Nondestructive Inspection Results From Mockups of Spent Nuclear Fuel Storage Canisters Using Shear-Horizontal Waves Generated by an Electromagnetic Acoustic Transducer

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Introduction
The spent nuclear fuel from commercial power generation in the United States first cools down in pools, then is packaged for dry storage before being transported to a repository for disposal. Since there are no repositories in the United States, the time duration of dry storage must be extended. And the extended dry storage period must be managed to ensure confinement of the irradiated fuel materials for the duration of storage, which means that the structural integrity of the dry storage canisters needs to periodically be assessed nondestructively.

The dry storage community has identified chloride-induced stress corrosion cracking as the primary threat to the structural integrity of dry storage canisters [1–3]. The threat is due to the ingress of airborne chloride-bearing salts, which has a higher probability of occurring in coastal environments. A possible degradation scenario is that the airborne salts enter the protective concrete and steel overpack system through the ventilation system, some of which are deposited onto the outer surface of the canister. The canisters of interest in this work are fabricated from 12.7 mm (or 15.9 mm) thick austenitic stainless steel plates that have been rolled and then welded into cylindrical shells 1.74 m in diameter and 4.83 m long. Over time, as the canister surface cools, and given sufficient humidity, the salts can deliquesce. Stress corrosion cracking can occur due to salt deliquescence [4] since in the heat-affected zone of the full-penetration welds (i) thermal residual stresses are tensile [5] and (ii) the material is sensitized by chromium depletion at the grain boundaries [6].

The need for extended storage was not foreseen during the design of dry cask (i.e., overpack and canister) storage installations, and limited provisions were included for the examination of the canisters during service. Thus, there are significant access challenges for nondestructive inspection of the canisters. A schematic of a canister and overpack manufactured by Holtec International (Camden, NJ) is shown in Fig. 1. The annulus between the canister and overpack is nominally 63.5 mm wide, but some casks have guide channels as shown in Fig. 1 that are 50 mm deep and extend along a majority of the overpack. Furthermore, the temperature is elevated inside the overpack and there is substantial gamma radiation.

The progress toward our objective of developing a robotic nondestructive inspection (NDI) capability for dry storage casks has been documented in a number of publications [7–10] that are highlighted below in the chronological order. First, we realized that ultrasonic guided waves provide the unique NDI potential to interrogate all of the welds regardless of the access challenges associated with the guide channels, and selected shear-horizontal (SH) waves as the type of guided waves. Both electromagnetic acoustic transducers (EMATs) and magnetostrictive transducers were considered for robotic delivery in the dry cask environment. EMATs were selected due to dry-coupling concerns with the magnetostrictive transducers [7]. A broad but concise description of the dry storage canister robotic inspection challenge is given by Lissenden et al. [8] that includes sensing of salts on the canister surface, which is subsequently described in more detail elsewhere [11–13], crack detection methodology, and development of the robotic delivery system [14–16]. An assessment of the EMAT’s tolerance to elevated temperatures and gamma radiation is given by Choi et al. [9] along with the sensitivities to notches located in the vicinity of a weld. Next,
Choi et al. [10] determined the range of distances over which a crack-like defect could be detected for crack orientations both perpendicular and parallel to the wave propagation direction. Recently, Cho et al. [17] summarized the performance of the EMATs in a prelude to the current article. The purpose of this article is to report on results obtained from the EMAT-based NDI system on a series of mockups created to test the system’s capabilities. The mockups include the following:

(i) an actual canister in pristine condition;
(ii) a partial canister containing realistic, but artificially implanted flaws;
(iii) a flat welded plate containing artificially implanted thermal fatigue cracks;
(iv) a surrogate canister section at elevated temperature; and
(v) a full-height mockup having reflectors (saw-cut).

In the final mockup, the inspection is conducted by the complete robotic system. None of these results are described in the previous publications [7–10]. The article is organized into sections that summarize the robotic delivery system and the NDI system, and then describe results acquired on various canister mockups: a full pristine canister, canister mockups having realistic defects, at elevated temperature, and with the EMATs delivered by the robotic system. Finally, conclusions about the nondestructive inspection capabilities of the EMAT-based system are offered.

Robotic Delivery System

The proactive robotic inspection of nuclear storage enclosures (PRINSE) system is a marsupial type of robot, which is manually inserted through an outlet vent in the overpack as shown in Fig. 2(a) with the help of a vent bracket. The robotic arm has a garage down into the annulus between the overpack and the canister as shown in Figs. 2(c) and 2(d). Notice that the lid of the overpack is not in place in Figs. 2(b) and 2(d), while it is in place as shown in Figs. 2(a) and 2(c). The end of the arm has a shielded camera that enables the operator to manipulate the pivot point in the arm to launch the train between guide channels. A video showing the operation of the PRINSE system is available on YouTube2. We envision that the full inspection of a canister will entail launching and relaunching the train between each of the sixteen guide channels around the inside of the overpack.

Ultrasonic Nondestructive Inspection System

The ultrasonic NDI of a canister is accomplished while the robotic train is being pulled back up between the overpack guide channels by a winch mounted outside the vent. The first car of the train contains two EMATs [7,18,19], one that transmits ultrasonic SH waves in the circumferential direction, and the other that receives them. The design of these EMATs has been described elsewhere [10,20]. The NDI methodology [8,10] is based upon the reception of reflections and scattering from cracks in the vicinity of the welds, which may be 180–360 mm from the EMATs. While the EMATs are noncontact transducers, to maximize the signal and promote consistent signals, the EMATs use zero liftoff with the canister surface. However, 305-µm thick wear-resistant tape is used to protect the coils. The robotic car is equipped with a restraint arm to ensure that the EMATs have zero liftoff (Fig. 3(a)) as well as a mechanism to extend the EMATs out of the car in order to make measurements (Fig. 3(b)). Both mechanisms shown in Fig. 3 are operated by pneumatics. The EMATs and their mounting bracket are shown in Fig. 4. The mounting bracket is angled to orient each EMAT tangent to the canister and is 3D-printed from polyetherimide, which has suitable radiation and elevated temperature...
resistance. Likewise, the magnets and coils are suitable for the environment [9]. The aluminum housing was designed to be sufficiently compact for the tight geometric constraints inside dry storage casks. The BNC (Bayonet Neill-Consolman) connectors for the coaxial cables are located inside the robot’s tether. The control/acquisition instrumentation for the EMATs is located in a command center outside of the cask and is described in detail elsewhere [10,20]. A five-cycle toneburst having a 250 kHz central frequency was used for the excitation signals.

Electromagnetic Acoustic Transducer Tests on a Pristine Canister

The EMATs were tested on empty 12.7-mm-thick 304L stainless steel canisters at the Holtec Manufacturing Division (Pittsburgh, PA). The welds had already been ground flush. Three aspects of the tests are described in this section: remnant magnetism of the canister, SH wave reflection and transmission from the welds, and long-range guided wave propagation.

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**Fig. 2** Elements of the robotic delivery system: (a) vent bracket supporting the flexible delivery arm with garage containing sensor-car train, as well as the winch; (b) delivery arm with garage in position on canister lid (visible because the overpack lid is removed); (c) sensor-car train emerging from the garage viewed from outside the vent opposite the entry point; and (d) sensor-car train entering the annulus between the canister and the overpack. For these tests, the cask is in a pit to provide easy access to the outlet vents at the top of the overpack.

**Fig. 3** Renderings of the EMAT sensor-car actuation mechanisms: (a) EMAT in default retracted position for storage (left) and EMAT extended by air bladder for measurements (right) and (b) air bladder that extends both the EMAT and the restraint arm. The components are labeled as 1, EMAT (yellow); 2, EMAT mounting bracket (blue); 3, sensor-car passive wheels (pink); 4, sensor-car chassis; 5, air bladder; 6, restraint arm; 7, passive wheels to contact inside surface of overpack; and 8, air hose.
Despite austenitic stainless steel being nonmagnetic, a normal force of 15–22 N was required to pull the EMAT pair away from the canister surface. We note that the axial weld had a larger remnant magnetism than the shell itself, but that force was not measured. While the magnetic force is not large, it does need to be accounted for in the design of the EMAT retraction/extension mechanism inside the robotic car (Fig. 3(b)). It also needs to be considered for the robotic winch to enable scanning parallel to the axial weld. Additional discussion of the magnetic force is given by Cho et al. [17].

The NDI methodology relies upon reflection and wave scattering from cracks in the vicinity of the welds as evident from A-scans (plots of amplitude versus time at a fixed point) and B-scans (intensity plots obtained from spatially stacking A-scans). An example A-scan and B-scan of a pristine weld are shown in Fig. 5 to provide a reference. Therefore, it is important to know how much of the SH wave energy is reflected by the weld itself. An EMAT transmitter was positioned 305 mm from an axial weld, and an EMAT receiver was positioned 152 mm from both the transmitter and the weld to record the incident and reflected waves. The receiver was then repositioned to 152 mm on the opposite side of the weld to record the transmitted waves. The amplitudes of the reflected and transmitted SH waves were 3.6–7.1% and 70–77% of the incident wave amplitude, respectively. Clearly, the majority of the wave energy is transmitted through the flush full-penetration welds. Therefore, it would be interesting to assess the long-range capabilities of the SH waves in the canister.

To assess the long-range capabilities of the EMATs, the receiving EMAT recorded signals for 9500 µs to determine for how many traversals (laps) around the canister that the signal would be detectable. Figure 6(a) shows the recorded A-scans obtained from 50 averages for three different axial positions on the canister. The EMAT transmitter sends both SH0 and SH1 wave modes in both directions around the canister. The EMAT transmitter more effectively excites the antisymmetric SH1 mode than the SH0 mode. The group velocity of the SH0 mode is faster than the SH1 mode so it arrives first. The SH1 mode is dispersive, while the SH0 mode is nondispersive, so the SH1 signal dies out faster than the SH0 signal. The SH0 signal can be distinguished for at least four laps around the canister. Additional research would be necessary to assess whether the long-range capabilities of the EMATs are useful for stress corrosion crack screening tests in either the circumferential or axial directions. The feasibility of long-range screening tests is suggested by the results in Fig. 6(b), where defect reflections are apparent.

**Electromagnetic Acoustic Transducer Tests on Mockups With Realistic Defects**

We tested the ability of the EMATs to detect hidden defects in a canister at the Pacific Northwest National Laboratory (PNNL) on a welded stainless steel mockup of a horizontal axis cask having artificially implanted, closed, crack-like flaws. The closed nature of these flaws is intended to be the representative of stress corrosion cracks, except there is no crack branching. The mockup has a full circumferential weld and two axial welds, and the weld caps have been ground flush as shown in Fig. 7. The number, locations, and sizes of the defects were unknown to us, and they are not visible by eye, so we conducted blind tests on the 12.7 mm thick, 1.5 m long, full-diameter canister with its axis oriented in the vertical direction. Although the EMATs were not delivered by the PRINSE system, the same NDI methodology was followed, i.e., the EMATs were translated vertically to mimic the robotic cars being constrained to a vertical path by guide channels inside a cask and SH waves were sent circumferentially. In keeping with this being an inspection for cracks in the vicinity of welds, only...
the axial and circumferential welds were inspected, although the same methodology could be used for volumetric inspection of the entire canister. In order to preserve the ability to use the mockup for future blind tests by others, we will not disclose specific information about the flaws.

Snapshots of the NDI are shown in Fig. 7. In Fig. 7(a) the EMAT bracket is being translated vertically to scan the axial weld, while in Fig. 7(b) it is positioned to send SH waves along the heat-affected zone below the circumferential weld. In both cases, the vertical translation of the EMATs enables the construction of B-scans from the acquired A-scans. The vertical axes of the B-scans in Fig. 8 denote the vertical position on the canister, although the scale has been removed intentionally. The vertical axis is quite long for the axial weld, but only 120 mm for the circumferential weld (starting below the weld and ending above it). However, the circumferential weld is scanned from 16 positions around the circumference corresponding to the robot-accessible positions between the overpack guide channels.

A self-imposed functional requirement for the EMAT-based NDI system design was to detect open notches (as surrogates for real cracks) that are surface-breaking and semi-circular with a radius of at least 5.3 mm. After completing our NDI, we were able to assess our results. A definitive criterion necessary to automate the defect detection process has not been implemented, that is, a future work opportunity. Rather, the indications in the B-scans were assessed with respect to weld echoes. Indications that could not be interpreted as a weld echo were identified as defects. Confidence in the defect detection was assigned based on its amplitude and whether there were redundant indications of the same defect. The hidden flaws (which are not open notches) can be classified as larger than, nominally the same as our requirement, smaller than, and much smaller than our requirement. We detected all of the flaws larger than our threshold with high confidence and 50% of the flaws in the other categories. Three indications of flaws that were detected at a moderate confidence level turned out to be false positives. As a result, it would be preferable to provide additional redundancy in the data by sending SH waves in both the circumferential and axial directions. This should improve the reliability of the detection of circumferentially oriented cracks.

A 304 stainless steel plate 12.7 mm thick having a full-penetration weld was also available. Four thermal fatigue cracks ranging in depth from 10% to 90% through-thickness had been artificially implanted in the plate. Localized thermal fatigue was used to create branched cracks, which is a characteristic of stress corrosion cracking not represented in other mockups. The EMAT pair was scanned parallel to the weld in 6.4 mm increments with the center of the EMAT mounting bracket a distance of 165 mm from the face of the weld. This is the methodology that would be used for an axial weld in a canister. The B-scan shown in Fig. 9 was constructed from 55 A-scans. The high amplitudes between 0 and 50 μs are from the electromagnetic interference (EMI) and the high amplitudes between 200 and 250 μs represent end-wall reflections (these do not exist in a canister). Most importantly, the signal just before 150 μs is the crack/weld reflection, which indicates the presence of four cracks by the variability of the intensity (i.e., reflection amplitude) in the scan direction.

Fig. 6 (a) EMAT bracket held by magnetic force to a pristine canister and wrap-around signals in A-scans taken at three different axial locations and (b) A-scans showing wrap-around signals from a mockup at PNNL, the bottom A-scan contains defect reflections.

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Electromagnetic Acoustic Transducer Tests at Elevated Temperature

A requirement for the EMATs was that they function for canister surface temperatures up to 177 °C. Based on the finite element simulation, this is the highest temperature on the canister surface when the lower portion of the canister passes the salt deliquescence threshold. Prior thermal testing of the EMAT magnets reported by Choi et al. [9] indicated that the neodymium magnets are temperature-dependent and are degraded by temperatures above...
121 °C. We evaluated two grades of neodymium alloys from K&J Magnetics\(^2\): N52 (for which the earlier results apply) and N40UH. The magnetic force and SH wave amplitude generated by an EMAT were measured after the magnets were exposed to temperatures of 149, 157, 166, and 177 °C for 15 min. The results for the N40UH grade magnets were that neither magnetic force nor SH wave amplitude was affected by the temperature excursions [17].

The EMATs with N40UH magnets were tested on the canister mockup shown in Fig. 10 for temperatures of 21, 121, 149, and 177 °C. The canister mockup is 15.9 mm thick stainless steel. A carbon steel shell with guide channels serves as a surrogate for the inside of the overpack structure. Inside the canister, the mockup is a chamber heated by two forced-air heat guns. The EMAT pair was raised from bottom to top as A-scans were recorded in order to construct a B-scan along the axial weld as shown in Fig. 11(a). The center of the EMAT pair was located 152 mm from the axial weld line. Two notches were machined into the canister mockup. Notch B is 22 mm long and is located at the plane of fusion between the axial weld and the canister. The depth of Notch B varies from zero at the ends to 3.4 mm at the middle.

The B-scans in Fig. 11(b) show the reflection from Notch B and the weld. The time axes have been truncated such that neither the electromagnetic interference nor the end-wall reflections are shown. At positions away from the notch the wave packets between 100 and 200 µs correspond to the weld reflections from the SH0, SH1, and the SH2 (very faint) modes. Elevated temperatures decrease both the wave speed and the amplitude. However, the reflections from Notch B are quite clear at the elevated temperatures and the signal-to-noise ratios are relatively constant for this temperature range. Figure 11 indicates that the EMAT performance is not adversely affected by elevated temperatures.

Electromagnetic Acoustic Transducer Tests Using the Robotic Delivery System

A full-height canister mockup was constructed at Penn State to develop and test the robotic inspection system. The mockup is not the full diameter but has sufficient surface area on top of the canister for the delivery arm and garage, as well as an outlet vent structure to attach the vent bracket [20]. The 15.9 mm thick stainless steel canister section shown in Fig. 10 is inserted in the bottom of the mockup. The deployed train of sensor-cars is shown on the mockup in Fig. 12; the surrogate overpack is not in place to allow the cars to be seen. The robotically controlled train, with the EMATs in the first car (at the bottom), is in position to inspect the bottom weld of the canister mockup in Fig. 12. A schematic of the train’s upward path and the two machined notches (flaws) is provided in Fig. 13(a). The path was selected to maximize the separation between notch reflections and end-wall echoes. Each time an A-scan is recorded, the robotic system records the position of the train of sensor-cars based on an encoder on the winch. The A-scans are used to construct the B-scan of the canister mockup showing indications of both notches in Fig. 13(b). The flaw indications are somewhat difficult to see due to the end-wall echoes that follow soon after the weld and flaw reflections, but these end-walls do not exist in real canisters because real canisters are closed cylinders. The B-scan (Fig. 13(b)) exhibits quite a few instances of spurious electrical noise that do not exist on the other B-scans, which are believed to be associated with the operation of another component of the robotic system. Finally, we note that the flaw depth of 3.4 mm is less than our functional requirement (5.3 mm).

Conclusions

In this article, we have studied electromagnetic acoustic transducers (EMATs) for nondestructive inspection (NDI) of stainless steel canisters used for dry storage of spent nuclear fuel. The EMATs were designed to send and receive ultrasonic shear-horizontal (SH) waves having a central frequency of 250 kHz in a confined space at elevated temperatures and in the presence of gamma radiation. In particular, we assessed the detection capabilities of the EMATs for crack-like flaws in various mockup structures that were constructed to test various critical aspects of flaw detection in the dry storage environment. The results were presented in chronological order as summarized below:

1. The austenitic stainless steel canister has remnant magnetism that must be overcome to remove or translate the EMATs from or along the canister, which affects the robotic delivery system. Reflections and transmission of SH waves from full-penetration welds were measured on pristine canisters. The amplitudes of the transmitted SH waves were 70–77% of the incident waves, suggesting that long-range testing might effectively supplement the planned shorter-range pulse-echo NDI methodology. The SH wave signal was detectable for at least four revoluitions around (wrap-arounds) the canister circumference. Conclusions: (i) The robotic delivery system must be designed to overcome the remnant magnetic force between the EMATs and the canister. (ii) Long-range SH waves that wrap-around the canister
could provide supplementary NDI data for redundancy. Likewise, long-range SH waves that wrap-around the canister or reflect back and forth in the axial direction could potentially provide rapid screening of a canister and minimize the travel distance of the robotic device inside the cask, thereby simplifying the inspection. Furthermore, these ultrasonic signals could also provide locational triangulation for the guidance of the robotic system.

(2) Results from canister mockups having realistic defects instill some confidence that the EMAT-based NDI methodology will perform as intended. The blind NDI on a partial-height full-diameter mockup detected all closed defects larger than the functional requirement threshold for open defects and 50% of all closed defects at or below the threshold for open defects. Moreover, branched cracks were detected at a weld in a flat plate and the flaw indication was proportional to the size of the branched crack. Conclusion: The EMAT-based NDI methodology, which enables robotic inspection of 100% of the canister full-penetration weld lines, effectively detects flaws with features representative of stress corrosion cracks (i.e., crack closure and branching). A comment on crack closure seems fitting. Field experience with stress corrosion cracking in stainless steel components in the commercial nuclear power industry indicates that these types of cracks are notoriously closed, making the detection difficult. These cracks form in-service at elevated temperature and then are viewed later at room temperature, where thermal residual stresses could close the cracks. However, canister NDI will be conducted at the service temperature, and thus,

Fig. 11 (a) Schematic of the B-scan setup and (b) B-scans for four different temperatures (measured by the middle thermocouple located at 533 mm), which is where the surface temperature is maximum. Signal-to-noise ratios (SNR) were computed at the location of notch B (761 mm). Temp/SNR: 21 °C/8.34 dB, 121 °C/9.32 dB, 149 °C/10.53 dB, and 177 °C/7.00 dB.

Fig. 12 Train of robotic cars carrying sensors on the canister mockup. EMATs are in the first (bottom) car and the position shown is for the inspection of the bottom weld.
the cracks (if they exist) could be more open than prior experience indicates.

(3) Nondestructive inspections were conducted on a mockup at temperatures up to 177 °C with grade N40UH neodymium magnets with minimal to no reduction in the detection capabilities. Additionally, prior testing indicated that the EMATs were insensitive to gamma radiation [9]. Conclusion: The EMATs perform their design function in the dry storage cask environment.

(4) The EMATs were scanned along the axial weld line of a full-height mockup by the robotic delivery system. Surface-breaking crack-like flaws having a maximum depth of 21% of the wall thickness were indicated in the B-scan. Conclusion: The control of the robotic inspection system was sufficient to yield high-quality B-scans of the canister’s axial weld.

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