SEALING THE DEAL

Pacific Northwest National Laboratory leveraged simulation to develop an optimized method for inspecting sealed containers in verifying nuclear arms control treaties.

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New START (Strategic Arms Reduction Treaty), signed in 2010, is intended to reduce the number of strategic missile launchers and nuclear warheads in American and Russian arsenals. Implementing the treaty requires monitoring the numbers and locations of launchers and warheads. Future nuclear arms reductions treaties will most likely require the monitoring of warheads and warhead components and verifying dismantlement of warheads. To establish a chain of custody during dismantlement of a weapon, the contents of a closed metal container must be verified without opening it. Research performed at Pacific Northwest National Laboratory (PNNL) demonstrates that low-frequency electromagnetic signatures of sealed metallic containers can confirm the presence of specific components on a yes/no basis without revealing classified information. The signatures are acquired by using an encircling electromagnetic induction coil to produce a magnetic field that penetrates the container. Objects located inside the container that respond to the magnetic field generate a response field that can be measured externally through changes in the coil impedance. Simulation with ANSYS Maxwell helped in optimizing the design and excitation frequency of the coil for various types of nuclear containers.

In 2012, the U.S. Department of State announced that "negotiations on future treaties to further reduce nuclear weapons may move away from the traditional focus on strategic delivery systems and toward limits on nuclear warheads. This will require the new approaches that balance the need to protect sensitive information with the inherent difficulty of remotely detecting nuclear devices." To account for all nuclear material and components, and to prevent diversion or substitution of material, material verification is required. During the weapons dismantlement process, nuclear warheads, pits and secondary stages are stored in sealed metal containers that cannot be opened by the verification authority, to avoid revealing design secrets. During the verification process, it is necessary to verify that some containers actually contain specific nuclear weapons components and that other containers are actually empty and contain no nuclear material intended for diversion from the chain of custody. Radiation

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measurements alone may be insufficient for verification of an empty container, since the nuclear materials could be concealed through the use of shielding materials, such as lead.

ELECTROMAGNETIC SIGNATURE TECHNIQUE

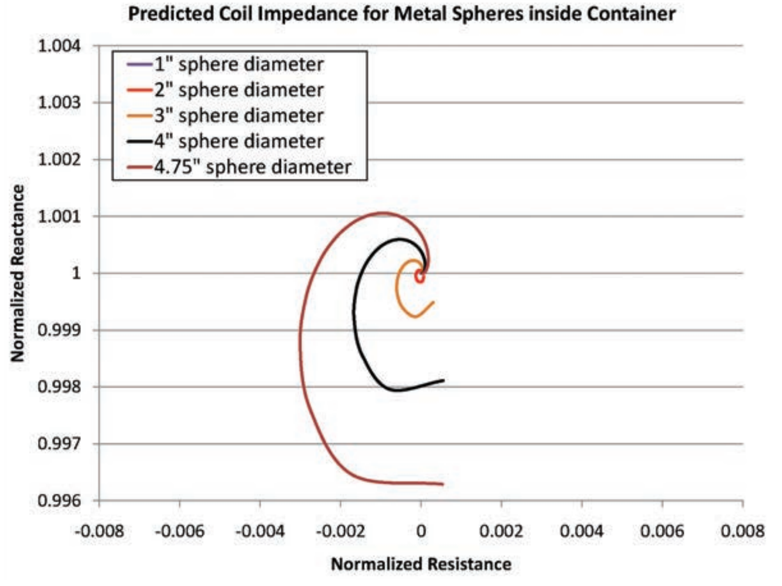
Over the past several decades, PNNL has developed and demonstrated an electromagnetic signature technique that can be used to quickly verify the contents of a sealed nuclear storage container. Low-frequency magnetic fields, generated by an encircling induction coil, penetrate the walls of the metal container to interact with the electrically conductive contents. Materials of interest such as uranium, plutonium and lead are electrical conductors and, therefore, may be characterized using the coil fields. The eddy currents that are induced in the objects inside the container create a distinct impedance signature at the coil terminals. This impedance is a function of many factors, including size, mass distribution, orientation and electromagnetic properties of the container and its contents. Every container with a certain type of component and every empty container has its own characteristic electromagnetic signature. Since the measured impedance response is dependent upon a large number of parameters, it can be used as a template dataset without revealing sensitive design features of the concealed objects.

SIMULATING COIL IMPEDANCE

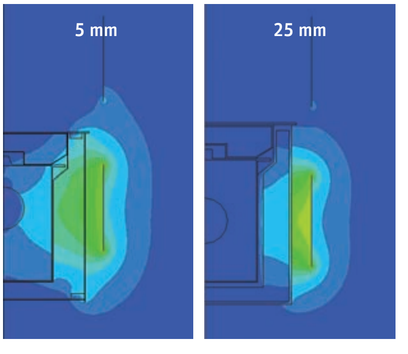
During recently renewed interest in the capabilities of this technology for different verification and detection scenarios, PNNL researchers used the eddy current solvers in ANSYS Maxwell to efficiently model the container and magnetic field interaction; they used ANSYS Optimetrics to automate parametric simulations. A simulation-based approach was necessary for this work because of the cost and time required to physically prototype various coil designs and test their performance. Test data also provides limited direct information about the magnetic field interaction with the contained object, which is crucial to the successful application of the coil technique. Maxwell was the logical choice for this analysis because it has provided accurate results on similar problems in the past for PNNL. Furthermore, Maxwell affords access to both 2-D and 3-D solvers from a single interface. Since the induction coils have rotational symmetry, engineers used 2-D simulations to quickly compute the coil impedance and magnetic fields using only a cross section of the full coil and container.

To determine the coil design parameters for a given closed metal container, PNNL researchers simulated impedance signatures for various test objects placed inside the container by sweeping the coil frequency and then normalizing the result to the empty container. One scenario is an AT-400R stainless steel container that has a double-walled construction with insulation material between the inner vessel and the overpack. The test objects consisted of a series of solid metal spheres of different diameters and types of metal. Impedance traces were created by sweeping the coil frequency over a range of 100 Hz to 3 kHz. For a given metal type, the smallest test object produced the smallest impedance variation, while the largest sphere produced the largest impedance variation. All of the responses approached the center of the plot as frequency increased. This is because higher-frequency fields are less able to penetrate the container walls and interact with the contents. The magnetic field plots illustrated the impact of container wall thickness on the field distribution at an example frequency of 500 Hz. As expected, the results showed that field interaction with an object placed inside a container is reduced for a thicker metal wall. Simulations were used to quantify the effects of container dimensions and electromagnetic properties as well as to determine fabrication tolerances required to obtain repeatable results from the coil technique.

PNNL researchers also simulated the coil impedance for different types of solid metal spheres placed inside the closed container. In this case, the spheres are all the same physical size but have different electrical conductivities. This results in a similar family of traces in which the highest conductivity produces the largest coil response and the lowest conductivity produces the smallest response. All of the traces again approach the center



▲ Simulated impedance signatures for family of metal spheres inside closed metal container



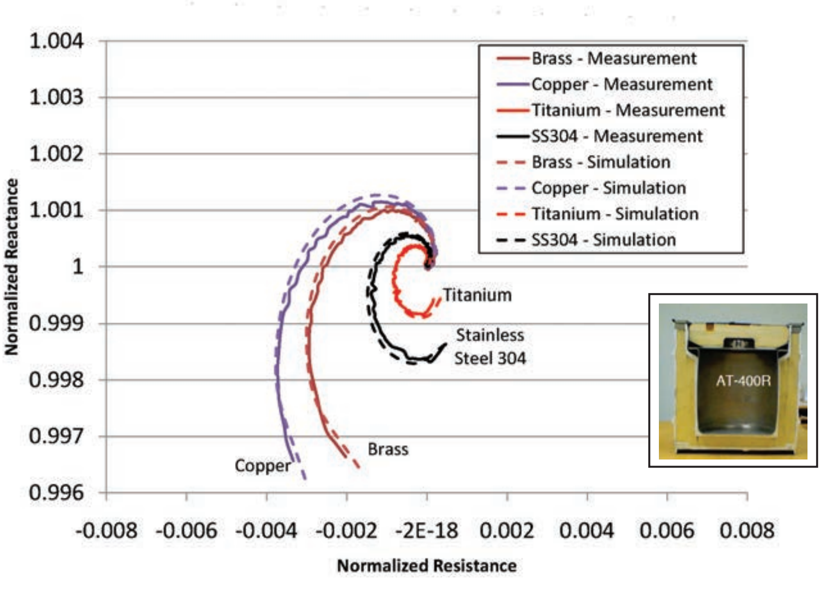
▲ Magnetic field simulation shows the impact of different container thicknesses.

ANSYS Maxwell helped to optimize the design and excitation frequency of the coil for various types of nuclear containers and internal contents.

of the plot as the frequency increases. Very good agreement was achieved between measurements and simulations due to careful modeling of the container's construction. Both the simulations and the measurements show that the coil can create unique impedance signatures for each object over this frequency range.

Selecting an appropriate operating frequency band is an important design decision. The optimum frequency range is dependent upon the specific scenario, with variables including container dimensions, construction material and wall thickness. An important factor is whether the container is made from nonmagnetic materials, such as stainless steel or aluminum, or from a ferromagnetic material, such as carbon steel. This is because the electrical conductivity and magnetic permeability of the container structure have a major impact on the field interaction. It is important to choose a frequency range in which the magnetic fields are able to penetrate the container and induce a measurable amount of eddy currents in the internal objects. Also, the number of frequencies should be sufficiently high to create a robust impedance signature but no more than necessary to minimize measurement time. Using only the minimum number of frequencies allows collection of multiple frequency sweeps to improve measurement accuracy through an averaging process.

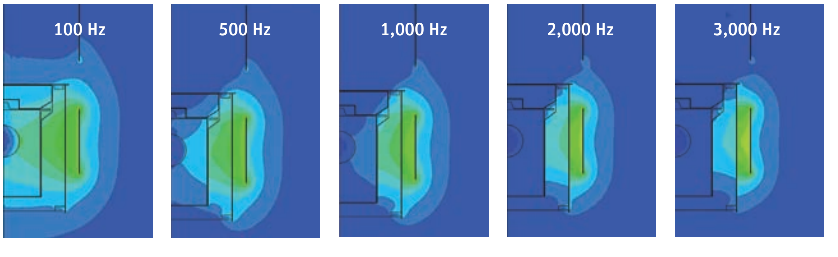
Measurement of electromagnetic signatures is complementary to traditional radiation-based measurements used in arms control treaty verification and chain of custody implementation. The electromagnetic signature technique does not require physical contact with the container and provides an inherent information barrier to protect sensitive information. The electromagnetic signature technique based on a low-frequency impedance measurement of an encircling coil placed over the container offers a number of advantages: short measurement times, low-cost implementation, safe and portable operation, and inherent protection of sensitive information. The coil has demonstrated the ability to differentiate between components from different weapons programs inside sealed metal storage containers. This method also can be used to discriminate between different chemical forms of concealed nuclear materials, since some nuclear materials are metals that are electrical conductors and others are oxides that are electrical insulators, and these materials interact differently with a magnetic field. ANSYS Maxwell was instrumental in helping to enable an efficient simulation-based methodology for designing optimized coils to determine the contents of sealed containers.



Plot shows an overlay of measured and simulated coil impedance for different types of solid metal spheres placed inside a closed container. The stainless steel container has double-walled construction and insulation material between inner vessel and overpack. Simulation results closely matched experiments.

Reference

Verification Technology Research and Development Needs, U.S. Department of State Bureau of Arms Control, Verification and Compliance, Office of Verification and Transparency Technologies, Washington, D.C., April 24, 2012.



Effects of changing frequency of electromagnetic field