INSPECTION AND MONITORING OF DRY CANISTER STORAGE SYSTEMS

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Due to the ongoing need to store used nuclear fuel on site at nuclear plants in dry storage facilities for extended periods beyond the original licensing period, the importance of inspection and monitoring of dry cask storage systems (DCSS) has increased. The DCSS environment presents a nontrivial challenge for performing inspections due to elevated temperatures on the canister surfaces, potentially high radiation fluxes, and the confined spaces available for performing inspections. With the increasing need to perform inspections of DCSSs in the challenging environment in which the canister resides, a flexible and robust canister inspection solution must be developed that is also technically and economically feasible for performing inspections capable of detecting the degradation mechanisms of concern. This paper presents the ongoing efforts to prepare, demonstrate, and eventually qualify nondestructive evaluation techniques to industry codes and standards. These techniques ideally should be remotely deployed into the canister environment to provide inspection and monitoring options for canisters. These techniques are intended to detect the presence of stress corrosion cracking as well as the initiation of corrosion and other relevant forms of degradation.

I. INTRODUCTION

Used nuclear fuel remains radioactive for long periods after its use. Due to radioactive decay, the fuel also remains at elevated temperatures. For these reasons, long term storage of used nuclear fuel is an important part of the nuclear fuel cycle. Initially, used nuclear fuel from the United States was intended to be stored indefinitely at the Yucca Mountain facility. Due to a number of challenges, the Yucca Mountain facility has never been operated. Therefore, used nuclear fuel is currently stored in interim DCSS storage facilities located onsite at nuclear facilities until a final repository can be licensed and operated.

Due to the challenges related to startup and operation of a final repository facility, interim storage facilities will be required to operate for longer than their initial license period of 20 years. Therefore, activities related to license renewal efforts have increased in importance, such as performing studies related to failure modes and effects analysis (FMEA)[1], crack initiation and growth modeling, and nondestructive evaluation (NDE).

This paper will detail efforts related to NDE (inspection) of dry cask storage systems (DCSS).

II. BACKGROUND/THEORY

There are a number of potential degradation mechanisms that can occur in onsite DCSS facilities[1]. These degradation mechanisms include general corrosion, pitting, chloride-induced stress corrosion cracking (CISCC) and general stress corrosion cracking (SCC) and are outlined in detail in the references.[1,2,3]

Dry canister storage systems are designed with a high degree of safety and are structurally robust under normal and accident loads. The calculated length of a critically-sized defect (a defect that could cause a canister to rupture during storage or transport), is much larger than the canister wall thickness.[2]

While the physical and radiological consequence of a through-wall flaw is minimal, such a flaw violates the licensing basis of the canister. License renewal and aging management require inspections to ensure that canisters continue to provide their intended safety function, confinement integrity. Thus it is necessary to detect flaws with sizes on the order of the canister wall thickness.

Based on the FMEA produced by the Electric Power Research Institute (EPRI), the degradation mechanism with the highest relative probability and significance is CISCC[1]; therefore, inspection development has been tailored to detection of CISCC and other similar degradation mechanisms.

III. MOCKUP DEVELOPMENT

An important step in the inspection development process is to manufacture mockups that contain simulated or real defects that are representative of the types, sizes, shapes, and morphologies of defects that might occur in the field. Additionally, to be useful for NDE demonstration and qualification activities, the mockups themselves must be representative of the materials, welds, geometry, and other important features of the material or component system to be inspected, such as the material thickness, bend radius, welding type, weld geometry, weld material, and any subsequent heat treatments and other relevant parameters.[4]

The use of representative mockups is vital for demonstrating the performance of the inspection technologies and techniques to be used. This is readily apparent in a number of documents related to both examination system qualification and license renewal documents for nuclear power plants.[4,5,6] Relevant testing and evaluation efforts aimed at fulfilling both Materials Reliability Program (MRP) inspection requirements for aging management (Ref. 7-8) and other aging management requirements at nuclear power plants, such as for concrete (Ref. 9), are readily available. All of these demonstration and qualification efforts must be performed on representative samples to be properly understood and applied. Therefore, manufactured mockups for the DCSS inspection qualification must be as close as reasonably achievable to the actual canisters in the field that are to be inspected.

EPRI has been developing representative mockups for dry storage canister systems that are intended to model the actual materials, manufacturing methods, and geometry as closely as possible. Fig. 1 presents some of the stainless steel materials that are being utilized for flaw mockup manufacturing for the dry storage canister mockups.

Fig. 1. Stainless steel materials used to fabricate dry storage canister flaw mockups for demonstration and qualification purposes.

Generally, mockups used for qualification/demonstration purposes are used in one of two fashions. The first is in a fully blind fashion where no information is provided regarding the number, types, or locations of defects. Performing inspections in a blind fashion helps to ensure that the capability of a technique in the field is accurately represented, since it is often not known at the outset of an inspection where defects are located or the sizes and orientations to be identified.

The second method is to perform inspections on open mockups, where complete information regarding the flaws is available, generally in the form of design drawings. This technique does not provide as much information for capability studies, since knowing where flaws are and are not located can influence the final determination of the analyst in his or her decision to call a flaw. However, this second method is much more useful for technique development since an engineer or technician can learn from mistakes and make appropriate technique modifications to improve detection – and potentially sizing – method(s) versus having only a final grade without knowing what calls were correct and which were incorrect, as in the case of blind testing.

Since canisters have only been examined using simple inspections in the past, open mockups may be the most useful form of demonstration/qualification mockups at the present time until more development work is completed related to NDE of DCSS facilities.

IV. COLLABORATION

The final deployment of an inspection system for a canister will likely require collaboration between different groups, such as NDE development scientists/engineers, roboticists, utility staff, inspection vendors, and others. EPRI is working to organize collaborations between organizations with different applicable specialties related to DCSS inspection to properly address the issue of dry canister storage system inspection. Part of this collaboration involves the mockup development described previously so that vendors can utilize the manufactured flaw mockups for their individual NDE technique demonstration and qualification purposes.

The final deployment of a capable inspection system will likely require collaboration between a number of organizations, so developing effective and productive collaboration models is an important step towards addressing the DCSS inspection issue.

V. NDE DEVELOPMENT

Adequate NDE options are required to find cracks and other defects that could at some point in the future grow through the canister wall. Currently, no system has been identified that is capable of performing ASME code level nondestructive examinations. Further, there is no ASME code level acceptance standard that is specifically applicable to DCSS canisters.

There are a number of applicable and appropriate NDE options for generic inspection of welded stainless steel canisters, however, due to the difficult access restrictions of the DCSS environment, including confined spaces, elevated temperatures, and potentially high radiation fields, some techniques are not applicable to this type of inspection environment, such as penetrant testing. Other standard techniques, such as ultrasonic testing (UT), are still applicable, but must address challenges related to the usage and subsequent cleaning or removal of the couplant that must be applied to an inspected surface to obtain high quality signals.

Table I presents a generic qualitative assessment of several NDE technologies that were evaluated for their applicability to inspect DCSS based on the capabilities and limitations of each technique to detect primarily CISCC and, secondarily, other relevant degradation mechanisms in a confined space at elevated temperature and in an irradiated environment. This assessment is intended to be generic and will not be applicable to all of the different varieties of an NDE technology. For example, UT could include pulse-echo, pitch-catch, time of flight diffraction, phased array inspection, and other simple or complex embodiments of UT, hence, a simple table cannot capture all of the advantages and limitations of each technique and all of its variants. Further, the timeframes in this table do not reflect additional time that would be required to develop ASME code approved inspection procedures and acceptance criteria for these inspections. Existing codes may be adapted and modified for this application, but the standards may not be applied uniformly unless/until the code body chooses to take action.

TABLE I. Evaluation of various NDE technologies related to inspection of DCSSs

NDE Technique	Temperature Resistant	Radiation Resistant	Small Form Factor	Sensitive to ODSCC	Compatibility for DCSS Inspection	Time to Delivery
Visual (VT)						
Eddy Current Testing (ECT)						
Ultrasonic Testing (UT)						
EMAT/Guided Waves (GW)						
Acoustic Emission (AE)						
X-ray (RT)						
Penetrant Testing (PT)						N/A
Thermography						
Muon Imaging						

Now		Not Applicable
< 1 year		Good Performance / Yes
< 3 years		Fair Performance / Maybe
4+ years or N/A		Poor Performance / Not Well Suited

The primary output of Table I is that a number of technologies are readily available that could potentially be used to perform inspections at DCSS facilities in the near future. Some of the most applicable techniques are UT and eddy current testing (ECT) while other techniques, such as penetrant testing (PT) are not well suited to inspection of DCSS systems for CISCC.

It is also important to note that Table I is only applicable to in situ inspection of the dry storage canisters for CISCC and other similar degradation mechanisms. If canisters are removed from the overpack or the environment surrounding a canister is otherwise modified, the information in this table is no longer accurate or valid. Similarly, the NDE techniques presented are evaluated against their capability to detect CISCC and other similar degradation mechanisms. This table does not reflect the capabilities of these techniques to inspect the canisters or casks for other significantly different conditions that may be of interest.

One of the outputs from Table I is the fact that ECT methods appear to be well suited to the inspection of dry storage canister systems and could be deployed in the near future.

Many sensors can be grouped into an eddy current array (ECA) that can be used to quickly inspect relatively large areas quickly for crack-like defects and outer diameter surface corrosion of the canister. ECAs are generally temperature resistant to temperatures up to approximately 176 °F (80 °C) and can also withstand relatively high levels of radiation. Additionally, they can be made to a wide range of dimensions and are very sensitive to the detection of cracking.

Another item of particular interest related to ECAs is the use of flexible arrays to conform the ECA sensor to the inspected surface. This facilitates the inspection of surfaces that are not perfectly smooth. While ECAs can conform to many types of surfaces, including some weld crowns, they generally cannot operate well with significant changes in surface roughness, such as very rough welds or other significant surface gouges or protrusions.

In general, however, ECAs are an excellent choice for a quick, yet detailed, inspection option for DCSSs. Fig. 2 shows one envisioned concept for an eddy current array probe that could potentially be coupled with a robot to perform surface inspections on a loaded canister.

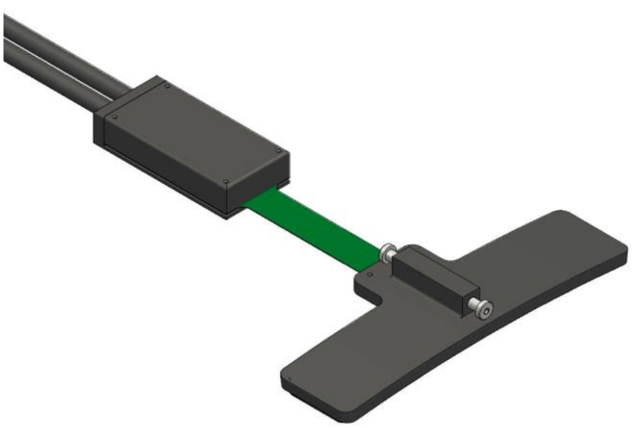

Fig. 2. Proposed eddy current array transducer for inspection for CISCC and other similar degradation mechanisms that could potentially occur in dry storage canister systems.

VI. ROBOTIC DEVELOPMENT

While the NDE inspection portion of a dry storage canister system is somewhat challenging, it is anticipated that the robotic delivery will be somewhat more challenging.

To be useful for inspection in a DCSS environment, a robot must be able to carry the NDE payload, associated electronics, cables, tether, etc. while being able to maneuver in a confined space that is both at an elevated temperature and potentially highly radioactive. The confined spaces within the concrete overpack's inlet and outlet vents may also present a challenging entrance. Figure 3 below shows the entry and exit vents from one concrete overpack design that could potentially be used as entrance/exit paths for a robotic crawler carrying an NDE payload. Since the inlet vent pathways in most canister designs are generally more challenging (tortuous) than the exit vent designs, it is anticipated that the deployment of an inspection robot would more likely be through the exit vent.

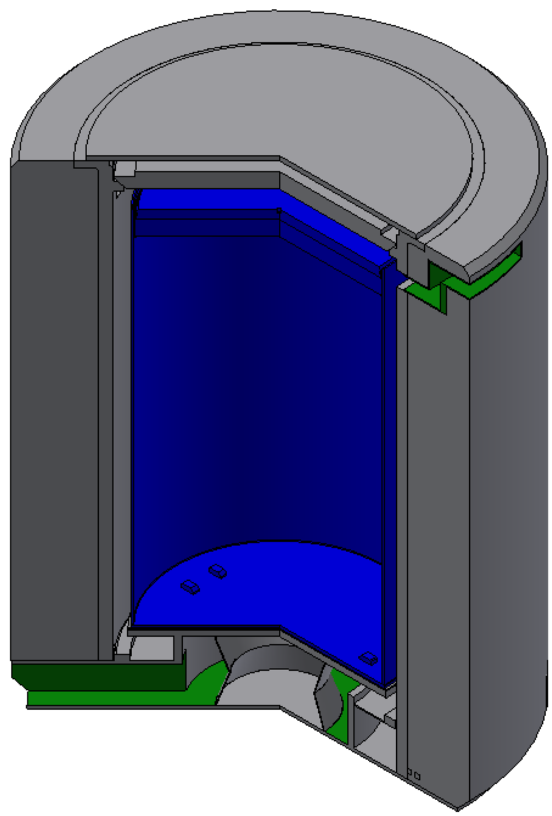

Fig. 3. Model of a DCSS system showing potential entry pathways (in green) through the DCSS inlet and outlet vents.

Specialized robotics using radiation-hardened materials and electronics are being investigated to meet the challenges of inspecting DCSSs. This effort will include evaluating capabilities for sensitive electronic components to be operated from outside of the canister overpack or to be replaced with less sensitive equipment. Such developments would allow for longer lifetimes of both the robot and inspection equipment in a radioactive environment.

While current robotic manipulator development efforts are focused on deployment of NDE equipment, future investigations could demonstrate applications such as cleaning, mitigation, and repair work on the storage canister surfaces.

VII. CONCLUSIONS

Due to the need to store used nuclear fuel in dry stainless steel storage canisters for longer periods than originally planned, canister inspections will become necessary to demonstrate continued confinement integrity. EPRI is working in collaboration with a number of other organizations to address the challenges of performing inspections in this unique environment. Collaboration between numerous organizations will be necessary to develop demonstrated and qualified NDE techniques on appropriate, realistic mockups. Further collaboration will be required to show that these approaches can be applied remotely using a robotic delivery tool. NDE techniques are being identified and developed in parallel to robotic delivery systems. While current robotic designs are focused on deployment of NDE inspection equipment, future versions of these robotic manipulators could also potentially perform cleaning, mitigation, and repair work on the storage canister surfaces.

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