AGING MANAGEMENT FOR DRY STORAGE CANISTERS

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Abstract

Aging management is applied to dry storage systems used to store used nuclear fuel to ensure that material degradation does not affect the function and safety of these systems as they remain in service beyond the initial licensing period. Chloride-Induced Stress Corrosion Cracking (CISCC) is a potential degradation mechanism for welded stainless steel canisters that serve structural and confinement functions in some dry storage system designs. EPRI has developed aging management guidelines to address the potential for CISCC in these canisters. The guidelines include recommendations for screening and inspection methods and frequency with a technical basis built on literature survey results, qualitative failure modes and effects analyses, deterministic flaw growth and tolerance calculations, susceptibility assessments, and probabilistic canister confinement integrity assessments. EPRI's work is being referenced by the American Society of Mechanical Engineers (ASME) Boiler Pressure Vessel (BPV) Section XI Task Group on In-service Inspection of Spent Fuel Storage and Transportation Containments which was formed in April of 2015.

1. INTRODUCTION

Many Dry Cask Storage Systems (DCSS) in place throughout the world are comprised of a ventilated concrete overpack with a welded stainless steel canister that confines the used nuclear fuel. Instances of CISCC in atmospherically exposed stainless steel have been observed in a range of applications, including piping and tanks at seacoast nuclear power plants. The potential for similar cracking to occur in dry cask storage canisters has been recognized and is being proactively addressed by aging management programs.

EPRI's development of aging management guidance started with a failure modes and effects analysis (FMEA) [1], that relied on review of existing literature to identify degradation mechanisms that may act on welded canisters during extended storage and the potential impact to the function of the canister (confinement). This effort concluded that through-wall growth of a tight CISCC crack is the aging degradation mechanism with the most potential to cause loss of confinement. EPRI's literature reviews also investigated the state of knowledge regarding atmospheric corrosion of stainless steel, chloride-induced stress corrosion cracking, and atmospheric conditions relevant to dry cask storage [2]. This knowledge was applied to develop a set of criteria for ranking the relative susceptibility of welded stainless steel canisters at Independent Spent Fuel Storage Installations (ISFSIs) to CISCC degradation [3]. This susceptibility ranking is applied in EPRI's aging management guidance to prioritize canisters for inspection [4].

EPRI has published guidance with recommendations for the scope and frequency of inspections that are re-evaluated and may be adjusted based on the initial and subsequent inspection findings. EPRI is engaged with an ASME task group that is also developing guidance for in-service inspection of spent fuel storage and transportation containments [5]. The ASME guidance will be published in a code case. This code case is expected to have many elements that are consistent with the EPRI guidance, with some modifications. It is anticipated that the ASME code case will be the governing document for dry storage system aging management inspections once it is published.

2. KEY ELEMENTS OF AGING MANAGEMENT GUIDANCE

EPRI's guidance for the development of an aging management programs (AMP) to address the potential for the degradation of external surfaces of austenitic stainless steel canisters due to chloride-induced stress corrosion cracking applies to all licensed dry cask storage systems with welded austenitic stainless steel canisters. The guidance includes recommendations for monitoring and trending, development of an inspection program, acceptance criteria, and guidance for corrective actions.

2.1. Monitoring and Trending

EPRI's aging management guidance employs the use of sample inspections on the highest ranked (most susceptible) canisters because there are thousands of canisters in storage and the level of risk associated with aging degradation of these passive components does not justify the effort required to examine all of them. Recording and trending of inspection results is fundamental to an aging management program that utilizes sample inspections. EPRI's guidance identifies key parameters that should be recorded in ISFSI records and reported to the ISFSI Aging Management INPO Database (ISFSI AMID) [6]. These include the examination methods and associated sensitivity and uncertainty; the visual appearance of the canister surface, presence of any deposited material, location, size, and extent of any indications identified, and the disposition of any indications. Results from the initial inspections will be key in reducing the uncertainty associated with CISCC initiation and through-wall growth probability and to confirming or adjusting recommendations for the sample size for later canister inspections.

The selection of canisters for initial sample inspections is based on the relative susceptibility to CISCC. EPRI developed criteria for ranking canisters [3] which use an ISFSI (site) ranking in combination with canister specific parameters to identify the most susceptible canisters at a site based on the ranking parameters listed in Table 1. Prioritization among equally ranked canisters may be based on canister fabrication information, preservice inspection results, duration of preservice environmental exposure, and environmental conditions (such as canister placement relative to prevailing wind direction). Canisters from the same loading campaign will have very similar storage durations and typically will utilize the same material; their inspections may be prioritized by heat load in the absence of other distinguishing factors.

TABLE 1. CISCC SUSCEPTIBILITY RANKING PARAMETERS

ISFSI Ranking Parameters	Canister Ranking Parameters (At Time of Inspection)
Atmospheric Chlorides (based distance to marine shore, elevation, cooling tower proximity and salinity, salted highway proximity; use of measured value is allowed as an alternative)	Storage Duration (elapsed time since canister placed within overpack)
Annual Average Absolute Humidity	Current Decay Heat Load
	Canister Shell and Outer Lid Material (stainless steel alloy)

2.2. Inspection Program

The inspection status and the inspection results for a given set (or "population") of canisters under the same license at the same ISFSI are used to determine categories for the inspection program. In some cases, the population will include all canisters at the ISFSI, but this will not apply to ISFSI's using multiple canister designs with different licenses. Three categories of populations are defined with increasing inspections recommended as findings of corrosion or cracking trigger a change in category for a population. Category A applies prior to the first in-service inspection of the population and this category remains applicable whenever

no corrosion has been found in the population. If corrosion has been found on one or more canisters in a population but no cracking has occurred, then category B applies. If cracking has been found in one or more canisters in a population, then category C applies. EPRI's guidance recommends an initial inspection within twenty years of the first loading campaign followed by a ten-year inspection interval for category A populations and a five-year inspection interval for categories B and C. The guidance allows for delay of initial inspections for populations with low-ranking canisters contingent upon the availability of previous favorable inspection results from higher ranked canisters.

EPRI's guidance includes different recommendations for canister sample selection for each category A, B, and C. The minimum recommended sample size is one canister for category A populations with five or fewer canisters. EPRI recommends a sample size of two canisters in populations with more than five canisters, wherein the most susceptible canister should be selected for successive future examinations for trending purposes and additional inspected canisters in the sample rotate between the highest susceptibility canisters as long as category A applies.

The guidance for category B populations is to rely on a site's corrective action program for sample selection considering that the sample size should be sufficient to provide a reasonable chance of detecting cracking if it is occurring in the population and to confirm whether corrosion is widespread in the population or limited to the most susceptible canisters. Similar guidance applies to sample size determination for category C populations. The corrective action program is engaged to determine a sample size sufficient to ensure that canisters likely to have CISCC are inspected within a timeframe that enables detection prior to through-wall growth. The sample size should be sufficient to confirm whether cracking is widespread or confined to only a small number of the most susceptible canisters in a population. It is recommended that any cracked canisters be re-inspected after the shorter of 5 years or the predicted time for 75% through-wall growth.

EPRI's guidance recommends a general visual examination of all accessible canister surfaces. A qualified (VT-3) visual examination of the surface area within 50 mm of any full penetration weld through the shell (i.e., shell seam and girth welds) or any full-circumference weld adjoining the shell with a weld thickness (or fillet weld throat) of 9 mm or greater is also recommended. Inspection coverage for qualified visual examinations should not be less than 80% of the recommended surface, averaged over the canisters in the sample. If the inspection coverage is lower, then inspections can be performed on additional samples to meet the areal coverage recommendation, for example, examination of 60% of the full examination surface of three canisters is considered equivalent to 90% coverage of two canisters.

If a qualified visual examination finds indications of corrosion, an augmented examination is recommended. This is defined as an examination performed using a technique capable of directly

assessing whether cracking is present on the examined surface. The recommended surface area for augmented examinations is the same as that for qualified visual inspections, except that it extends 25 mm beyond the outer extent of any as-found relevant corrosion indication.

2.3. Acceptance Criteria

Inspection indications may be classified as major, minor, or insignificant. EPRI's guidance provides definitions for each of these classifications as well as a comparison to the Japanese Industry Standard (JIS) for reference [8]. The ASME code case is also expected to reference JIS for classification of corrosion. The code case may not utilize the same detailed definitions of insignificant, minor, and major corrosion as the EPRI guidance and it may also differ in recommended actions for each classification.

Evidence of water intrusion, areas of light corrosion that follow a fabrication feature or surface anomaly, and/or indications of iron contamination such as from contact with a tool, chain, or roller during fabrication and/or handling may be classified as minor corrosion. Minor corrosion within 50 millimeters of a weld may be accepted by performing a supplemental examination that confirms that there is no CISCC present. Minor corrosion away from the weld region is acceptable without a supplemental examination. Minor corrosion should be recorded for trending purposes but does not result in a change of category for the inspection program.

Inspection results that include cracking of any size, corrosion products with linear or branching appearance, evidence of pitting corrosion, under deposit corrosion, etching with measurable depth, evidence of water intrusion with rust staining at the edge of a crevice, and/or corrosion product deposit present at the mouth of an occluded region that includes a portion of the canister shell weld are classified as major corrosion. A

category A population is changed to a category B population after detection of major corrosion. Supplemental surface or volumetric examinations for the presence of cracking are recommended for canisters with indications of major corrosion. If a surface or volumetric examination confirms the absence of flaws, no further actions are recommended. A flaw may be accepted if it does not have a crack-like morphology and it is in an area with no corrosion products.

If a supplemental examination finds any cracks or crack-like indications, the population category is changed to C and flaw evaluation is recommended to determine the time at which any sizable crack would be expected to reach through-wall. EPRI analysis [7] indicated that CISCC is not expected to pose a structural challenge to canisters, the purpose of the flaw evaluation is to address the challenge to confinement that may be posed by CISCC. The flaw evaluation approach employs a crack growth assessment, further discussion on this is included in section 3.

Indications that do not meet the criteria for minor or major corrosion may be considered insignificant. Insignificant indications of corrosion do not require follow up action or changes to the population category for the inspection program. The guidance recommends that insignificant indications should be imaged and saved for trending purposes. Evidence of dust, debris, or fabrication defects that are not corrosion may also be noted for trending purposes.

2.4. Corrective Actions

EPRI recommends that all inspection results, including those with no indications of corrosion, be submitted to the ISFSI AMID in a timely manner. Additional actions and reporting may be required by the applicable corrective action program for canisters with corrosion or cracking indications. It is recommended that the corrective action program be engaged to determine if the inspection sample and/or frequency should be increased upon detection of corrosion or cracking. This determination should be based on the severity of individual indications, the quantity and distribution of indications, the number of canisters with indications, past inspection results, and CISCC susceptibility rankings. A small sample may be considered sufficient if detected indications are localized and not severe. If indications are representative of an outside surface connected planar flaw, then additional canisters should be examined. The corrective action program should be used to determine the number of additional canister inspections necessary to provide reasonable assurance that cracks are detected prior to through-wall growth.

EPRI's guidance provides a brief description of flaw remediation but does not offer specific recommendations for the timing or methods to be applied. Flaw remediation may include repair of the CISCC affected area, mitigation using a technique capable of halting flaw growth, providing an alternate confinement boundary, or canister replacement. EPRI's Extended Storage Collaboration Program (ESCP) includes a subcommittee on canister mitigation and repair; guidance and options for flaw remediation will be developed collaboratively with this group [9].

3. TECHNIAL BASIS FOR AGING MANAGEMENT GUIDANCE

The technical basis for EPRI's aging management guidance is comprised of the previously mentioned EPRI references [1, 2, 3] along with a probabilistic confinement integrity assessment which is documented in an appendix of the guidance report [4]. The guidance also references EPRI's flaw growth and flaw tolerance report [7] for crack growth assessment methodology. The challenges and limitations associated with the current technical basis for modelling crack growth in stainless steel in the dry cask storage environment are briefly discussed below.

3.1. Chloride-Induced Stress Corrosion Crack Growth Rate

The crack growth model referenced by EPRI's aging management guidance [7] is a two-phased crack growth rate, different crack growth rate coefficients are applied at shallow and deep depths. The transition from shallow to deep growth is modelled to occur once a crack has reached a through-wall depth of 3.16 millimeters. This model relied on published crack growth rate testing results that were specifically relevant to canister operating conditions. Data from experiments where crack growth rate was measured in pre-cracked specimens

placed in humidity chambers was utilized to develop the crack growth rate coefficients. Alternate models have been suggested and are under consideration within the ASME task group. The task group member experts are still working to reach a consensus recommendation. They are working on development of a single-phase crack growth rate relying on a larger experimental data set that includes the data selected for the EPRI model along with additional data, including results from experiments under immersed conditions [5].

3.2. Probabilistic Confinement Integrity Assessment

EPRI developed a probabilistic assessment that models CISCC degradation and sample inspections. This model was used to explore how different inspection sample sizes and inspection frequencies affect the probability that a crack could be left undetected long enough to grow through-wall. Given the high uncertainties in crack initiation probability and crack growth rates, this model is considered useful only for making comparisons of different approaches, not for making predictions of the timing of cracking onset or growth to though wall for any given canister.

EPRI's model compares the cumulative probability of canister leakage (CPL) over selected timeframes and canister populations when varying inspection sample sizes and frequencies are applied. In this model the CPL is defined as the average probability of a canister developing it's first through-wall crack during a specified time period of interest. This cumulative probability is normalized such that a scenario in which no inspection occurs has a CPL of 1. The model was applied to a population of 10 canisters with equal ISFSI susceptibility rankings and very similar canister rankings and to a population of 100 canisters with eight different canister rankings. Results are reported for a 60-year time period during which the onset of inspections occurs at the end of the 20th year.

Several sensitivity studies were performed with varied inspection programs and with varied modelling parameters (see the Appendix of the EPRI Aging Management Guidance [4]). It was noted that increasing the number of canisters inspected in the initial sample was more beneficial than increasing the inspection frequency. The effectiveness of inspections (as measured by change in CPL) was highly dependent on inspection coverage area but did not vary significantly with earlier onset of the inspection program. One sensitivity study used a depth-independent (single-phase) crack growth model, which is more similar to, but not the same as, the model currently being considered by the ASME task group. The results of this study were very similar to results obtained using the EPRI recommended crack growth model. In both studies, the CPL predicted for populations using EPRI's recommended inspection program was about half of the CPL the no inspection case. The benefit was slightly less in the population of 10 canisters than in the population of 100 canisters.

4. AGING MANAGEMENT PROGRAM IMPLEMENTATION

Aging management programs are expected to be implemented near the time an ISFSI reaches 20 years in-service. This timeline is not based on a technical assessment, rather it is based on the typical initial licensing period. EPRI's aging management guidance follows a learning aging management approach. Each completed inspection will augment the understanding of CISCC susceptibility and likelihood. EPRI's guidance uses inspection results to update population categories with increased monitoring recommendations once corrosion or cracking has been found in a population. It also recommends use of industry inspection results from AMID as a factor in aging management decisions made under the corrective action program following indications of aging degradation. While EPRI does not have a specific planned update for the aging management guidance, EPRI remains engaged with users of the guidance, including the ASME task group members who are drafting their own consensus code case to address canister inspection requirements. EPRI ESCP provides an opportunity for industry, vendors, universities, government organizations, etc. to collaboratively develop and demonstrate the tools needed for aging management program implementation. ESCP subcommittees are actively working on nondestructive evaluation tools and in-situ delivery systems [10] as well as repair and mitigation technologies.

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