EPRI's CISCC R&D Roadmap and Development of CISCC Aging Management Guidelines

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Chloride-Induced Stress Corrosion Cracking (CISCC) is a potential degradation mechanism for welded stainless steel canisters containing used nuclear fuel in dry cask storage systems. The Electric Power Research Institute (EPRI) is committed to developing susceptibility criteria to assess the likely timeframe for CISCC initiation and propagation in a given canister. EPRI directed efforts encompass several key elements of the body of work discussed in the research and development roadmap leading to identification of canisters potentially susceptible to stress-corrosion cracking. This roadmap is a living document that provides a current summary listing of recently completed, on-going, and near term planned work that will enable CISCC susceptibility assessments and aging management plans. EPRI developed and maintains this roadmap with input from members of the Extended Storage Collaboration Program (ESCP) CISCC sub-committee. This group includes used nuclear fuel cycle experts from university, government, vendor, and utility organizations. Elements of the roadmap include EPRI's Literature Survey Report and Failure Modes and Effects Analysis, voluntary inspections of canister surface conditions, development of canister thermal models, weld residual stress calculations and measurements, thermodynamic models, and stress corrosion crack initiation and propagation models. Much of this work will culminate in the publication of CISCC aging management guidelines in 2016. EPRI will provide recommendations for screening, inspection, and mitigation activities with solid technical bases 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.

I. INTRODUCTION

Nuclear fuel cycle and materials experts are working collaboratively via the Electric Power Research Institute (EPRI) led Extended Storage Collaboration Program (ESCP) to evaluate the susceptibility of welded stainless steel canisters storing used nuclear fuel to aging degradation, particularly Chloride-Induced Stress Corrosion Cracking (CISCC). A research and development roadmap[1] is maintained by EPRI to aid in coordinating efforts to identify susceptible canisters and develop aging management plans to ensure continued integrity for the necessary storage lifetime. This paper will discuss the current status and recent results of the EPRI sponsored portions of this work.

Results from recently completed roadmap elements that will form the technical basis for EPRI's aging management guidance are included in section II. Section III outlines continuing research and development efforts. Section IV provides a brief conclusion to summarize this paper.

The timeline for key roadmap elements is described in Figure 1. While the collaborative efforts listed in this figure are a vital part of the overall research effort, this paper will not provide a detailed discussion of these items.

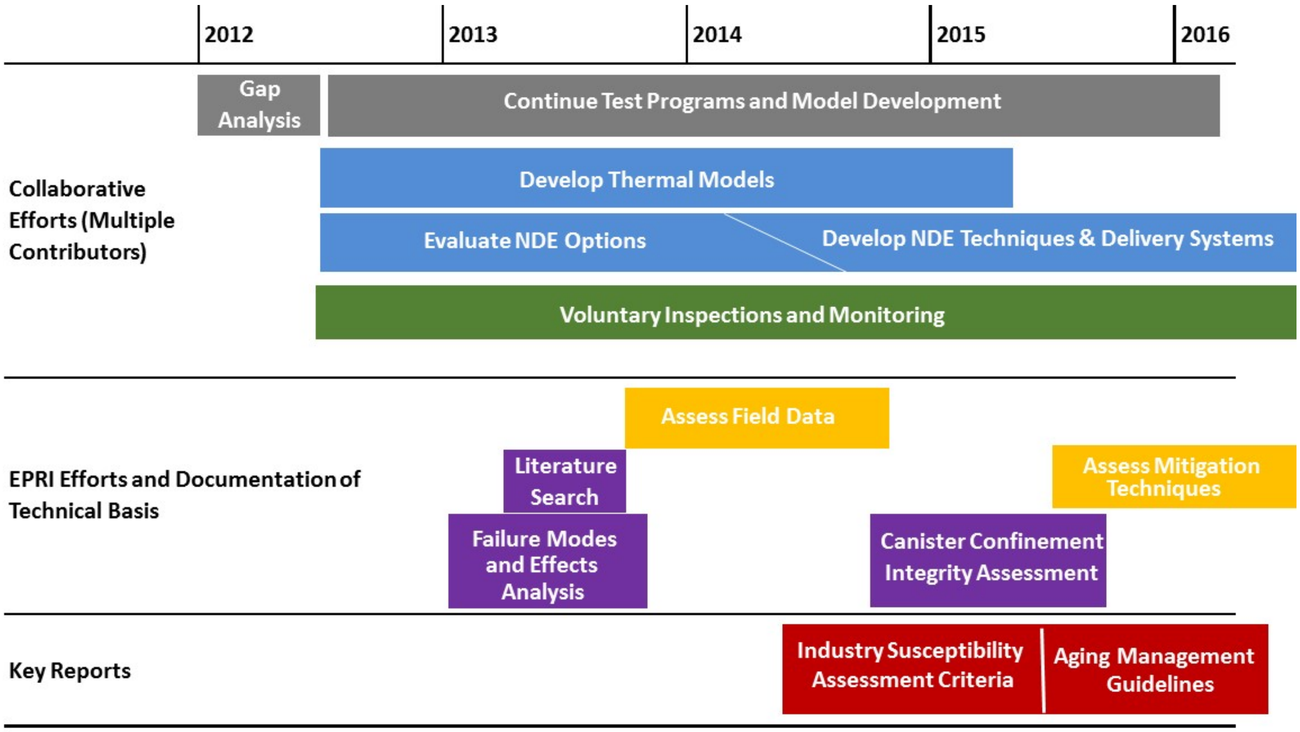

Fig. 1. Roadmap Timeline

II. ROADMAP ELEMENTS – TECHNICAL BASIS

EPRI has the opportunity to utilize knowledge gained during development and implementation of aging management programs for stainless steel components used in operating reactors in order to develop guidelines specific to managing the potential for CISCC of used fuel canisters.[2,3] However, dry storage conditions and licensing requirements are significantly different from those for operating plants. EPRI is working to develop a balanced approach considering these factors. The participation and collaboration of ESCP members is the key to achieving this balance and filling in information gaps.

II.A. Literature Search

EPRI conducted a literature search in 2013 in order to identify the available references for defining the necessary conditions for CISCC initiation and growth and comparing these conditions to the environment inside an independent spent fuel storage installation (ISFSI).[4] Key resources identified included summaries of CISCC events in stainless steel piping exposed to environmental conditions, laboratory testing to initiate and grow CISCC in stainless steel, and climate databases to define conditions at ISFSI sites.

II.A.1. Operating Experience with CISCC

There is a substantial amount of literature regarding SCC occurrence in Types 304, 304L, 304LN, 316, 316L, and 316LN austenitic stainless steels in the nuclear and other industries. The occurrence of stress corrosion cracking (SCC) at low temperatures requires the presence of chloride ions, and becomes more severe as the concentration of chlorides increases. Experience with SCC initiating on the outer diameter (OD) of piping and water storage tanks exposed to ambient conditions at marine sites is thus expected to be chloride induced and was the main focus of EPRI's literature survey regarding operating experience as no experience with SCC of welded dry storage canisters was found. ODSCC generally becomes more severe as temperature increases (as long as the metal surface stays wet), Types 304, 304L, 304LN, 316, 316L, and 316LN can experience SCC and the survey results found examples of ODCCC at temperatures as low as 25 to 30°C. The ten instances of ODSCC at nuclear power plants discussed in EPRI's literature survey report were mainly detected after about two decades in service. However, in two cases where severe sensitization, weld flaws, and cold work were identified as contributing factors, ODSCC was discovered after only a few years. Service experience with ODSCC in nuclear industry applications indicates that it could affect stainless steel canisters in ISFSIs, and that it is likely to be most severe at weld joints and at crevices, such as those where supports contact the canister. Locations where supports form crevices that intersect welds may thus be especially susceptible.

II.A.2. CISCC Testing

EPRI's literature review also summarized information on the potential for SCC initiation under conditions potentially present at ISFSIs at marine sites where chloride deposits serve as the primary source of environmental contaminants that could lead to SCC, and liquid comes from the deliquescence of deposited salts. The conditions considered were: (1) temperatures ranging from 0°C to 90°C; (2) materials in the as-received, welded, and sensitized material conditions; and (3) stainless steel grades 304, 304L, 304LN, 316, 316L, and 316LN.

The most relevant results came from laboratory testing sponsored by CRIEPI[5] and by NRC[6], with additional work of interest identified on a variety of corrosion themed publications and conference proceedings.

II.A.3. Canister Environment

The literature review identified some available data and models to predict the conditions at the canister surface. Surface chemistry, temperature, and humidity are of key relevance to the issue of CISCC.

The chloride concentration in the air entering the cask may be predicted using models of atmospheric chloride transport based on factors such as distance and elevation relative to the source of sea salt and wind direction and speed. There are networks of environmental monitoring stations collecting concentration data for several key cations and anions that may be used for comparison and adjustment, however, most ISFSI locations in the United States are hundreds of miles away from the nearest network monitoring location.

Networks of weather data including atmospheric temperature and absolute humidity are also available, with monitoring locations within twenty miles of most ISFSI locations in the United States. This data may be used in combination with canister thermal models to predict the relative humidity on the canister surface.

Models of aerosol deposition may be applied to predict the rate of deposition on the canister surface given the values of key parameters such as atmospheric chloride concentration entering the cask, air flow rate, air velocity, temperature, heat flux, and surface orientation.

II.B. Failure Modes and Effects Analysis

A Failure Modes and Effects Analysis (FMEA) was completed to systematically identify credible failure modes that could impact performance of the stainless steel dry storage canisters. The purpose of the FMEA is to identify conditions that may lead to a loss of the confinement function of stored dry cask storage systems (DCSS)s, to identify which of these conditions are most likely to occur, and to identify the most likely consequences associated with loss of confinement function.

The FMEA considered general (uniform) corrosion, pitting, crevice, and localized corrosion; microbiologically-influenced corrosion (MIC); and stress-corrosion cracking (SCC).

The chromium in austenitic stainless steels forms a stable passive oxide layer on the surface of the metal. This chromium oxide film prevents the general dissolution or oxidation of the underlying metal. Consequently, general corrosion is not credible due to the absence of an environment that can strip this layer from the metal.

In stainless steels exposed to ambient conditions, aqueous chloride is the most common aggressive contaminant for pitting and crevice corrosion. Pitting is most likely to be superficial, but could grow through-wall under particularly aggressive conditions. Pits can act as stress/environment concentrators and initiate SCC. Crevice conditions are similarly more likely to facilitate SCC rather than penetrate through-wall by bulk material dissolution.

Microbiologically-influenced corrosion (MIC) is limited where relative humidity (RH) is below 90%, and negligible where RH is below 60%. There is no operating experience for MIC of stainless steel under atmospheric conditions.

CISCC is the most likely degradation mechanism leading to a through-wall crack of stainless steel canisters. Chlorides are the most credible atmospheric species to cause degradation and chloride aerosol concentration decays rapidly moving inland. Establishment of conditions conducive to CISCC initiation may occur at sites particularly close to the open ocean. Conditions at sites farther from the ocean but still exposed to sources of chloride are expected to vary greatly.

The FMEA identifies particular locations on a canister surface where susceptibility to CISCC initiation and growth is expected to be highest. Table I summarizes this analysis.

TABLE I. Canister Surface Locations Most Susceptible to CISCC Degradation

Factor for CISCC Susceptibility	**Locations on Horizontal Canister**	**Locations on Vertical Canister**
Tensile Stresses on OD	Regions in the vicinity of welds (e.g. within about 2 thicknesses)	Regions in the vicinity of welds (e.g. within about 2 thicknesses)
Low Surface Temperature	Lids; shell along canister underside and lids	Outside of bottom lid and lower part of shell
High Chloride Deposition	Top of canister shell	Top lid; to a lesser extent, vertical areas in the vicinity of the overpack inlets
Crevice Environment	Support rail contact region	None identified
Material Condition	Areas of grinding or mechanical abuse (e.g. gouges)	Areas of grinding or mechanical abuse (e.g. gouges)
Most Susceptible Location(s)	Shell welds at canister ends (top surface); support rail interface near welds	Canister sides near welds at the bottom of the canister

SCC cracks are concerns for through-wall penetration and leakage but not concerns for rupture. Once a crack grows through wall, it releases helium and any fission gasses in the canister cavity and allows air to enter. The consequences of confinement penetration depend on cladding temperature with air as a cover gas and fuel rod conditions. Fuel burnup, time in storage, and initial enrichment affect the cladding temperature over time. Canisters that have been stored for a long enough time to reduce cladding temperature are not expected to experience assembly degradation as consequence of canister penetration and will have a greatly reduced inventory of radioactive gasses.

II.C. CISCC Flaw Growth and Flaw Tolerance

EPRI developed a flaw growth model and applied it in order to estimate the time to through wall flaw growth in various climate conditions; CISCC initiation time is not included in the results. Cracks are most likely to occur in the canister shell near welds and can lead to loss of confinement integrity.

II.C.1. Flaw Growth Model

The model provides a deterministic calculation of potential flaw growth rate. Prior crack initiation is assumed for the flaw growth calculation. The model is based on typical form of SCC growth equations with factors based on empirical data to account for dependences (for example ASME BPVC Section XI, Article C-8500). It is primarily an empirical model that fits available data to expected dependences on environmental factors. The form of the model is as follows:

$$\frac{da}{dt} = \alpha\left(K_I - K_{Ith}\right)^n f_T f_H f_S \qquad (1)$$

Where:

α = SCC crack growth rate coefficient (m/s)

n = stress intensity factor exponent

K_I = stress intensity factor (MPa-m$^{0.5}$)

K_{Ith} = stress intensity factor threshold (MPa-m$^{0.5}$)

f_T = Arrhenius factor of temperature

f_H = CGR dependence factor on humidity

f_S = CGR dependence factor for chloride areal density on the surface

The data available from crack growth rate experiments shows little dependence on chloride areal density and stress intensity factor. Thus the stress intensity exponent was set to zero and the dependence factor on chloride areal density was set to one for the analysis included in the EPRI report. This leaves crack growth rate as a function of an experimentally determined crack growth coefficient, an Arrhenius factor of temperature, and a factor based on local humidity conditions.

The crack growth rate coefficients used in the EPRI model are based on experimental data[5] which shows relatively rapid crack growth in the first few millimeters and then significantly slower crack growth at deeper depths.

The flaw growth model includes a step function which is set to one (crack is growing) when the relative humidity at the canister surface is above deliquescence relative humidity and to zero (crack is not growing) when it is not. The relative humidity is a function of the canister surface temperature and the ambient absolute humidity. The surface temperature is a function of the canister decay heat and the atmospheric temperature. The surface temperature of dry storage canisters is not uniform, the hottest portions are near the (top for horizontal designs) center of the shell and the coolest portions are near the (bottom for vertical designs) canister ends. The EPRI report includes an analysis of the combined effects of temperature and humidity as a function of the difference between local canister surface temperature and ambient temperature. This analysis assumes constant decay heat for one year and utilizes hourly temperature and dew point data from 2011 for several locations in the United States. The resulting hourly environmental factors are averaged over one year as shown in Figure 2.

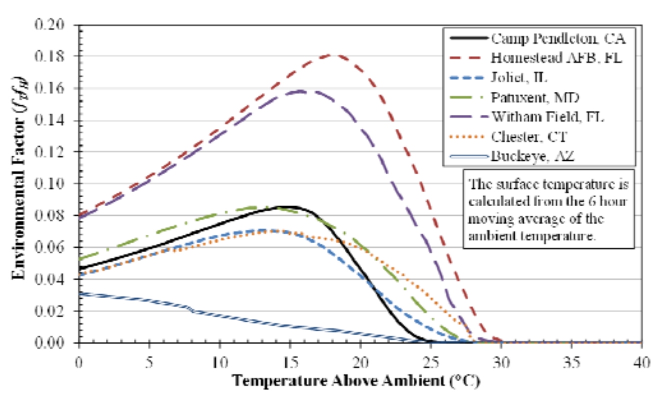

Fig. 2. Average of the Environmental Factor on CGR ($f_T f_H$) Based on One Year of Hourly Climate Data

II.C.2. Flaw Growth Results

The flaw growth model was applied to estimate the time required for an assumed initiated CISCC flaw to grow through wall in select climate conditions. Sample results are provided in Table II.

TABLE II. Sample Results for Time to Through Wall Flaw Growth

Climate Condition	Canister Wall Thickness	Canister Surface Temperature at Initiation Time	Time for Crack to Grow Through Wall
Homestead	0.5”	Amb. + 35C	41.0 years
Homestead	0.5”	Amb. + 25C	26.5 years
Homestead	0.5”	Amb. + 15C	30.9 years
Homestead	0.625”	Amb. + 25C	35.6 years
Camp Pen.	0.5”	Amb. + 35C	81.3 years
Camp Pen.	0.5”	Amb. + 25C	63.2 years
Camp Pen.	0.5”	Amb. + 15C	61.7 years
Witham Fld	0.5”	Amb. + 25C	32.3 years

II.C.3. Flaw Tolerance Results

Analysis based on a normal “handling” load (normal internal pressure with handling/lifting load) and an accident load (accident internal pressure with normal handling/lifting load) were considered for determining critical flaw size. The calculated critical flaw sizes for the designs evaluated were roughly 1 meter (much longer for some cases) in length and over 70% through wall (over 90% for many cases).

In the event of a through wall crack, the time required for any depressurization of the helium backfill is short relative to the timescale for helium replacement with air. Replacement is heavily dependent on the through-wall flaw geometry, for very tight cracks and small crack opening areas typical of SCC cracks, the time required for the canister to have an appreciable mole fraction of air can be on the order of years.

III. CONTINUING RESEARCH AND DEVELOPMENT

EPRI will utilize the reports discussed in the prior sections as a technical basis and input for future reports leading up to CISCC aging management guidance. EPRI will also collaborate with ESCP members to facilitate development of the necessary tools and resources for implementing CISCC aging management at used fuel dry storage installations.

III.A. Susceptibility Assessment Criteria

EPRI will develop criteria to assess the relative susceptibility of dry storage installations to canister degradation, particularly CISCC. Criteria will rank ISFSI susceptibility based on factors such as ambient temperature and humidity and geographic proximity to salt water source. Criteria will also be provided to identify the most susceptible (lead) canisters for a particular ISFSI based on factors such as cask system type, canister design, time in service, and decay heat.

III.B. Canister Confinement Integrity Assessment

A confinement integrity assessment will be performed for the stainless steel canister designs installed at susceptible installations. This assessment will include consideration of estimated initiation times and propagation rates, and associated probabilities and uncertainties. The objective is to provide data necessary to set useful monitoring frequencies. This work will include additional crack growth calculations using the deterministic flaw growth assessment results along with Monte Carlo probabilistic model simulations of crack initiation, crack growth, and crack detection. The investigation shall be performed as a function of time up to 120 years of operation.

A key aspect of the probabilistic simulation model will be to treat the range of chemical environments that may be produced on the canister surface in a probabilistic manner, considering the variability in key ambient conditions including salt concentration, temperature, and relative humidity.

The assessment will include results for alternative inspection and monitoring strategies, so the implications for confinement integrity can be examined as a function of the type and frequency of inspections or monitoring performed.

III.C. Nondestructive Evaluation (NDE)

There is a near-term need to develop and qualify nondestructive examinations capable of detecting CISCC in used fuel storage canisters prior to loss of confinement integrity. EPRI has begun a multi-year effort that will provide mockups for demonstrating inspection capabilities, develop and test acoustic emissions and eddy current technologies, and support development and demonstration efforts for robotic delivery systems to enable in-situ inspections. EPRI is also coordinating industry NDE research applicable to canister degradation via a dedicated subcommittee of ESCP. Inspections will be a key element of CISCC aging management plans.

III.D. Repair and Mitigation

Given that inspections of used fuel canisters may result in findings of degradation, prudent inspection planning requires the capability to repair or replace degraded components should they be identified. Repair of stainless steel piping and vessels is not a novelty for the nuclear industry, there are many proven technologies available for this purpose. However, none of them have been specifically qualified for use on canisters in service in dry storage casks. EPRI has proposed future projects to fill this gap. Similarly, experience in reactor vessels and piping suggests there are many techniques which could be applied during canister fabrication or even in-situ that could prevent or delay CISCC degradation. Efforts to qualify these technologies for application to used fuel storage canisters have also been proposed along with efforts to identify and demonstrate mitigation techniques that may be uniquely applicable to dry storage canisters.

IV. CONCLUSIONS

Recent results from EPRI's research to evaluate the susceptibility of welded stainless steel canisters storing used nuclear fuel to aging degradation, particularly CISCC, suggest that some canisters may be susceptible. EPRI's research has not included prediction of flaw initiation time. When flaw initiation is assumed to occur, the flaw growth scenarios predicted for sites with very high environmental factors on crack growth project that confinement integrity will remain intact for decades after a flaw has initiated. A research and development roadmap is maintained by EPRI to aid in coordinating industry efforts to identify susceptible canisters and develop aging management plans to ensure continued integrity for the necessary storage lifetime. Aging management guidelines will include recommendations for nondestructive examination along with mitigation and repair capabilities in order to achieve this goal. Thus development and demonstration of inspection techniques capable of demonstrating confinement integrity is a near-term research priority.

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