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Eddy-Current Testing of Welded Stainless Steel Storage Containers to Verify Integrity and Identity

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Abstract

An eddy-current scanning system is being developed to allow the International Atomic Energy Agency (IAEA) to verify the integrity of nuclear material storage containers. Such a system is necessary to detect attempts to remove material from the containers in facilities where continuous surveillance of the containers is not practical. Initial tests have shown that the eddy-current system is also capable of verifying the identity of each container using the electromagnetic signature of its welds.

The DOE-3013 containers proposed for use in some US facilities are made of an austenitic stainless steel alloy, which is nonmagnetic in its normal condition. When the material is cold worked by forming or by local stresses experienced in welding, it loses its austenitic grain structure and its magnetic permeability increases. This change in magnetic permeability can be measured using an eddy-current probe specifically designed for this purpose.

Initial tests have shown that variations of magnetic permeability and material conductivity in and around welds can be detected, and form a pattern unique to the container. The changes in conductivity that are present around a mechanically inserted plug can also be detected.

Further development of the system is currently underway to adapt the system to verifying the integrity and identity of sealable, tamper-indicating enclosures designed to prevent unauthorized access to measurement equipment used to verify international agreements.

Purpose and Need

The U.S. Department of Energy (DOE) stores nuclear materials in DOE Standard 3013 containers at various sites around the country. For example, the Actinide Packaging and Storage Facility (APSF) at the Savannah River Site (SRS) was proposed to hold 5000 of these containers filled with nuclear materials. Most, but not all, of the containers at that site would be under IAEA safeguards. Because the storage vault will not have utilities, the safeguarded containers cannot be kept under surveillance inside the vault and the containers themselves must serve as the primary containment boundary when surveillance is not possible. The IAEA must have a means of verifying the identity and integrity of each container.

DISCLAIMER

Sandia National Laboratories (SNL) was tasked with developing a method for verifying the integrity of each DOE-3013 container. This method had to be able to find extremely small penetrations or breaches to provide continuity of knowledge. Also, the method was required to detect the presence of welds. For example, if a container was breached at a weld point, the method had to be able to detect re-welding. A team of SNL engineers developed a laboratory prototype eddy-current scanning system that meets these requirements.

In addition to DOE-3013 containers, the technology is suitable for other stainless steel and aluminum tamper-indicating enclosures that require very high levels of assurance that they have not been penetrated. The method can be applied to a variety of metallic enclosures.

Technical Background

The containers specified by the DOE-3013 standard are made of an austenitic stainless steel alloy. This nonmagnetic alloy has a magnetic permeability of approximately one, the same as air. It is also electrically conductive, and has a conductivity of approximately 70 micro-ohm-centimeter. When the material is cold-worked by forming or machining or by local stresses experienced in welding, both the permeability and conductivity change. Also, any intrusion into the container such as drilling, cutting, plugging, or re-welding will also change these properties. If a probe-coil assembly is placed near (or in contact with) the stainless steel, these properties can be determined by measuring the probe's electrical impedance at one or more frequencies. This is a frequently used measurement commonly referred to as "eddy current" testing. Because of the welding process, variations measured in the vicinity of the welds are significantly greater than they are elsewhere on the container. The rest of the container, however, also has an intrinsic pattern of smaller variations. These property variations taken together constitute an "electromagnetic signature" that is unique for each container.

A mechanical repair of a penetration through any metal will show a localized change in electrical conductivity. A coil's complex electrical impedance will change when it is near a metal surface. The impedance will vary according to the metal's electrical conductivity, its magnetic permeability, and the separation between the coil and the surface.

System Description

The DOE-3013 container proposed for use at APSF is a right circular cylinder consisting of bottom and top end caps welded to a central tube. The bottom is flat while the top has a lifting lug machined into its top surface.

The eddy-current scanning system accurately positions this container while rotating it to allow the scanning of all surfaces. The system consists of the following components:

- A fixture that rotates the container and moves a set of probes over its surfaces to record variations in conductivity and magnetic permeability. Sandia designed a scanning fixture that allows the system to read the eddy-current data from all sides of the cans. Sandia also designed special electronic circuits that provide excitation to and acquired data from the eddy-current sensors.

- A small computer that controls the fixture and communicates with the site computer through a cryptographically authenticated data link.
- Software used to acquire data, control the system, and analyze and display the data.

Software

The system software consists of the following three modules:

- control and acquisition,
- authentication and communication, and
- display and analysis.

These modules operate independently and could reside on separate computers. The first two will reside on an embedded DOS computer inside the sealable, tamper-indicating enclosure that houses the scanning hardware. The display and analysis module will reside both on the facility computer and on the IAEA computer. This module needs to be on the facility computer to allow the facility operator to ensure that the data taken is complete and not corrupted and to allow domestic safeguards conclusions to be made. A separate copy will reside on the IAEA computer to allow the inspector to perform the analysis for international safeguards determinations without relying on the host's computer.

The display and analysis software allows the inspector to view the data and to perform specified analyses. The software is currently interactive, but additional software can be developed to perform some automated analysis. The analysis will include weld signature correlation to verify that the container has not been opened and rewelded, hole detection, and inspection for anomalies in the data that could represent plugged holes. The determination of the algorithms to be used for each of these functions is part of this follow-on project.

Weld Detection and Identification

The data taken to date indicates that the system can:

- Detect the presence of a weld and
- Differentiate between any two welds.

Figure 1 shows an eddy-current scan of the side wall of a DOE-3013 container (without penetrations). Within the frame (below the File, View, and Help commands), the air above the container displays as a medium gray area. The diffused heavy gray lines just below this denote the weld connecting the lid of the container to the sidewall. The smooth light gray area with faint patterns is the main body of the central cylinder of the container. The heavy dark line near the bottom of the screen shows the bottom weld, followed by the mixed gray area of the bottom plate. The final medium-gray area is the air below the container.

Even in this low magnification representation of the data, the presence and location of the welds are obvious. The area of the lower weld is machined smooth and it is almost impossible to detect the presence of this weld by visual inspection. This demonstrates that any weld in the surface of the container can be detected quite easily.

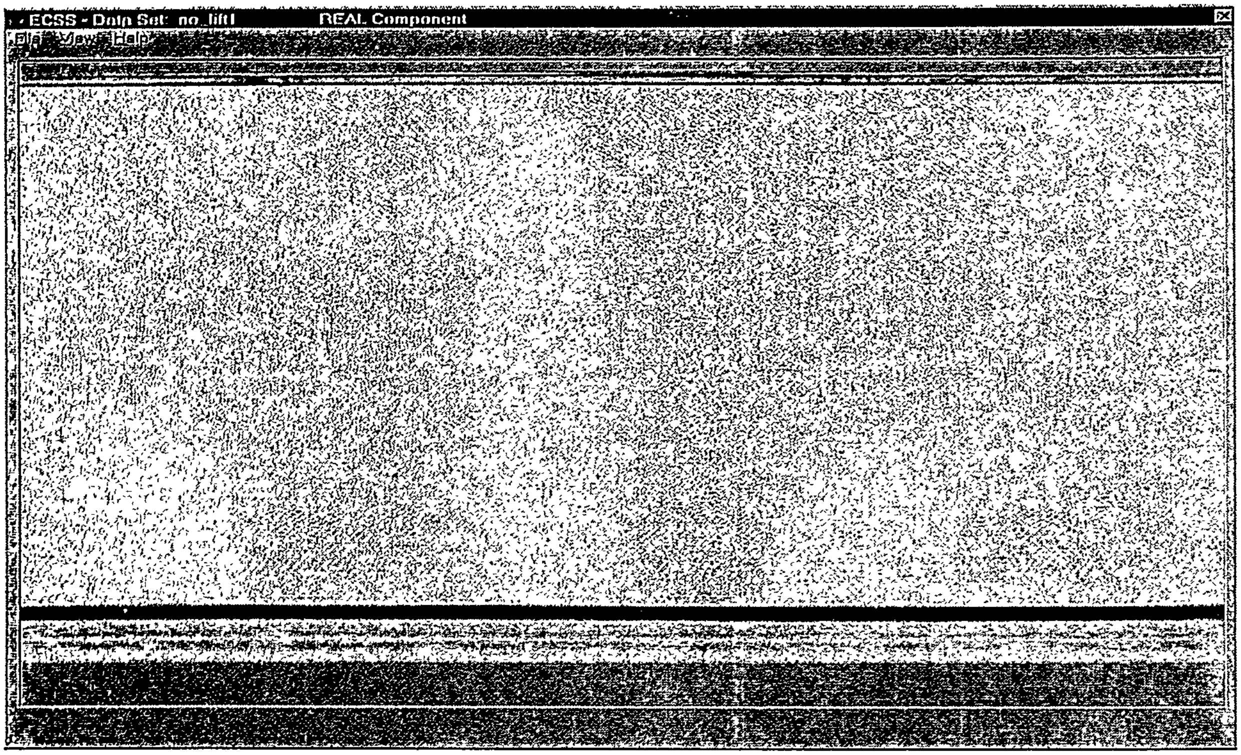

Figure 1. Eddy Scan of a DOE-3013 Container (without penetrations)

Besides being able to detect a weld, the system must also be able to differentiate between the original welds used to create the container and any new welds that were introduced by anyone attempting to divert nuclear materials. In order to accomplish this, the system must be able to uniquely identify each weld. Any data gathered must be repeatable to allow comparisons between data sets to be made. Each weld has a unique "electromagnetic signature". The system needs to be able to scan each container and record the signatures of its welds. When it is scanned again, the signature must match the original with slight variances. Figure 2 shows two important facts: 1) Individual welds have very different signatures and 2) Those signatures are repeatable. The illustration actually shows four scans (see legend on the right of the graph.) The top two scans appear as almost one line, showing two scans for the bottom weld of container R79. The two bottom scans also appear as almost one line, showing the two scans for the bottom weld of container T52. Conceivably, at the start of an IAEA inspection, the inspector could scan the containers and record the signatures in an electronic database. At the next inspection, the inspector would again scan the containers under IAEA safeguards. Any containers that did not match their stored electronic signature would be suspect.

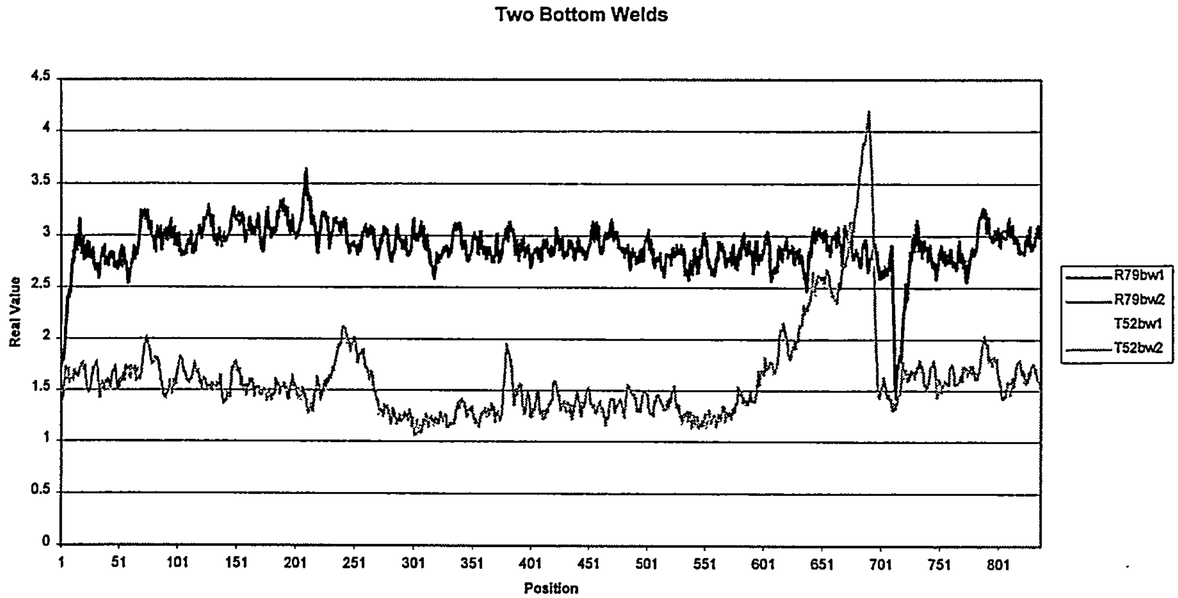

Figure 2. Weld Differentiation between Two Containers and Repeatability of Signatures for One Container

Hole Detection Test

Four holes were drilled and reamed in a 5 × 10 × 1 cm flat SS-304 plate. Two of these were 1 mm and two were 2 mm in diameter. Next, the holes were plugged by pressing precision-machined SS-304 plugs into them. The plugs were made from the same piece of material as the plate in order to match the material properties exactly. One plug of each size was plated with gold before being pressed into place to increase the conductivity of the interface between the plug and the plate to more closely match that of the undisturbed material. The ends of the plugs were within 15 micrometers of the surface after the pressing operation.

The entire surface was ground smooth, in order to remove the effect of this small error on the eddy-current data. This grinding also made both visual and tactile detection of the plugs extremely difficult. To the human eye, the surface appeared unblemished. The image below (Figure 3) is the response from scanning the ground surface with an eddy-current probe operating at 2.0 MHz. Samples were taken on 0.63-mm centers and the image is 144 by 65 pixels. The gold-plated pins are on the right of each set. The gold plating reduces the signal from the interface appreciably, but the plugged hole is still easily detectable.

The eddy-current output is analog within the range of plus 5 Volts to minus 5 Volts. An A/D converter operating over the same range was used to quantize the signal. This particular image (Figure 3) is of only one of the two quadrature outputs (as opposed to a vector magnitude). After quantizing, 5 Volts were added to the real data so that the range was now unipolar, ranging from 0 to 10. The data were then multiplied by 25 to expand the range to 0 to 250 for compatibility with image-processing software. All data are floating point with sixteen bits of resolution. This is the image format that is output by the development scanner.

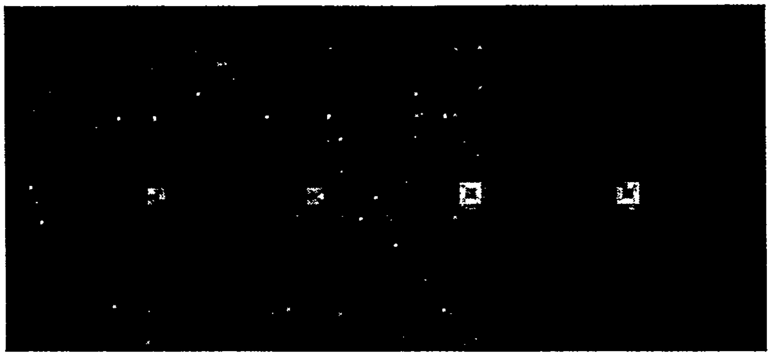

Figure 3. Response to Eddy-current Probe Scanning

Using PMIS software, we subtracted 120 from the data then multiplied by 5 to enhance the contrast in the region of the plugs. The file was then converted to the 8-bit grayscale Tiff file used above. None of the original variation in data is missing from this image.

Conclusions

The data taken to date indicates that Sandia's eddy-current scanning system can:

- Detect the presence of a weld.
- Differentiate between any two welds.
- Detect small penetrations that have been carefully repaired with plugs made from the parent material.
- Containers can be uniquely identified.

Sandia is confident that the eddy-current scanning system can detect hidden welds and covert penetrations in stainless steel containers. The technique can be used to differentiate between any welded stainless steel container and all other similar containers. The process can be used on almost any welded stainless steel container. The system could be used to provide an additional layer of Containment and Surveillance at any site using such containers and could be used to inspect other types of containers, such as enclosures for electronics.

The ultimate sensitivity of this technique is determined by the repeatability of the signature scan. Factors such as the precision of the scanning fixture and the stability of the eddy-current electronics play a large role in determining repeatability. Further testing will be required to determine long-term stability of the readings and possible vulnerabilities, but it appears to be an attractive approach, because measurements based on three-dimensional subsurface material properties are generally more tamper resistant than those that rely on surface features.

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