition.

Apart from information regarding the fissile core, further design features could be reverse-engineered. By conducting a number of measurements in different positions relative to the warhead, information regarding the form of the warhead (e.g. degree of spherical symmetry) could be revealed. Also, information about other materials present such as a neutron reflector or a tamper could be exposed. Knowing the neutron cross-sections and gamma attenuation coefficients of absorbing materials which vary at different energies, a well calibrated detector could reveal this information, when peaks at different energies (in the case of gamma spectroscopy) are analyzed with regard to the measured and expected intensities in relation to each other. An assessment of the thickness of the absorbing material can also be given once the absorbing material has been identified by comparing peaks at different energies, see for example [3].

It is important to note that reverse-engineering requires a lot of experience. Especially in the reverse-engineering of absorbing material, expertise is needed that inspectors might not have. It is therefore not easy to assess how much sensitive information could be revealed.

3. Information barrier (IB) setup

3.1. Requirements

The IB is a computing system that receives the raw classified data and calculates the unclassified output. The system has to protect the information from unauthorized access by the inspector. Also, the data collection and processing equipment must be protected from the inspected party so that no tampering with the measurement system is possible. This means that input possibilities of both the inspected and inspecting party should be reduced to an absolute required minimum.

After initial authentication (testing), the system should be designed in a way to minimize the possibility of alteration and maximize the detectability of alteration by any party. The system should have a simple design that is easy to check and understand.

As a last major requirement, as few sensitive data should be stored as possible for the shortest time possible. No permanent storage of sensitive data should be necessary because in case the system is tampered with, sensitive data could possibly be extracted. This danger should be minimized which especially sets the requirement that no sensitive data should be stored which could be assessed even in between inspections.

3.2. Solutions

The Trilateral (US-Russian-IAEA) Initiative that was conducted between 1996 and 2002 aimed to establish a system of verification under which states in possession of nuclear weapons might submit excess fissile material to IAEA monitoring [1]. During the Trilateral Initiative, the so-called "Attribute Verification System with an Information Barrier Utilizing Neutron Multiplicity Counting and High-Resolution gamma ray Spectrometry" (AVNG) has been developed. This system is designed to contain a minimal non-volatile memory; all classified data are stored on volatile memory. This means that after power shut-down which could either happen during inspection if irregularities are discovered or after the inspection has been performed, all sensitive data will automatically be deleted. The software resides on non-rewritable programmable read-only memories [4]. This is to ensure that no alteration of the algorithm is possible and there is also no possibility to obtain access to classified information. Furthermore, there are neither hard drives, nor other mechanical drives, nor network capabilities in the computers. The only possible operator input is through simple switches. All measurements are controlled by these switches and to further minimize possibilities to interact with the system, it is specified to include appropriate shields and other devices to prevent transmission of electromagnetic signals into (to alter it) or out (to reveal classified information) of the system [4]. The AVNG can operate in an open and in a secure mode with the latter one being the default. In the open mode, access is given to all raw data while in the secure mode - designed for the verification of classified materials - only unclassified outputs will be given. The open mode could be used to search for errors and to solve them. A "security watchdog" overlooks the modes of operation. This device controls the system in combination with an emergency "scram" switch [4]. This system would shut-off power when an intrusion into the system is detected. This results in complete information loss in the volatile memory. The system's security functions are separated from the measurement function. There is no direct communication possible between security watchdog and measurement/analysis system except for power [4]. Therefore, measurement equipment cannot be influenced.

A physical IB was also built during the Fissile Material Transparency Technology Demonstration (FMTTD) performed at Los Alamos National Laboratory. It has a very similar design as the AVNG. It has a shielded electronics rack with a sensor at the door. When doors are closed, only a green or red LED is visible to indicate binary outputs. Once the door is opened, all power is automatically removed from the system [5]. A scheme of the entire system is provided in Fig. 1.

The detector systems transmit the classified measurement data to the computational block that applies the algorithm to obtain the unclassified output. The next step is the data barrier (which is not the same as the IB introduced in this paper). Its function is to pass the unclassified information in only one direction (towards the LED output) and prevents information flow in the other direction [5]. It also disallows passage of classified information. This is a double check since under normal circumstances, only unclassified information passes the data barrier anyway.

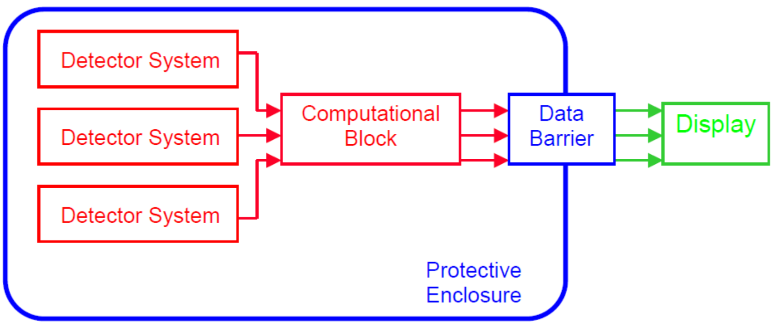

Figure 1: Attribute Measurement System with Information Barrier scheme that shows the attribute measurement detectors, the attribute-analysis computational block and the data barrier [5].

4. Information barrier concept

The IB prevents the leakage of classified information but at the same time gives confidence the system is performing: Detailed and sensitive measurements will be performed, but the result will be delivered in unclassified output (for example a binary “yes”/”no” output). There are two basic concepts that will be described in this section, the template and the attribute approach.

4.1. Templates

In the template approach, properties of all existing warhead designs will be measured and stored. For example, this could be a gamma ray spectrum of the warhead containing detailed and sensitive information. The inspecting party should never be able to have access to the stored data; in addition, it has to be guaranteed that there is no possibility for the inspected party to alter the stored data. Before dismantling a warhead of a certain design, a gamma spectrum will be recorded and the IB will compare the recorded spectrum with the stored data. If the two spectra match within a certain deviation, the IB output will display a “yes” signal, if there is no match it will display “no”. This procedure does not need to be limited to gamma spectroscopy, but the approach can possibly be applied to other measurements as well. It If a template IB works correctly than the deviation of a measurement compared to the template is small enough to ensure that dummies will be detected, but large enough to ensure that real warheads will not be detected as dummies (false negative).

The U.S. Department of Energy has sponsored the development of template IBs and tested their reliabilities. Brookhaven National Laboratory developed the Controlled Intrusiveness Verification Technology (CIVET) which was modified by Sandia National Laboratories for use with the Radiation Identification System to produce the Trusted Radiation Identification System (TRIS). Tests of TRIS conducted at the Pantex plant confirmed that it is able to identify various types of weapons and weapon components. During the test, templates for five weapon types were able to identify the corresponding five weapon types during the test that were previously unknown to the inspectors [6].

The main advantage of the template approach is that it is considered impossible to design a dummy warhead that matches within uncertainties with a particular warhead in the template since it is very difficult to reproduce the identical comprehensive characteristic spectrum. Since the exact signatures of the recorded warhead are given, only small deviations will be detectable. The probability of dummy warheads not being detected is very small.

There are also significant disadvantages with a template information barrier. First but foremost, the inspecting party has to have confidence that the warhead to serve as a template is indeed a warhead. The inspecting party needs confidence that the inspected party does not cheat during this initial step. One option would be to require measurements from a number of weapons with the same design that are randomly chosen by the inspecting party [7]. A separate information barrier could analyse the templates in regard to their deviation from each other. If it turns out that one of the weapons has a significantly different gamma spectrum for example, it might be considered that this was not a true warhead. Measuring a larger number of warheads would make a cheating scenario easier to be discovered. The final template to be used could be the average of the measured warheads; in addition measuring a number of warheads and combining them into a template already gives a measure of standard deviation of single warheads from the template. But even when randomly choosing a number of warheads, there is still no full guarantee that the devices were actually warheads. Another very significant disadvantage is the storage of the template. The template which contains very sensitive information on the specific warhead design has to be permanently stored on a storage medium. It must be ensured that there is no possibility for the inspecting or even third parties to gain access to it. Furthermore, there must not be a possibility for the inspected party to make changes to the data. This could be done by placing the storage medium in a safe that requires two combinations - one in possession of the inspecting and one in possession of the inspected party - to open it. Additional protection could be provided by encrypting the data with a two-part cryptographic key (again one for the inspected and one for the inspecting party). An alternative is to give the storage medium to the inspected party while the IB would provide the inspecting party with a digest or secure hash of the template when it is made and each time it is used. It would unambiguously confirm the template's authenticity [8]. If a number of warheads were measured for the template, an assessment of the variations exist. If, however, only one warhead was used for the template, it is not known how much other warheads of the same type deviate. Such an estimate is required because it must be defined what level of deviation from the template is allowed and what level indicates a dummy. This could be hard to define.

4.2. Attributes

In the attribute approach, no reference data is needed. Instead, the two parties agree on a set of attributes that define a nuclear warhead. All nuclear warheads will in an ideal situation fulfil the attributes, while no object other than a nuclear warhead will. Attributes can relate to nuclear measurements (for example gamma spectroscopy and neutron counting) and to non-nuclear measurements as well. There is the possibility of defining quantitative values for each attribute and acceptable deviations; another possibility is defining an allowable range of values, for example minimum or maximum allowable thresholds [9]. Crucial to an attribute IB is the development and agreement among the parties involved on the algorithm of the IB. Again, the output of the IB could be a “yes” or “no”. Different output options (such as a deviation from threshold or mean values or a fuzzy logic approach that yields an index) might be considered as long as they prevent sensitive information from being revealed. On the one hand, a binary output is the best solution from the point of view of not exposing sensitive information, while on the other hand, different outputs might be preferred from a point of view of giving the inspector sufficient information to reach a conclusion regarding the authenticity of the presented warhead.

The Trilateral Initiative developed an attribute IB. Although detailed descriptions are not publicly available, some technical information was released [4]. In 2000, the FMTTD was performed at Los Alamos National Laboratory, where the determination of attributes of unclassified plutonium and a US nuclear weapon component was demonstrated . The IB was sufficiently robust to allow measurement of a classified weapon component without revealing classified information[1]. Some technical information in regard to this project can be found in [5, 10, 11]. During the U.K.-Norway Initiative, IB designs were also developed [12]. This initiative was a project between the U.K. and Norway, where a warhead dismantlement verification simulation exercise was performed, see [1]. However, instead of a nuclear weapon or a material that could somehow be significant for nuclear weapons dismantlement verification, a Co-60 source was analyzed which only has limited technical relevance when it comes to nuclear weapons dismantlement verification.

In comparison to template IBs, the most significant advantage is that no data has to be stored permanently. Measurement results can be stored on volatile memory which is erased after power shut-down. This significantly decreases the danger that classified information will be released.

Attributes IB also have a number of disadvantages: Depending on the quality of attribute definitions, there might be the possibility that a dummy warhead could result in an IB output indicating that it is an actual warhead. It is a challenge to create and agree on a set of attributes where cheating becomes virtually impossible. That said, it will still be a tremendous challenge for an inspected party to cheat - especially in the case of a very comprehensive set of attributes.

This project will deal with the attribute approach and not with the template approach because of very limited knowledge about nuclear weapons design that is publicly available. For independent research on the template approach, detailed design information is necessary which does not exist in public. This is not the case for the attribute approach where more general (and available) knowledge is sufficient.

5. Effect of shielding

Performing necessary technical steps to authenticate a nuclear weapon at the nuclear weapon itself prior to its dismantlement poses significant technical difficulties. These difficulties mainly come from the shielding of the nuclear weapon pit containing the fissile material. Naturally, most attributes would be related to verifying certain characteristics of the fissile material in the weapon. Because exact nuclear weapon design details are neither available for independent researchers, nor for inspectors performing verification measures, it is fairly unknown what surrounds the fissile material. It is unknown

[1] see http://www.lanl.gov/orgs/n/n1/FMTTD/index_main.htm for more information on the project including technical papers with descriptions of the used components as well as lessons learned.

how much material (and which) acts as shielding of radiation. This information is however important for assessing quantitative information.

This paper does not intend to focus on the design of nuclear weapons. While little information has been de-classified, a number of papers exist in open literature. The fissile material of a nuclear weapon could possibly be surrounded by a tamper, which delays the expansion of the fissile material after the fissile mass becomes critical. A neutron reflector could be used to increase the yield. Depleted uranium or tungsten / tungsten carbide could be used among others; neutron reflectors could be made of beryllium. Nuclear weapons need conventional high explosives to initiate nuclear fission that contain large amounts of hydrogen, carbon, oxygen and nitrogen [13]. Advanced weapons make use of a primary (similar to a fission weapon described above), but also include a secondary (fusion stage).

Gamma rays are effectively attenuated by high-Z materials (Z being the atomic number) which are very likely to be present in some warheads (e.g. uranium or tungsten):

$$I = I_0 \cdot e^{-\mu\rho L}$$

where I_0 is the original gamma radiation intensity, I is the intensity after attenuation by attenuation coefficient μ over length L and absorbing material density ρ [14]. The photoelectric mass attenuation coefficient τ is given as [14]

$$\tau \propto \frac{Z^4}{E^3}$$

Neutrons can also be shielded. Neutrons can react via elastic scattering, neutron-induced nuclear reactions or inelastic scattering. Elastic scattering slows them down and changes their direction [15]. Neutron-induced reactions include the radiative capture reaction (n,γ). The probability of many neutron-induced reactions drops off rapidly with increasing neutron energy. In elastic scattering, the neutron can transfer an appreciable amount of energy in one collision. The average energy loss due to elastic scattering is given as $2E \cdot A/(A+1)^2$, where A is the mass number of the nucleus and E the energy of the neutron [14]. It is clear that the energy loss decreases with increasing atomic number A. It is very small for heavy elements. For heavier nuclei, partial energy transfers take place [15]. If the neutron energy is sufficiently high, inelastic scattering can also take place. For neutrons, the intensity equation becomes

$$I = I_0 \cdot e^{-\Sigma_{tot} L}$$

where $\Sigma_{tot} = \Sigma_{scatter} + \Sigma_{rad.capt.} + \dots$ is the total macroscopic cross-section, the sum of the individual reaction cross-sections. The neutron free path is $\lambda = 1/\Sigma_{tot}$. In solid materials, λ for slow neutrons may be in the order of magnitude of a centimetre or less, while it is normally in the range of tens of centimetres for fast neutrons [15]. Because of this, neutrons are more likely to escape absorbing material in a warhead than gamma-rays. Although neutron emission from fission process is smaller than gamma-ray emission, neutrons might be more detectable in passive measurements.

While high-Z materials are not very relevant in shielding neutrons, other nuclides likely to be present in warheads can have a significant effect. Beryllium for example can be used in nuclear weapons as neutron reflector. Beryllium is ideal because it has a low atomic weight and therefore a large energy transfer in elastic scattering. In fact it has the largest macroscopic elastic scattering cross-section of all elements due in part to its high packing density. This could shield neutrons emitted from the fissile material. Furthermore, neutrons could be shielded by the conventional high explosives which are composed of low atomic weight molecules.

In order to evade problems due to unknown shielding, authentication steps have been developed, that rely less on gamma and neutron measurements performed directly at the weapons before dismantlement.

6. Authentication steps

A different verification mechanism is proposed that overcomes these problems (related to shielding of radiation coming from the fissile core which is an unknown parameter as explained above) to great extent while still ensuring a chain-of-custody:

The actual dismantlement of a nuclear weapon (after it has been removed from the carrier system and transported in a sealed and ID-tagged container) happens in a facility specifically designed for this purpose. Inspectors verify that the facility has just one (or a known number of) exit(s) and that no secret exits exist to ensure that no material can be transported in and out of the facility undetected by inspectors. The exit(s) are monitored by gamma and neutron detectors in order to detect any nuclear material entering or leaving the facility. In addition, inspectors enter the facility before the container with the warhead arrives to check that no additional (hidden) material is present. If for example fissile material is already present prior to dismantling the warhead, it could be presented as the actual warhead's fissile material, while the warhead is kept hidden without being dismantled.

While inspectors are present, the container with the warhead inside is brought into the facility, the seal and ID tag are verified. Behind the IB a number of measurements could already be performed. These could serve two main purposes: A very rough template could be recorded (e.g. very rough assessments of isotopic compositions or fissile masses, if possible behind the shielding) or rough attributes (e.g. the general presence of fissile material). Whether these measurements are possible without knowledge of shielding is a question that needs to be addressed.

After these measurements, the inspectors leave the facility so that the weapon can be removed from the container and be dismantled. During the dismantling process, the warhead will be separated into several components that will be put into separate containers. One container will contain the original fissile material without any shielding. Another container will contain the conventional high explosives. Other containers contain additional material present in the previous nuclear warhead.

Once the containers are closed, the inspectors enter the facility again. Now detailed gamma and neutron measurements of the separated components take place (behind an IB) which should in the end authenticate the nuclear weapon as a whole. The advantage of this authentication after the actual dismantlement is that only known shielding (i.e. the container) is present so that quantitative attributes can be assessed.

In the end, the IB can compare end results with the measurements taken at the beginning at the actual (not yet) dismantled warhead to create confidence that the material in the various containers after the dismantlement came indeed from the nuclear weapon so that the authentication of the components authenticate the nuclear weapon as a whole. If this is possible because of the shielding has not been determined yet.

While this entire process happens behind an IB, he/she needs to know the fissile material mass, which will most likely be one of the attributes during the authentication. This is necessary because in further verification measures within the chain-of-custody, inspectors need to be sure that all fissile material is vitrified or used for civil purposes and that none can be diverted. Fissile material shall be declared (including its mass) and monitored. Fissile material mass of a single warhead could, however, be considered sensitive information. Therefore an IB should not declare a single warhead's fissile mass, but the total fissile mass of a number of warheads instead. This way the average mass, but not individual masses of warheads can be determined, as long as different types of warheads were dismantled. Further required information would be the average isotopic composition of the fissile masses which will also very likely be a measured attribute.

7. Possible measurements for attribute determination

This chapter deals with defining the attributes to be measured. This list of attributes will not be exhaustive and more attributes than presented here will be necessary. This is however a list of what the authors consider the most important attributes: For both uranium and plutonium warheads, the presence and mass of fissile material should be determined, since a threshold mass is required to reach criticality. Also, the fissile material should be a pure metal, with only a minimum allowable content of oxides Significant presence of oxides would increase the critical mass and will increase the spontaneous fission rate through (α, n) reactions which is not wanted and will most likely not occur in nuclear weapons. By introducing this attribute, dummies with nuclear fuel (containing oxides) will be detected. For plutonium, the age can be determined as dates of plutonium separation might be known. The isotopic ratio between Pu-239 and other plutonium isotopes should be determined and exceed a certain threshold. For uranium, the degree of enrichment should exceed a certain threshold. A very strong indication of a nuclear warhead is both the presence of fissile material and high explosives.

The defined attributes need to be measured, therefore measurement techniques are presented for each attribute. Often, more measurement techniques will be possible that are not all listed because this paper's scope is only to present some potential possibilities of attribute measurements; sometimes it is not clear yet if a measurement technique can work. This will be studied in the present work. Although non-nuclear measurement techniques could be helpful, the study will be limited to nuclear non-destructive assay (NDA) using gamma and neutron detectors. A summary is given in Tables 1, 2 and 3.

attribute	*measurement system*	*measurement technique*
presence	gamma spectrometry	Pu-239 peaks at 345.0, 645.0 and 658.9 keV
age	gamma spectrometry	332.4 keV / 335.4 keV ratio
pure metal	gamma spectrometry	870.7 keV peak from O-17 de-excitation absent
isotopic ratio	gamma spectrometry	642.5 keV (Pu-240) / 646.0 keV (Pu-239) ratio
fissile mass	passive neutron multiplicity counting	spontaneous fission rate (Pu-238, Pu-240, Pu-242)

Table 1: attributes and measurement techniques for plutonium

attribute	*measurement system*	*measurement technique*
presence	gamma spectrometry	185.72 keV (U-235) and/or 1001.03 keV (U-238) peaks
fissile mass	active neutron multiplicity counting	induced fission rate (U-235)
pure metal	neutron-initiated gamma spectrometry	6129 keV gamma peak produced by 14 MeV neutrons
isotopic ratio	gamma spectrometry	185.72 keV (U-235) / 1001.03 keV (U-238) ratio after intrinsic self-calibration
	active neutron multiplicity counting	ratio of induced fission (U-235) to total transmission (U-235+U-238)

Table 2: attributes and measurement techniques for uranium.

attribute	*measurement system*	*measurement technique*
presence	gamma spectrometry	prompt gamma ray neutron activation analysis,measuring N presence and ratios of N/C, H/C and O/C, described in [16, 17]

Table 3: attributes and measurement techniques for high explosives.

7.1. Neutron coincidence and multiplicity counting

While gamma spectroscopy is widely applied and does not need to be described, this section gives a short overview over both passive and active neutron coincidence and multiplicity counting techniques. Neutron coincidence counting is used to measure coincident neutrons. This can be used to distinguish between reactions with only one neutron as a product and those with multiple neutron emissions. In our case, fission events, where usually multiple neutrons are emitted (with a certain neutron multiplicity distribution) should be detected, while in particular (α, n) and other uncorrelated sources should not be measured. Information regarding the features of coincidence counters is found in [14].

Alpha particles can produce neutrons through (α, n) reactions. This can become significant when isotopes with high alpha decay rates (e.g. U-233, U-234, Pu-238 or Am-241) are present [14]. The range of alpha particles in uranium and plutonium dioxide is roughly 0.006 and 0.007 cm, respectively[2]. If oxygen is intimately mixed with the alpha emitting material, a (α, n) reaction may take place. While there should not be large amount of oxygen present in nuclear weapon pits, impurities with oxides are possible.

The neutron flux emitted by the sample is affected by a number of possibly unknown properties [18]:

1. fission rate (the goal of neutron coincidence/multiplicity counting)
2. sample self-multiplication / variation across the sample
3. (α, n) reaction rate
4. other properties can be eliminated by careful calibration and counter design or are small or constant as described in [18]

The response function in passive coincidence counting can in particular be perturbed by the effect of self-multiplication that takes place in plutonium and uranium samples [14]. There are two common internal sources for self-multiplication: One is induced fission in an isotope by a neutron emitted by a previous fission event; the other is fission induced by a neutron from a previous (α, n) reaction [14]. Multiplication depends in particular on the sample composition and geometry [19].

For neutron coincidence counting (where both single and double multiplicities are measured), calibration using reference materials is necessary in order to obtain the fission rate. This is necessary because two parameters are measured, but at least three important parameters need to be solved, see above. Usually, the self-multiplication is not determined which requires representative reference materials. This is hard to achieve in the case of warhead authentication, where warhead designs remain unknown, so that representative reference materials can usually not be obtained.

Passive neutron multiplicity counting can determine the fission rate without the need of representative reference materials. For N unknowns in the function, N measured parameters are necessary. Multiplicity counting uses a third parameter (triple multiplicity) so that three unknowns can be solved, including the multiplication. Initial determination of detector parameters can be done with a Cf-252 source alone. Multiplicity counting based on this calibration can be slightly biased because of a detector's different efficiencies between Cf-252 and Pu fission neutrons [20].

Active neutron coincidence or multiplicity counting (using an external source to induce fission so that induced fission is measured as opposed to spontaneous fission) is more complex than passive neutron coincidence or multiplicity counting because of one additional unknown parameter, the coupling [21]. Coupling is the interaction of the source neutrons with the assay sample. The fission rate depends both on the induced fission rate and the coupling. This additional parameter has to be determined, as explained in [21]. It has to be noted that there is only limited literature and field experience on active neutron multiplicity counting [21]. Notably more field experience exists for active neutron coincidence counting: The Nuclear Materials Identification System (NMIS) [22] incorporates this technology; however application of NMIS to unknown weapon designs seems rather complicated because of reference measurements that are not available.
In general, it must be noted that in the mathematical models yielding the fission rate, assumptions have been made (explained in detail in [18]) that might not be entirely valid in the case of warhead authentication. How large the bias through these assumptions is needs to be assessed and what possible solutions could be. In particular, it is assumed that the neutron detector efficiency and probability of fission are uniform over the sample volume. This is called the "point model" as it is equivalent to the statement that all neutrons are emitted at one point [18].

[2] This range has been computed using the Bragg-Kleeman rule [14]:
$\text{range} = 0.00032 \cdot \sqrt{A} / (\text{density}(\text{g/cm}^3)) \cdot \text{range in air}$
The range in air for plutonium and uranium is 3.7 and 3.2 cm, respectively.

7.2. Measurements for plutonium attributes

From gamma spectrometry, the presence of plutonium, its age and isotopic ratio can be deduced. For these purposes, so-called Pu300, Pu600 and Pu900 systems were developed for the FMTTD [5] that analyze plutonium characteristics in certain energy regions. When comparing gamma ray count rates to deduce isotopic ratios, it is helpful if gamma rays that are compared have similar energies so that the energy-dependent attenuation of absorbing material can be assumed to be the same for the peaks. It is more difficult to compare peaks that have very different energies because of significantly different attenuation coefficients. The age of plutonium can be determined by looking at Pu-241 and its daughter nuclides U-237 and Am-241 that have peaks between 325 and 350 keV [2]. Freshly separated plutonium contains Pu-241, U-237 results from alpha-decay of Pu-241, Am-241 is the result of beta-decay. Both U-237 and Am-241 decay further to two identical states of Np-237 by gamma ray emission including two intense peaks in the 325 and 350 keV range. The Pu300 code resolves the Am-241 and U-237 peaks from the Pu-239 peaks in the region [2]. The gamma ray emissions can be seen in Fig. 2. The branching decay of Pu-241 causes the levels that emit the 332.4 and 335.4 keV gamma rays to be populated at different rates. These are a known function of time, which allows for age determination (see Fig. 2).

The isotopic ratio $^{240}Pu/^{239}Pu$ can be determined using the Pu600 code which looks at the 630-670 keV region. The ratio can be determined by examining the peak areas of the 642.5 keV Pu-240 peak and the 646.0 keV Pu-239 peak [2]. This can be seen in Fig. 3.

The general presence of plutonium follows from Pu300 and Pu600 analyses: Pu-239 peaks can be found at 345.0, 645.0 and 658.9 keV. A criterion for determining the presence of plutonium could be that the peaks exceed the underlying continuum (due to background) by at least five standard deviations.

Gamma ray spectroscopy can also be utilized to analyze the possible presence of PuO_2 which should not be present in significant amounts in weapons built with metal plutonium. The presence of oxides can be determined for example by the Pu900 code that can analyze an 870.7 keV peak that is present if oxide is present. It results from de-excitation of the first excited state of O-17. The excitation results from alpha particles from the decay of plutonium that interact with O-17 via coulomb excitation which is an inelastic $^{17}O(\alpha,\alpha')$ process [2]. Another process leading to the same gamma ray emission are alpha particle reactions with nitrogen impurities in the oxide, $^{14}N(\alpha,p)$ [2].

Passive neutron coincidence or multiplicity counting can be used to determine plutonium mass. The mathematics of neutron multiplicity counting that give the plutonium mass is presented in [18]. The method detects the correlated fast neutrons emitted as a result of spontaneous fission decays in mainly Pu-240, but also Pu-238 and Pu-242. The primary quantity determined in passive neutron coincidence or multiplicity counting is an effective amount of $^{240}Pu_{eff}$ and consequently m_{240eff}, which represents a weighted sum of the three isotopes. m_{240eff} is the mass of Pu-240 that would give the same coincidence response as that obtained from all the even isotopes in the actual sample [14]:

$$m_{240eff} = 2.52 \cdot m_{238} + m_{240} + 1.68 \cdot m_{242}$$

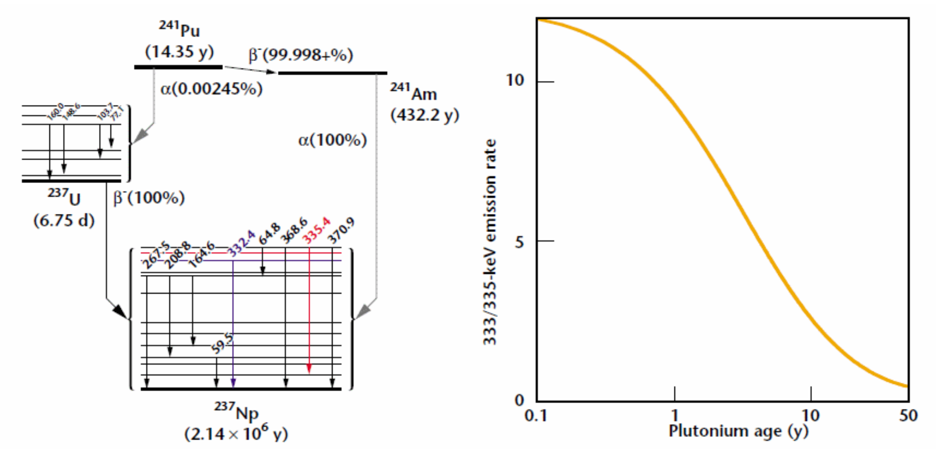

Figure 2: Left: The branching decay of Pu-241 shows the gamma ray transitions measured by the Pu300 method [2].

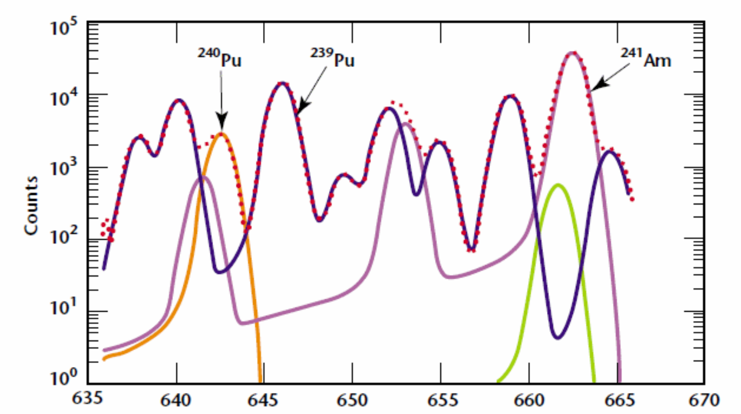

Figure 3: The 630-670 keV region of the gamma ray spectrum shows its resolution by nonlinear regression into its isotopic constituents for the Pu600 method [2]. The orange line corresponds to Pu-240, the light purple line to Am-241. The dotted line represents the total spectrum.

For the conversion of m_{240eff} into the total Pu mass, the isotopic mass fractions R_{238} , R_{240} and R_{242} must be known to calculate

$$^{240}Pu_{eff} = 2.52 \cdot R_{238} + R_{240} + 1.68 \cdot R_{242}$$

The total plutonium mass is then given as

$$m_{Pu} = \frac{m_{240eff}}{^{240}Pu_{eff}}$$

7.3. Measurements for uranium attributes

Measuring uranium attributes via gamma spectrometry is significantly more difficult because of the low gamma emissions rate. Therefore alternative measurement techniques are also suggested for attribute determination.

Presence of uranium could be determined by measuring the strongest gamma peaks: U-235 has its strongest peak at 185.72 keV, U-238 through its Pa-234m daughter at 1001.03 keV. The isotopic ratio would also be determined by comparing these two peaks. Since the attenuation of gamma radiation is, however, dependent on energy, these two peaks suffer from different attenuation coefficients, as their energies are not in the same region. The solution is to determine the ratio of the relative efficiency at the two energies by intrinsic self-determination. It can be shown that – for a series of gamma rays from a single isotope – the quotient of the photo peak counts at energy E_j^i and the branching ratio BR_j^i is proportional to the efficiency at energy E_j, $C(E_j^i)$ being the photo peak area of gamma ray j emitted from isotope i, N^i being the number of atoms of isotope i and $T_{1/2}^i$ being the half-life of isotope i [23]:

$$\frac{C(E_j^i)}{BR_j^i} \propto [\frac{N^i \ln 2}{T_{1/2}^i}] \cdot \varepsilon(E_j)$$

For this intrinsic self-calibration, gamma rays from several isotopes can be used as long as they have the same physical distribution [23]. Models exist to interpolate between gamma lines where the efficiency has been calculated [23]. In the case of uranium, intrinsic self-calibration can be done by comparing the peaks of the U-238 daughter nuclide Pa-234m, which also has a weak peak at 258.26 keV, which is close to U-235 peaks. Therefore, the isotopic ratio could also be calculated by comparing the 1001.03 keV (Pa-234m as indicator of U-238) with the 185.72 keV U-235 peak. However the spontaneous fission rate of U-235 is very small, it might be difficult to measure in reasonable time.

Therefore, a system using active neutron multiplicity counting might be more feasible. By adding an active neutron source, U-235 undergoes induced fission. In contrast, the total uranium (235+238) attenuates the transmission of active source neutrons through absorption and inelastic scattering. Therefore, the enrichment of uranium can be determined by measuring the rate of induced fission and the rate of direct source-neutron transmission [19]. The transmission is measured at the count distribution that corresponds to the time-of-flight of the source neutrons, as seen in Fig. 4.

The mass can also be obtained by active neutron multiplicity counting. The math works similar to determining plutonium mass as explained above, but coupling has to be incorporated.

To determine whether the fissile material exists as a pure metal or not, neutron induced gamma spectrometry can be used. A 6129 keV gamma line from oxygen can be observed by irradiating the fissile material with 14 MeV neutrons due to inelastic scattering, see Fig. 5. More information and further techniques are found in [19].

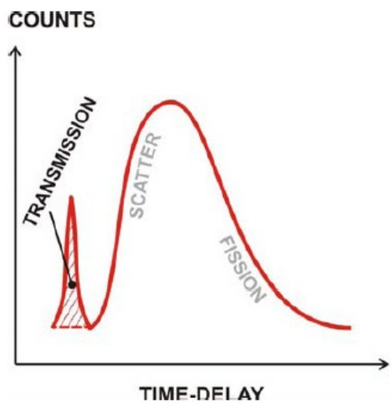

Figure 4: The integral of the first peak in the count-distribution is proportional to the neutron transmission rate and thus total uranium [19].

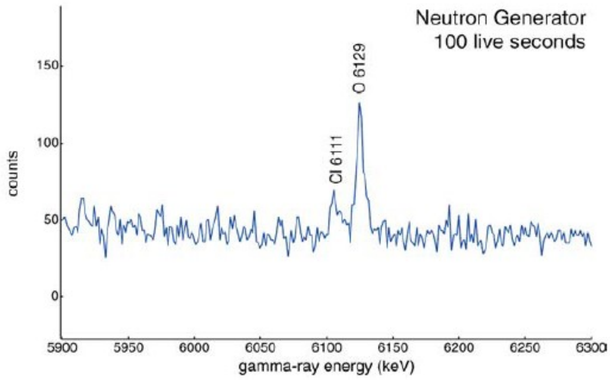

Figure 5: Gamma ray spectra for 14.1 MeV neutrons on oxygen, as obtained by A.J. Caffrey, INEEL, the sample was $COCl_2$ [19].

8. Conclusion and outlook

This paper has suggested warhead authentication as one element of the entire warhead dismantlement verification process. Information barriers, in particular the template and attribute approaches have been presented that allow warhead authentication without revealing sensitive information. Regarding the attribute approach, possible attributes have been presented including options to measure them. In the future, these options need to be validated. If possible, the following steps should be followed to validate the measurement options and build the IB:

1. Neutron and gamma signatures should be simulated for a variety of uranium and plutonium samples that differ in the relevant properties, especially isotopic composition, masses and geometry. Simulations can be performed by using Monte Carlo techniques. For neutron multiplicity analysis, the MCNP POLIMI code [24] can be used. The purpose of these simulations is to determine what signatures can be used to determine attributes and how the attribute determination depends on the signatures.
2. Experiments need to be performed with a couple of uranium and plutonium samples to compare the experimental results to the simulation results in order to assess the bias of the simulations. It is helpful if the samples could be to some degree representative of the items to be authenticated. It is obviously not possible for independent research to get access to fissile material used in nuclear weapons, and it needs to be assessed to what extent other samples that are available are useful for this task.
3. Knowing what attributes can be measured, the optimum set of attributes must be defined so that false positives and false negatives are minimized.
4. From the simulation and experimental results, an attribute algorithm needs to be written that uses the raw measurement data as an input and calculates an unclassified output using the attribute definitions.
5. Finally, such a system should be tested with unknown samples. As tests cannot be performed with nuclear weapon components, a “proof-of-concept” IB algorithm that uses different attributes that can be tested on non-classified forms of fissile material (e.g. reducing a threshold for minimal mass or enrichment degree) needs to be used.

9. References

[1] Cliff D, Elbahtimy H, Persbo A; *Verifying Warhead Dismantlement: Past, present, future;* VERTIC; 2010.

[2] Department of Energy; *Technology R&D for Arms Control;* Defense Technical Information Center; 2001.

[3] Klingberg F; *Capability to determine shielding around radioactive substances using gamma ray spectrometry*; Department of Physics, University of Hamburg; 2009.

[4] Langner D G *et al.*; *Attribute Verification Systems with Information Barriers for Classified Forms of Plutonium in the Trilateral Initiative;* Proceedings of the Symposium on International Safeguards Verification and Nuclear Material Security; IAEA-SM 367/17/02; 2001.

[5] Fissile Material Transparency Technology Demonstration; *Technical Overview of Fissile Material Transparency Technology Demonstration Executive Summary;* retrieved from http://www.lanl.gov/orgs/n/n1/FMTTD/presentations/pdf_docs/exec_sum.pdf.

[6] Mitchell D J, Tolk K M; *Trusted Radiation Attribute Demonstration System;* Sandia National Laboratories; 2000.

[7] Fetter S, Cochran T B; *Verifying the Authenticity of Nuclear Warheads Without Revealing Sensitive Design Information;* Third International Workshop on Verified Storage and Destruction of Nuclear Warheads; 1991.

[8] Committee on International Security and Arms Control, National Research Council; *Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities;* National Academies Press; 2005.

[9] Kane W R *et al.*; *On Attributes and Templates for Identification of Nuclear Weapons in Arms Control;* Brookhaven National Laboratory; 2000.

[10] Avens L R, Doyle J E, Mullen M F; *The Fissile Material Transparency Technology Demonstration;* 42nd Annual Meeting of the Institute of Nuclear Materials Management; 2001.

[11] Whiteson R, MacArthur D W; *Fissile Material Transparency Technology Demonstration Attribute Measurement System with Information Barrier: Functional Requirements;* LA-UR-99-5634; 2000.

[12] Kingdom of Norway, United Kingdom; *The United Kingdom-Norway Initiative: Research into the Verification of Nuclear Warhead Dismantlement;* Working Paper NPT/Conf.2010/WK.41; 2010.

[13] Conn C; *Synthesis of Energetic Materials; Energy and Technology Review*; Jan/Feb 1988.

[14] Reilly D, Ensslin N, Smith H, Kreiner S; *Passive Nondestructive Assay of Nuclear Materials;* LA-UR-90-732; 1991.

[15] Knoll G F; *Radiation Detection and Measurement;* 2nd ed; Wiley New York; 1989.

[16] Caffrey A J, Cole J D, Gehrke R J; *Chemical Warfare Agent and High Explosive Identification by Spectroscopy of Neutron-Induced Gamma Rays; IEEE Transactions on Nuclear Science*; Vol. 39; 1992; p. 1422-1426.

[17] Twomey T R, Caffrey A J, Chichester D L; *Nondestructive Identification of Chemical Warfare Agents and Explosives by Neutron Generator-Driven PGNAA;* INL/CON-07-12304; 2007.

[18] Langner D G *et al.; Application Guide to Neutron Multiplicity Counting;* LA-13422-M; Los Alamos National Laboratory; 1998.

[19] Mihalczo J T, Mattingly J K, Mullens J A, Neal J S; *NMIS With Gamma Spectrometry for Attributes of Pu and HEU, Explosives and Chemical Agents;* Y/LB-16,123 Rev. 1; 2002.

[20] Carillo L A; *Uncertainty Analysis for Determination of Plutonium Mass by Neutron Multiplicity Counting;* LA-UR-98-3044; Los Alamos National Laboratory; 1998.

[21] Ensslin N, Geist W H, Krick M S, Pickrell M M; *Active Neutron Multiplicity Counting; ;* Passive Nondestructive Assay of Nuclear Materials 2007 Addendum, 2007.

[22] Mihalczo J T, Mullens J A, Mattingly J K, Valentine T E; *Physical Description of Nuclear Materials Identification System (NMIS) Signatures; Nuclear Instruments and Methods in Physics Research, Section A*; Vol. 450; Aug 2000; p. 531-555.

[23] Sampson T E; *Plutonium Isotopic Analysis Using PC/FRAM;* Passive Nondestructive Assay of Nuclear Materials 2007 Addendum, 2007.

[24] Marseguerra M, Padovani E, Pozzi S; *The Use of MCNP-POLIMI Code for Time Correlation Safeguards Measurements;* Smorn Symposium on Nuclear Reactors Surveillance; 2002.