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Supporting Technology for Chain of Custody of Nuclear Weapons and Materials Throughout the Dismantlement and Disposition Processes

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Verification technologies based upon electromagnetics and acoustics could potentially play an important role in fulfilling the challenging requirements of future verification regimes. For example, researchers at the Pacific Northwest National Laboratory (PNNL) have demonstrated that low frequency EM signatures of sealed metallic containers can be used to rapidly confirm the presence of specific components on a "yes/no" basis without revealing classified information. PNNL researchers have also used ultrasonic measurements to obtain images of material microstructures which may be used as templates or unique identifiers of treaty accountable items (TAIs). Such alternative technologies are suitable for application in various stages of weapons dismantlement and often reduce or eliminate classified data collection because of the physical limitations of the method. In such cases the need for an information barrier to prevent access to classified data is potentially eliminated, thus simplifying verification scenarios. As a result, these types of technologies may complement traditional radiation-based verification methods for arms control.

This article presents an overview of several alternative verification technologies that are suitable for supporting a future, broader and more intrusive arms control regime that spans the nuclear weapons dismantlement lifecycle. The general ca-

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pabilities and limitations of each verification modality are discussed and example technologies are presented. These technologies are relevant throughout a potential warhead monitoring regime, from entry into chain of custody (i.e., establishing confidence in the authenticity and integrity of the warhead) to dismantlement and final material disposition (i.e., maintaining confidence that chain of custody has not been broken).

INTRODUCTION

A fundamental challenge to implementing a nuclear warhead dismantlement regime is the ability to detect unauthorized material diversion throughout the dismantlement and disposition process through strong chain of custody (CoC) implementation. Verifying the declared presence, or absence, of nuclear materials and weapons components throughout the dismantlement and disposition lifecycle is critical. From both the diplomatic and technical perspectives, verification under these future arms control regimes will require new solutions. Since any acceptable verification technology must protect sensitive design information and attributes to prevent the release of classified or other proliferation-sensitive information, non-nuclear non-sensitive modalities may provide significant new verification tools which do not require the use of additional information barriers.

Article VI of the Treaty on the Non-proliferation of Nuclear Weapons (NPT) commits the United States and other nuclear weapons states "to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty of general and complete disarmament under strict and effective international control."[1] This article underlies the U.S. commitment, reiterated by President Barack Obama in his April 2009 Prague speech, "to seek the peace and security of a world without nuclear weapons."[2] If the five NPT nuclear weapon states are to fulfill their NPT Article VI obligations through arms control agreements, then they will need to develop, agree upon, and implement those with effective verifiability that go beyond anything the United States and Russia (or any other state) have adopted to date.

The ongoing successful implementation of the New START Treaty is widely regarded as a noteworthy security achievement for the Obama Administration and for U.S.–Russian relations. Future reductions in the U.S. and Russian nuclear arsenals may also require engagement with, and inclusion of, the three remaining nuclear weapons states identified in the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), namely the United Kingdom, France, and China (together with the United States and Russia known as the P-5) as well as other nuclear weapons not recognized by the NPT. Progress by the P5 is necessary in order to fulfill the obligations undertaken via Article VI of the NPT. Future verification needs could include monitoring the cessation of production of new fissile material for weapons, monitoring storage of warhead components and fissile materials, and verifying dismantlement of warheads, pits, secondary stages, and other materials.

Current U.S.–Russian strategic arms reduction obligations, embodied in the New START Treaty, limit accountable deployed strategic nuclear warheads to 1,550 for each party; a combined limit of 800 deployed and non-deployed intercontinental ballistic missile (ICBM) launchers, submarine-launched ballistic missile (SLBM) launchers, and heavy bombers equipped for nuclear armaments; and a separate limit of 700 deployed ICBMs, deployed SLBMs, and deployed heavy bombers equipped for nuclear armaments.[3] The 1,550 figure represents a 74 percent reduction from the original START Treaty's accountable limit of 6,000 warheads for each party. Non-strategic and non-deployed nuclear weapons production and disposition of fissile material for weapons are not addressed in the New START Treaty. The Treaty's verification regime is therefore designed to enable the two participating states to verify that each side's deployed strategic nuclear warheads and delivery systems do not exceed the agreed ceilings.

As the United States and Russia continue to move to lower numbers in the bilateral context, and as the other P-5 states (the United Kingdom, France, and China) begin to explore their participation in a future multilateral nuclear arms reduction regime, verification techniques may become substantially more complicated and intrusive. Verification systems implementing such techniques must continue to provide sufficient confidence to the inspecting parties, while at the same time protecting the inadvertent disclosure of classified information. These systems may make use of complementary verification technologies that do not collect classified or other proliferation-sensitive information particularly attractive. Development of effective verification scenarios and technologies is made especially challenging because typically the host country controls the item to be verified, called a treaty accountable item (TAI), as well as measurement equipment used for verification. The justification for such scenarios lies both in the interest of the host country to protect its own classified nuclear design information as well as the NPT requirement not to further the proliferation of nuclear weapons through the disclosure of such information.

There are many international agreements which address the materials production portion of the lifecycle to prevent proliferation in non-nuclear weapon states (NNWS) and a robust history of U.S.–Russian bilateral agreements which have focused on the deployed weapons stockpile portion of the lifecycle for those two states. As numbers of nuclear weapons decrease under current and future bilateral and multilateral treaties, there will be an increasing need for verification and transparency throughout the reduction process. This will likely include the need to verify the dismantlement of nuclear weapons and the conversion and disposition of those dismantled components.

Future warhead monitoring regimes will need to meet some basic requirements to provide sufficient evidence to treaty partners or any verification body that obligations are being met, and that no cheating has occurred. The first requirement is the need for a mechanism to enter TAIs into the verification regime. TAIs can include but are not limited to warheads, bombs, components, high explosives, and special nuclear material. This process of entering TAIs into the verification regime is called initialization. It can include anything from state reporting to application of a tag/seal and unique identifier to a complex series of radiation or non-radiation measurements.

Once initialized into the regime, the declared item must be confirmed to be, in fact, an accountable item (e.g., a nuclear weapon). The process of warhead confirmation is an active field of investigation which continues to explore the boundary between verification and classified data protection.[4–7] These first two steps create confidence in the integrity and authenticity of the item. A critical element of this step lies in gaining confidence in the correct operation of the measurement tools used to verify the TAI. Given that the inspecting party may be granted only limited access to these tools, ensuring correct operation presents its own challenges typically addressed through a process called *authentication.*

Authentication is “the process by which the Monitoring Party gains appropriate confidence that the information being reported by a monitoring system accurately reflects the true state of the monitored item.”[8] The host state imposes similar requirements on the inspecting party’s verification equipment, and must certify all such equipment prior to installation and use in its facility. Certification is therefore “the process by which a Host Party assures itself that a monitoring system ... will not divulge any classified information about an inspected sensitive item to a Monitoring Party.”[9] A common approach to reconcile the needs of these processes has been to implement an information barrier that serves to protect classified measurement data from the inspecting party.[10] Measurement data sufficient to verify the veracity of the TAI are collected and processed into an unclassified binary pass/fail result. The information barrier allows the inspecting party access only to this result and not to the overall measured data set. Given that the authentication process has confirmed the verification capability of the measurement system, the binary result reflects that the measured system, material, or component meets the criteria agreed by both parties.

Behind the information barrier, two approaches exist to derive the pass/fail criteria, the template approach and the attribute approach. The template approach utilizes intrinsic characteristics of the declared item to be compared to the same characteristics of a known and trusted item using the measured data.[11] This approach typically requires the persistent (long-term) storage of classified data, with its attendant risks. The attribute approach utilizes characteristics consistent with a nuclear weapon or material, such as a plutonium-240 to plutonium-239 ratio, so that an item can be verified without the persistent storage of classified data.[12]

Information barriers are necessary at all measurement stages where classified or sensitive information is being collected, but they are most commonly applied in the warhead confirmation and dismantlement phases of a monitoring regime. The verification needs at this point in the process have necessitated measurements that are intrusive and that collect potentially classified information. The complexity of such an approach makes the search for alternative and complementary verification methods desirable, especially beyond the stage of initial entry of the TAIs into the verification regime. Indeed, a recent report by the International Security Advisory Board to the U.S. Department of State advised to "develop technologies and procedures for the mid-and long-term for a systems approach to each country's nuclear enterprise that encompasses the spectrum from material production, to component fabrication, warhead assembly, deployed and non-deployed weapons, dismantlement, and material disposition."[13] In order to support such a systems approach, it is desirable to develop a range of technologies beyond those involving traditional information barrier systems in order to support all phases of the verification regime.

Technologies must be able to perform facility monitoring without releasing security details, and must verify both empty and full containers as well as shrouded items without the ability to visually inspect the interior. One disadvantage of many current radiation-based technologies is the fact that the measurement results are classified, and therefore require the use of an information barrier to protect the data. This adds complexity to the equipment and places an additional burden on the authentication and certification requirements. It also significantly restricts the data available for review and confirmation to a single red/green light readout.

Technologies that can provide a complementary verification measurement without collecting classified data would be preferred by all relevant parties. These technologies can use either a different modality than that of a radiation measurement (i.e., an "orthogonal measurement") or use a physical process that is prevented from collecting classified data (i.e., those having an "intrinsic information barrier"). Technologies in the latter category may produce useful points of verification without the need for complex information barrier technology. Additionally, data collected can form a "template" for a measured item, similar to that used in radiation measurements, to detect changes in physical characteristics of the item. Finally, they can further be used to verify non-nuclear components throughout the dismantlement process, something not possible through traditional radiation detection measurements. Several of these methods will be discussed in detail in this article.

Throughout the dismantlement portion of the nuclear weapons and material lifecycle, one of the fundamental challenges is the ability to deter and detect unauthorized material diversion. This challenge may be met via strong CoC implementation, wherein verifying both the declared presence and absence of nuclear materials and weapons components is a critical aspect. CoC is the process by which a controlled boundary is established and maintained around a TAI to both deter and detect unauthorized access to the item. Verification of CoC is often differentiated from the initialization process for a TAI. In this case, CoC verification maintains, rather than initially establishes, confidence in the authenticity and integrity of the TAI as it travels through the dismantlement and disposition process.

Typical CoC approaches utilize technologies to maintain the integrity and authenticity of items and facilities through unique identification and tamper detection.[14,15] A unique challenge occurs during dismantlement, where traditional CoC measures such as tags, seals, and surveillance are ineffective because the host must have complete access to the item to perform dismantlement. This means that all tags and seals protecting the item must be removed. Additionally, the process is highly classified, and surveillance will not be permitted. As a further complication, a single discrete TAI enters the process in the form of a complete weapon or warhead, but many containerized items exit in the form of dismantled components. This change in configuration and separation of components make confirmation that diversion or substitution has not occurred extremely difficult.

The final requirement of a warhead monitoring regime is to provide the ability to remove the item from the verification regime or hand it off to another regime without any loss in confidence in the integrity and authenticity of the item or material. Verifiable disposition of TAIs will most likely require their conversion into unclassified physical and chemical forms. Final disposition may also include long-term storage of these items or even fabrication into fuel assemblies in the form of mixed oxide (MOX) fuel and insertion into reactors to produce electricity and to alter the isotopic composition so it is no longer weapons-usable.

This article focuses on several tools that broaden the menu of available warhead confirmation and CoC technologies and methodologies while inherently protecting classified information that is not required for the verification regime. We consider one EM technique and several acoustic techniques with different means and approaches to apply these technologies throughout the CoC process. We also describe the manner in which non-nuclear technologies offer complementary methods and approaches to traditional radiation-based verification techniques. Since the strengths of these technologies address many areas where radiation-based technologies have limitations, they can be used in conjunction with radiation-based measurements to create a stronger and more robust CoC regime. The end result will be increased confidence in the overall verification regime, and an increase in confidence, transparency, and trust among treaty parties.

EM INDUCTION COIL

Operating Principles

Low-frequency electromagnetic (EM) signals have multiple advantages that are desirable for arms control treaty verification and CoC implementation. Since measurements at low frequencies are a function of the macroscopic electrical and magnetic properties of materials, it is feasible to consider the elimination of an information barrier that may otherwise be required to protect sensitive data related to the isotopic composition of nuclear weapons components. Potential operation in explosives facilities does not present a safety hazard since small magnetic field levels similar to the earth's background field can be used to collect the required data. In addition, EM measurements can typically be performed using standard instrumentation in a short time frame such as several minutes. The instrumentation can be designed to be battery-operated, lightweight, and free from export control restrictions. These characteristics make EM-based methods particularly attractive for rapid evaluation of large stockpiles of nuclear weapons or materials.

The behavior of low-frequency EM signals is governed by well-known physical principles such as Faraday's law of EM induction. Faraday's law is one of the four equations known as Maxwell's equations that formally describe the classical behavior of EM fields.[16] Low-frequency EM fields are extensively used in a broad array of technologies such as electrical power generation, metal forming, nondestructive testing, and induction heating. Low-frequency EM technologies are also widely used to inspect metallic containers and infrastructure to determine item integrity.[17–19] The low-frequency regime is distinguished from the high-frequency regime in that the electric and magnetic fields are effectively decoupled from each other and the energy distribution is locally concentrated around the component or device instead of propagated into space as EM waves. Practical frequencies for low-frequency operation are application-dependent and can range over a wide span from 10 Hz to 10 MHz or higher.

An important fundamental parameter in determining the interaction of EM signals with electrically conductive materials is the depth of penetration or "skin depth."[20] The skin depth formula is shown in equation 1 where f is the signal frequency, μ is the material magnetic permeability, and σ is the material electrical conductivity. This quantity is used in the design of low-frequency systems and relates the ability of an EM field to penetrate the material based on the applied field frequency as well as the material conductivity and permeability.

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

The amplitude of the induced current inside the material decays exponentially with increasing depth per the skin effect phenomenon, and the skin depth is defined as the depth below the surface at which the amplitude is 37 percent of its surface value. At three skin depths, the amplitude is 5 percent of its surface value and little interaction can be obtained with internal features at this depth.

Weapons Component and Material Storage

An example use of low-frequency EM signals for arms control treaty verification is the EM induction coil developed at PNNL.[21] This technology, shown in Figure 1, was initially demonstrated on DOE-funded projects in the late 1990s and further developed on a DTRA-funded project in the early 2000s for verification of stored nuclear materials. Using the skin depth principle, the low-frequency magnetic field from an encircling coil penetrates a conductive barrier such as a stainless steel storage container and interacts with the material placed inside the container. The method has the ability to examine components and materials used in the dismantlement and disposition process and stored or transported within sealed metallic containers without the need for physically contacting the seal or opening the container. It can be used to provide a history of the properties of an individual item using an inexpensive, rapidly obtained simple measurement. In this way, the coil can provide an unclassified template to verify and track the continuity of a TAI. Multiple field campaigns have been conducted at the Pantex nuclear facility to demonstrate the method for this purpose by measuring the properties of plutonium pits in AL-R8 and AT-400 storage containers. A failure modes and effects analysis approved by Pantex also determined that the method presented a minimal safety risk even in a worse-case scenario since the highest magnetic field amplitudes used in the measurement are comparable to the intrinsic field of the earth. Other field measurements were also performed to investigate the effects of container variations and the ability to discriminate between metal and oxide material forms.[22]

Overview of Method

The EM induction coil operates according to the procedure illustrated in Figure 1. The coil is placed around the container and is connected to a low-frequency signal source such that the current flowing in the coil creates a magnetic field. A portion of the coil's magnetic field penetrates the container walls and interacts with the stored object which has a certain electrical conductivity and magnetic permeability. Materials of interest for arms-reduction treaties and CoC scenarios such as uranium, plutonium, and lead are electrically

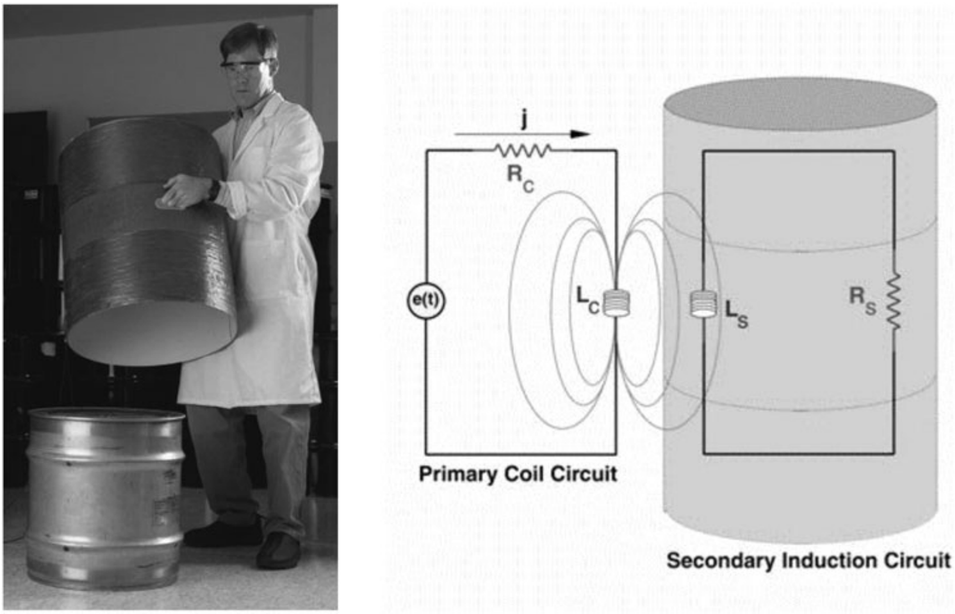

Figure 1: (left) EM induction coil developed at PNNL for arms control treaty verification and (right) its equivalent electrical circuit.

conducting and therefore may be characterized using the fields produced by the coil. Localized currents known as eddy currents are induced in the stored object and generate a response field according to Ampere's circuit law that is measured via changes in the coil impedance. The entire measurement process can be complete in several minutes.

During the data collection process, the coil frequency is swept over a frequency range appropriate for the configuration and the coil impedance is measured at each frequency. An empty container baseline measurement provides a reference dataset for the container with the enclosed object, and is used to normalize all measurements in the process as shown in Figure 2. Normalizing the results to an empty container allows the operator to confirm that the magnetic fields actually penetrate the container walls and interact with the contents. Since the normalization procedure assumes that all containers are identical to the empty reference container, the acceptable range of tolerances for the container materials and dimensions must be specified for a given inspection scenario. This has been studied for the AT-400R container and is expected to be part of the design process for use of the EM coil system with a given container type. The coil impedance is a complex-valued quantity which depends upon multiple factors such as the type of stored material, its volume, orientation, mass distribution, and the EM properties of the container.

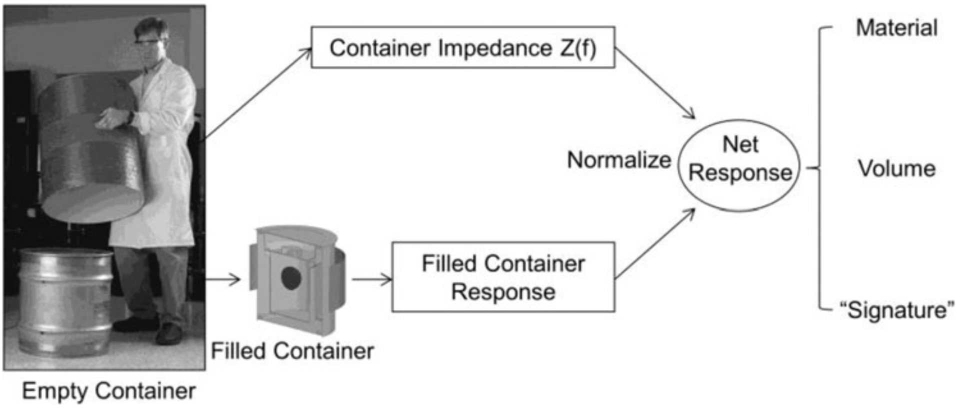

Figure 2: Normalization procedure used to obtain EM signatures for stored objects.

The resulting coil impedance can be separated into its real and imaginary components and normalized to the reference impedance of the empty container (R_0, X_0):

$$Z_{norm} = R_{norm} + jX_{norm} = \frac{Z_{filled} - R_0}{X_0} = \frac{R_{filled} - R_0}{X_0} + j\frac{X_{filled}}{X_0}$$

This normalized impedance response may be used as a signature or template of the stored object for comparison with other containers declared to store identical objects such as stored weapons components.[23]

Example Results

The use of commercially available finite element EM simulation tools has proven to be a powerful approach for evaluating the EM coil for various applications in the dismantlement, storage, and disposition process. Figure 3 shows typical results obtained at PNNL for variations in measured and simulated coil impedance for different test objects situated inside an AT-400R container. The AT-400R container is constructed from 304L stainless steel with a high density insulating foam liner and a welded inner containment vessel. The inner containment vessel sits between two foam-filled inserts inside the outer container. Each test object was supported inside the container on a tubular Plexiglas pedestal. The excellent agreement between the simulations and measurements show the value of using simulation tools to explore the use of this method for different proposed scenarios.[24]

In the data presented in Figure 3, the source frequency is swept from 100 Hz to 3 kHz. The normalization process yields a series of curves (one for each test object) converging to a single point with increasing frequency. All

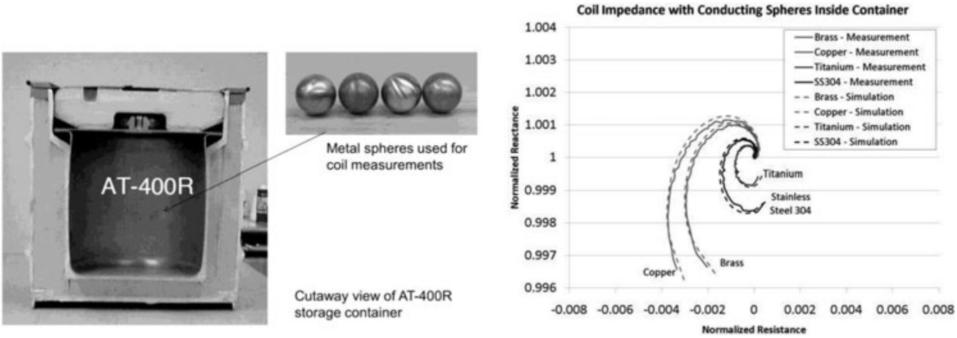

Figure 3: Use of the EM induction coil for stored metal spheres inside a nuclear storage container.

stored materials have a signature converging to this point since higher frequencies are completely shielded by the metal container. The results show clear distinctions among the different stored materials over the frequency range.

Selection of an appropriate frequency range is an important design consideration to ensure effective use of the EM coil technique. Simulations can be used to determine the frequency range as well as to study the effects of other parameters such as object size. Figure 4 shows the simulated frequency-dependent magnetic field distributions from 100 Hz to 3 kHz for the brass sphere test object inside the containment vessel.

The results show that lower coil excitation frequencies provide greater magnetic field penetration, as expected from the general skin depth equation. The plots also show that the magnetic fields are confined to regions outside the inner containment vessel of the AT-400R container for frequencies above approximately 1.5 kHz.

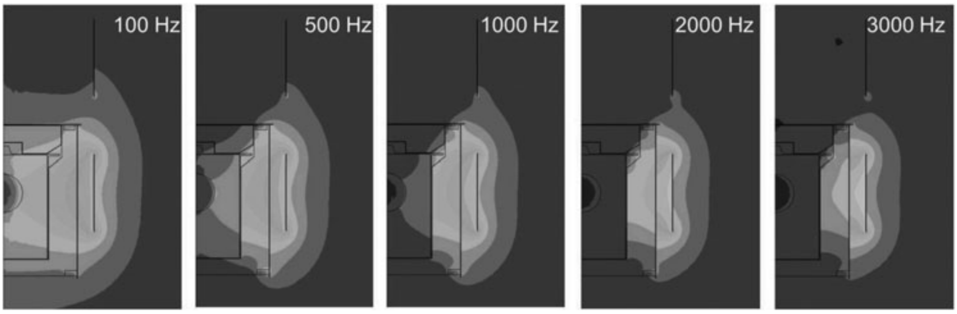

Figure 4: Effects of excitation frequency on magnetic field distribution for model of brass sphere inside AT-400R container.

Protection of Sensitive Information

An advantage of the induction coil technique is that the impedance measurement alone is not likely to reveal potentially sensitive information about the specific contained object. While this assertion has not been thoroughly studied in this context, theoretical work in determining uniqueness in eddy-current measurements supports this conclusion.[25] The conclusion arises from the fact that the overall impedance of the coil is a combination of the unloaded coil impedance along with impedance contributions due to the response of the coil magnetic field from the induced eddy currents in the container and the object. If the impedance measurements are normalized to the empty container, then the coil impedance response is due primarily to the characteristics of the contained object. These characteristics can be determined in some cases from knowledge of the tangential electric and magnetic fields around a boundary enclosing the object. These components are not extracted with impedance measurements since the coil impedance is related to net enclosed magnetic flux (related to the integral of the field) and not the actual spatial distribution of the field. In other words, the impedance represents a reduced subset of field data necessary to determine the unique characteristics of the object. Although the specific security requirements of each verification scenario must be carefully evaluated, the coil method provides a very promising avenue for inspecting items of interest without the use of an information barrier.

Since a particular impedance response does not imply uniqueness in the characteristics of the stored object, it is theoretically possible to change the physical or EM characteristics of the object to create two different objects having the same coil impedance response. The ability of the coil to protect sensitive design information may preclude the uniqueness of the impedance signature. A simple demonstration example has been studied in this regard using a finite element simulation model as shown in Figure 5.

The figure shows the predicted normalized impedance of two solid test objects placed separately inside an AT-400R stainless steel storage container. The first test object is an aluminum sphere of 4.75” diameter with an electrical conductivity of $2.45 \cdot 10^7$ mhos/m, and the second test object is an aluminum cylinder of 4” diameter and 4.6” height with an electrical conductivity of $2.7 \cdot 10^7$ mhos/m. Both test objects were centered geometrically within the container. The conductivity variation between these two example objects is within the expected range of aluminum alloys.[26] The close agreement between the resulting curves demonstrates that two different objects can theoretically yield the same impedance response.

In this example case, the results narrow the range of possible contained objects without revealing corresponding detailed information of physical characteristics. Such an approach can build confidence among treaty parties that the contained object is as declared, especially when combined with other

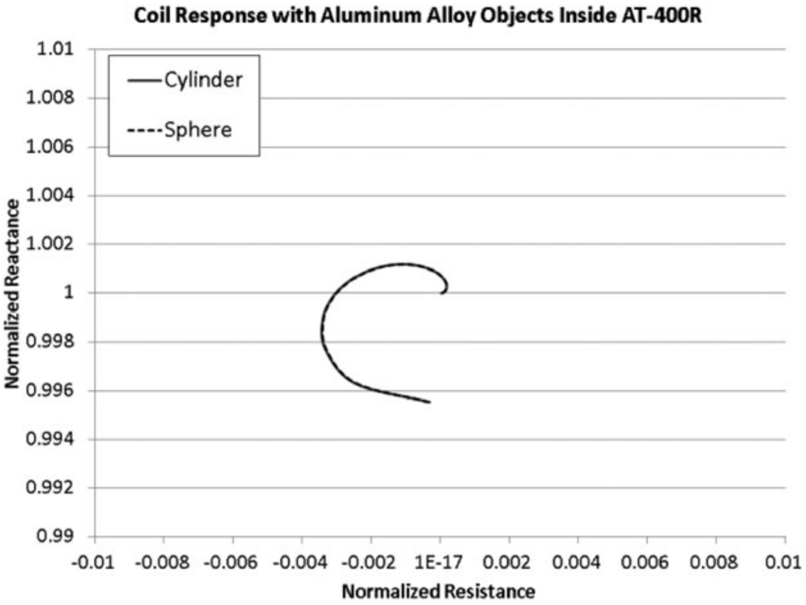

Figure 5: Predicted impedance results of different metal test objects showing identical results for each object.

attribute measurements. Modifying the container contents while maintaining the expected signature response is likely to be difficult in practice. A detailed scenario study of the limitations in change detection given physically possible variations in material size, properties, and geometries is likely to be necessary before a full implementation of the technology can proceed. Such a study may conclude that use of other, orthogonal technologies in combination with the EM coil method may support confidence in such a CoC regime.

Verification of Absence

During the weapons dismantlement process, it may be necessary to verify that large metal transport containers are actually empty and contain no nuclear material intended for diversion from the CoC.[27,28] Radiation measurements alone may be insufficient for verification since the nuclear materials could be concealed through the use of radiation shielding materials such as lead. This scenario illustrates the complementary aspects of the induction coil method which can detect the presence of the electrically conductive lead material, especially in amounts necessary to shield a substantial quantity of nuclear material.

A simulation model was used to evaluate the detection of a solid lead sphere centered within a smooth-walled cylindrical container. The stainless steel container was significantly larger in size than the AT-400R storage

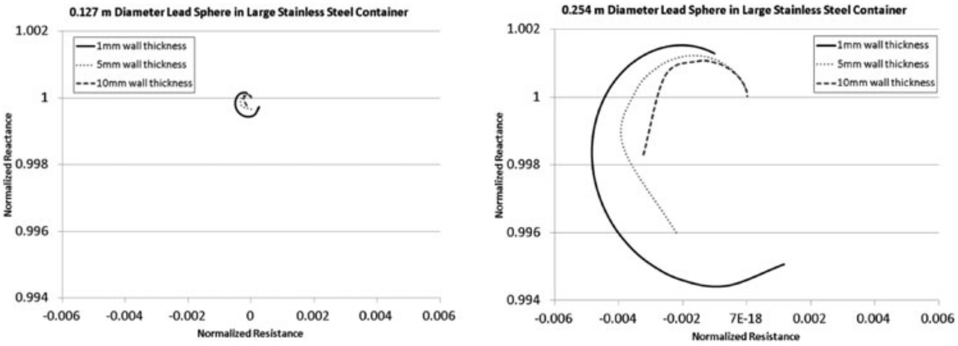

Figure 6: The simulated impedance for a 0.127 m and 0.254 m lead sphere placed inside the example container. Results are calculated over a range of container wall thicknesses ranging from 1–10 mm.

container discussed previously. Containers with a height of 1.52 m with a 1.07 m diameter were studied with wall thicknesses varying between 1 mm and 10 mm. A 0.3 m wide encircling coil is used to interrogate the container contents over a frequency range of 50 Hz to 2 kHz.

As shown by the normalized impedance plots in Figure 6, a 0.254 m diameter lead sphere should be easily detected even within a 10 mm thick stainless steel container. A 0.127 m lead sphere is also detectable, but may be near the minimal detectable size. The likelihood of detection is a function of the container wall thickness, electrical conductivity, magnetic permeability, and object size.

If access is allowed to empty containers under the monitoring regime, it would also be possible to generate a template of the empty container. Subsequent measurements of the declared empty container would then be compared to the original to ensure the expected impedance results were obtained.

Material Disposition

Another potential application for the EM induction coil method under an arms control framework is related to a material disposition scenario in which removed weapon pits are irreversibly converted into an unclassified form or into mixed oxide fuel for nuclear power reactors. For example, under the Plutonium Management and Disposition Agreement initially signed in September 2000, the United States and the Russian Federation agreed to "remove by stages approximately 34 metric tons of plutonium from their nuclear weapons programs and to convert this plutonium into forms unusable for nuclear weapons."[29] Under the original agreement, the declared forms for disposition plutonium were 25 metric tons of "Pits and Clean Metal" and 9 metric tons of "Pits, Metal or Oxide" for the United States with 25 metric tons of "Pits

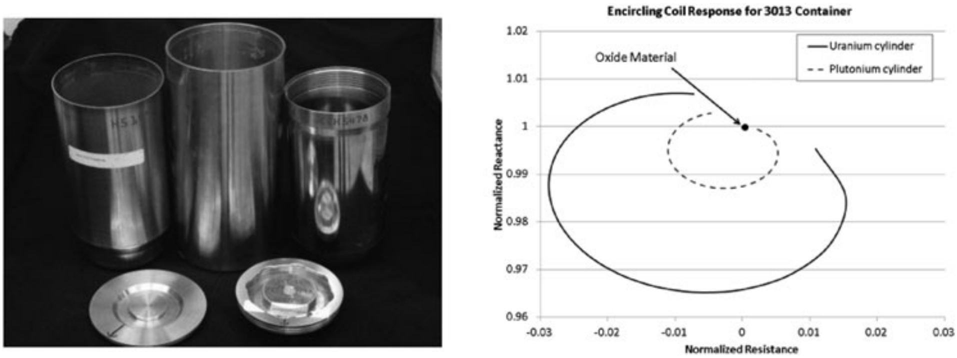

Figure 7: Simulations on stored nuclear metal in the 3013 container. A typical container (left), the simulated impedance results (right).

and Clean Metal" and 9 metric tons of "Oxide" for the Russian Federation.[30] According to this agreement, "monitoring and inspection activities shall be designed and implemented to ensure that the monitoring party has the ability to independently confirm that the terms and conditions of the agreement with respect to disposition plutonium, blend stock, spent plutonium fuel, immobilized forms, and disposition facilities are being met."[31] A protocol amending this particular agreement was signed in 2010 which specified the conversion of all plutonium to MOX fuel. In general, verification of declared forms could represent an important part of a nuclear material disposition process, and the EM coil technique can serve as a useful measurement tool.

While the PMDA does not provide for monitoring and inspection of material prior to conversion into oxide and fabrication into MOX fuel, future agreements may look to bridge the gap between monitored dismantlement and disposition as MOX fuel currently covered under the PMDA. This potential future agreement would need to have the ability to differentiate between metal and oxide forms of plutonium and uranium. With this potential future verification need in mind, simulations were performed to demonstrate that the EM coil can be used to distinguish between metal and oxide materials. The coil method can readily determine the difference in these material types since the metal form is an electrical conductor and the oxide form is an electrical insulator. Figure 7 shows simulated results from a DOE Standard 3013 nuclear material storage container with two different metals and an oxide material.[32] The 3013 Standard container is a double-walled stainless steel nested container with an additional inner convenience container which is used in practice.

The filled container models contain example metal cylinders representing 4.4 kg of plutonium or uranium. The size of the plutonium metal cylinder is limited by the criticality mass constraint, and the size of the uranium metal cylinder was kept the same for comparison purposes. The plutonium oxide case produces a point-like impedance signature at (0, 1) for all frequencies since the oxide forms do not interact with the penetrating magnetic field and the result is the same as an empty container. These results show that it is possible to use the coil method to easily distinguish between the different metals and between the metals and an oxide. In addition, since the interrogative magnetic field does not interact with the nuclear structure of the material, the coil method provides no direct information as to the isotopic nature of the disposition materials.

ACOUSTICS TECHNOLOGIES FOR CHAIN OF CUSTODY

Operating Principles

Acoustics technology is based on the interaction of acoustic waves with materials. In fluids (liquids and gases), acoustic waves propagate as compressional waves that can be described using the wave equation. In solids, both compressional and shear waves can propagate, although the fundamental behavior of these waves can be described using the same type of wave equations as those describing propagation in fluids. In solids, these waves are also referred to as elastic or stress waves.[33]

Acoustic wave interactions with solids depend on mechanical properties of the material such as density and elastic constants.[34] Variability in the spatial distribution of these properties results in an inhomogeneous material, with resulting spatial variability of the acoustic properties such as velocity and acoustic impedance. In contrast, in an anisotropic material, the acoustic property is a function of direction of propagation. The behavior of acoustic waves in solids is also a function of the wave mode. The three bulk wave modes usually considered are longitudinal (called L or P), horizontally polarized shear (SH), and vertically polarized shear (SV). In addition to these modes, surface and plate wave modes and other modes can also be generated, depending on the particular parameters and component geometry. In particular, specific modes may be generated that interact with the boundaries of a structure, and are able to be guided along the structure for long distances on the order of tens of meters. Such guided waves are of interest when examining inaccessible portions of structures.

Acoustic measurement technologies are generally classified into active and passive methods. In active methods, the measurement system applies energy to the test object and records the resulting interaction of the energy with the object. Passive methods do not apply any energy to the test object; rather they monitor or “listen” to interactions with energy from other external sources or sources internal to the test object.

Acoustic wave interactions with materials form the basis for a number of verification technologies of interest to CoC in the dismantlement process. For example, guided wave reflections from discontinuities in structures form the basis for acoustic technologies for design information verification. Guided waves are attractive for tamper detection because of their ability to provide valuable information on features such as pipe routing and locations of junctions and manifolds which may be hidden from view or visually indistinguishable. Changes in the guiding structure, such as a bend, defect, or material property change, as well as changes in the surrounding media, can alter the signature response of a guided wave and provide information regarding the type of change. Complex acoustic interactions with structures can therefore be used to create a baseline ultrasonic "fingerprint" to verify that structural integrity has been maintained. In this case, structures and material hidden from visual inspection may be periodically verified without knowledge of the structure configuration. Figure 8 shows a simple example of laboratory-scale measurements (signal amplitude vs. arrival time) that highlights the ability of ultrasonic guided waves to detect changes in piping structure, with three different kinds of joints.

Similarly, acoustic emission monitoring using piezoelectric sensors can continuously "listen" for acoustic or ultrasonic signals that may be generated as a result of activities representative of tampering, such as drilling or cutting as they occur. Alternative approaches utilize the resonance behavior of structures or materials to detect tampering. In these methods, a known (calibrated) excitation is applied to the structure and the resulting resonances are recorded. In most instances, tampering with the structure produces changes in the resonance modes that may be detected by comparing with a baseline. Most of these technologies (with the exception of acoustic emission monitoring, and the ultrasonic intrinsic tag) are still in their infancy with respect to being applicable to treaty verification.

Below, we briefly describe the ultrasonic intrinsic tag (UIT), an acoustic measurement technology that has as its basis the interaction of acoustic waves with microstructural features and results in signatures that are unique to the object under test.

Ultrasonic Intrinsic Tag for TAI Unique Identification

Background

Nonintrusive, nondestructive unique identification or verification of a declared TAI can be accomplished by using a component's intrinsic material properties, such as its material microstructure, as the signature or tag by which it is identified. Metals and other granular components possess grain structures that are random, even at different positions along the same component, that

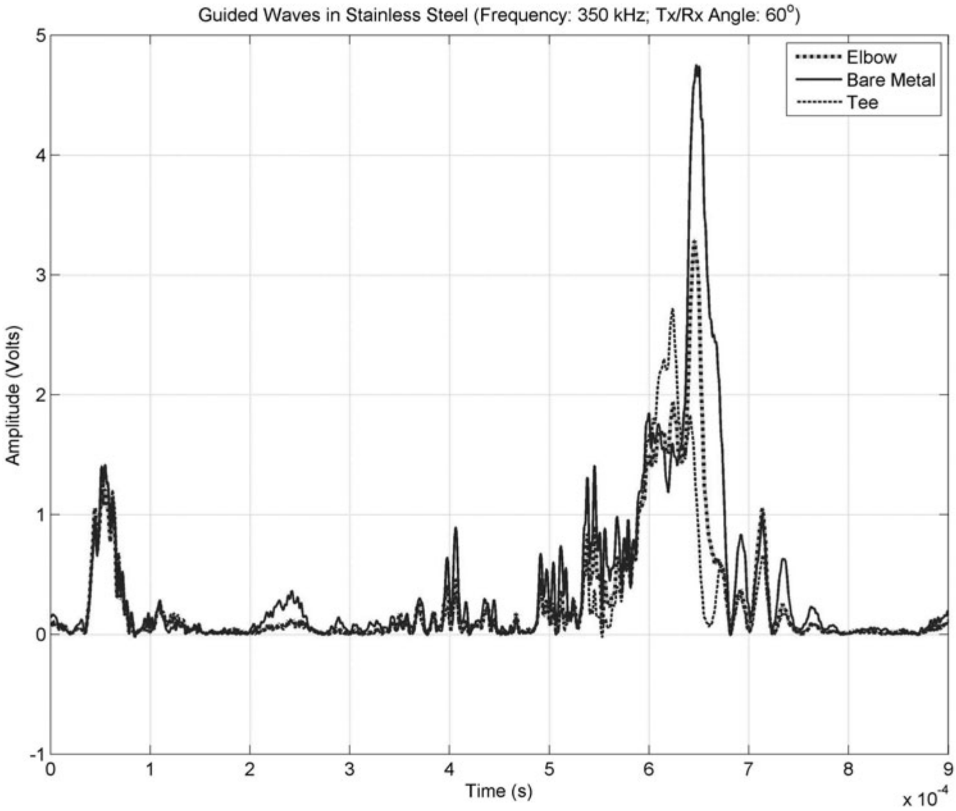

Figure 8: Guided ultrasonic wave response for a pipeline inspection. Horizontal axis is time (in seconds) and vertical axis is signal amplitude. Signal peaks represent reflections due to changes in acoustic impedance.

serve as unique signatures for these items. Acoustic waves, when applied to these components, interact with the microstructure, resulting in scattering of energy at interfaces such as grain boundaries. This scattering is a function of the mean scatterer (grain) size ($\bar{D}$), the wavelength λ of the applied acoustic wave, and the change in acoustic impedance across the grain boundary.[35,36] In materials used in the components of interest to a verification regime, the grain sizes can vary between different locations on the component, resulting in a unique ultrasonic signature that is intrinsic to the component.

The UIT system developed at PNNL uses this unique physical property for component identification (tagging).[37] Counterfeiting unique microstructure and grain orientations in a component is nearly impossible, which makes ultrasonic intrinsic tagging highly resistant to substituting original components for counterfeit ones. At the same time, the signature is characteristic of a small region on the component or object and is characteristic of the bulk elastic properties of the object and not related to isotopic or other sensitive

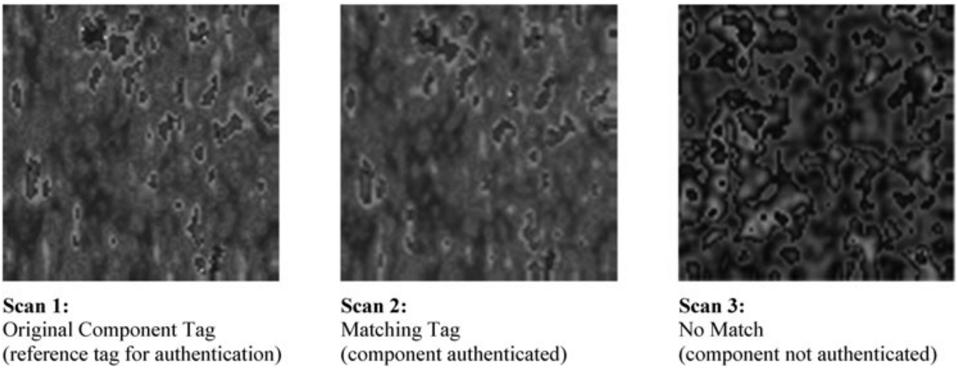

Figure 9: Examples of ultrasonic intrinsic tag images.

information. Since inferring sensitive information about the TAI from these measurements is nearly impossible, the method provides an intrinsic information barrier. This method is effective for essentially all engineering materials that lend themselves to microstructure imaging, including composites and metal alloys, and may be applied to either the TAI or to the container/delivery vehicle. The UIT can be used to complement nuclear detection techniques for component authentication.

The UIT system requires access to the TAI to generate the unique ultrasonic signature. However, in some cases, the components of interest are likely to be containerized. In these instances, two options may be available. First, if access to the item itself can be obtained, then UIT may be used to uniquely tag the item. Alternatively, the intrinsic tag may be obtained on the container, and when used with other techniques (such as tamper-resistant seals), may provide reasonable assurance that the item has not been tampered with.

Example Results

The UIT uses a high-frequency ultrasonic transducer to scan a small area on a component's surface to generate an ultrasonic image of its subsurface microstructure. The ultrasonic image of the subsurface microstructure serves as a unique "fingerprint" or subsurface intrinsic tag by which it can be identified and verified again by re-scanning the same area at different times during the CoC. Examples of ultrasonic intrinsic tags are shown in Figure 9. The far left image is the ultrasonic intrinsic tag generated for the original component, the middle image is a second intrinsic tag that verified the component, and the far right image is a third tag that revealed a component that is not original.

The UIT system stores the ultrasonic intrinsic tag scan images and allows the user to recall this data for analysis for component verification onsite. The UIT is insensitive to minor surface scratches since the microstructure that is imaged is on the order of millimeters below the surface of the component;

Figure 10: Photograph of the UIT unit used to scan a component.

however, significant surface scratches and dents that affect the microstructure can affect the method. For this reason, the use of more than one tag (i.e., at more than one location on the item) is recommended.

Readiness for Treaty Verification

The UIT has several potential applications within the dismantlement stage of a monitoring regime. The UIT unit shown in Figure 10 is a portable unit that scans and analyzes data images to verify the component's tag at the time of inspection. This type of technology is especially useful for tracking the non-sensitive, non-nuclear components such as the aeroshell encasing the gravity bomb shown in Figure 10. The technology has been lab verified and performance demonstrated using prototypical systems. However, authentication and certification of this system will be required prior to use for verification under any future treaty.

Unique Item Identification for Warhead Initialization

The UIT images acquired for an original component's microstructure at one or more discrete locations may be used as a robust method for uniquely identifying warheads or bombs as part of initialization. The intrinsic tags are unique to the scan location on the component, and the scan locations on the component will need to be accurately recorded or marked to enable repeat scanning to be performed at a later point in time for component confirmation. In the event the TAI is containerized, ultrasonic intrinsic tags can also be generated for a container sealed with a closure weld to uniquely identify the container in which the TAI is enclosed.

CONCLUSIONS

Future treaty verification regimes may depend upon a systems-level approach to the management of nuclear-weapons related materials and associated components throughout the dismantlement, storage, and disposition processes. Verification within each stage of the regime will likely impose different requirements for measurement and potential storage of data as well as different levels of information sensitivity. The ability to incorporate methods with intrinsic information barriers may help simplify key components of the verification regime. Technologies based on low-frequency EM induction coils, for example, have the advantage of being simple to build, easy to conceptualize, and simple to operate. These technologies can be designed to penetrate metallic walls to probe stored TAIs to provide indications of change and measurement of content. They provide bulk measurements which cannot be inverted to obtain sensitive or classified data about the stored item. Moreover, they can discern between metallic and oxide materials as well as give an indication of the identity of the material without providing, for example, an isotopic composition.

Methods based on acoustics provide similar advantages in their ability to determine information useful for the verification regime while concealing potentially classified information. As in the EM methods, the lack of detailed information results from physical principles which create a natural information barrier. Localized patterns in materials form the basis for ultrasonic intrinsic tags and can be compared to templating methods used in information barrier approaches. Alternative acoustic measurements that are passive (acoustic emission detection) or active (ultrasonic guided waves, acoustic resonance) may provide advantages for tamper detection and unique identification, but in most cases, need additional development before the technologies are ready for deployment. The methods described in this article provide a range of alternative tools for the verification regime which may result from a future nuclear arms reduction treaty. They are not exhaustive in scope, and it is expected that they may complement and strengthen existing verification methods currently used. It is likely that other methods will be found useful which also have potential use without information barriers. Those that can support the veracity of the TAI or provide additional verification measures will strengthen confidence in potential future arms reduction regime. It is hoped that further research into such methods can further the progress in a future nuclear arms reduction treaty.

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