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March 31, 2014

Mr. Aladar Csontos
Chief, Structural Mechanics and Materials Branch
Division of Spent Fuel Storage and Transportation
Office of Nuclear Material Safety and Safeguards

Subject: Transmittal of Research & Development Roadmap to address Potential Stress-Corrosion Cracking of Welded Stainless Steel Used Nuclear Fuel Dry Storage Canisters, Revision 1

Dear Mr. Csontos:

The subject document has been revised to address comments that were provided by the Structural Mechanics and Materials Branch last year[1] and to update the roadmap with the latest information on research and development results and near-term plans.

This revised roadmap is being provided to you as part of EPRI's continued engagement in the Regulatory Issue Resolution Protocol[2] for Dry Spent Fuel Storage Canister Chloride Induced Stress Corrosion Cracking.

Sincerely,

Shannon Chu
Senior Technical Leader

Attachment

cc: Keith Waldrop (EPRI), John Kessler (EPRI), Rod McCullum (NEI), Kris Cummings (NEI)

[1] Letter from David Tang to Keith Waldrop, Response *to Electric Power Research Institute Regarding Research & Development Roadmap to Address Potential Stress Corrosion Cracking of Welded Stainless Steel Used Nuclear Fuel Dry Storage Canisters*, July 30, 2013 (ML13217A398).
[2] Letter from Rodney McCullum to Aladar Csontos, *Regulatory Issue Resolution Protocol Screening Form and Resolution Plan for Chloride-Induced Stress Corrosion Cracking (RIRP-N-10-01),* February 7, 2014.

CHARLOTTE OFFICE
1300 West W.T. Harris Boulevard, Charlotte, NC 28262-8550 USA • 704.595.2000 • Fax 704.595.2860
Customer Service 800.313.3774 • www.epri.com

USED FUEL DRY STORAGE STAINLESS STEEL CANISTER STRESS CORROSION CRACKING SUSCEPTIBILITY ASSESSMENT:

R&D ROADMAP LEADING TO IDENTIFICATION OF CANISTERS POTENTIALLY SUSCEPTIBLE TO STRESS-CORROSION CRACKING

Rev. 1 (March 31, 2014)

1. INTRODUCTION AND PURPOSE

There are over 1500 welded stainless steel (SS) dry storage canisters in the United States which store spent fuel assemblies. These canisters provide the primary confinement barrier to prevent release of radionuclides into the environment. Laboratory studies have shown that stress corrosion cracking (SCC) of stainless steels can occur in specimens which have been subject to applied stresses and coated with chloride salts. This phenomenon is known as chloride induced stress corrosion cracking (CISCC).

Interest in the potential for this phenomenon to affect dry storage canisters prompted it to be addressed by industry and NRC as a pilot issue in the Used Fuel Storage and Transportation Regulatory Issue Resolution Protocol (RIRP) process (Issue Number N-10-01). The issue has been characterized as a lack of sufficient data to determine under what conditions (environmental and cask) and over what time scales CISCC could initiate.

This R&D Roadmap documents the status of recently completed, on-going, and near term planned research necessary to acquire sufficient data to understand the phenomenon of SCC in the context of dry cask storage.

The key elements of research and development in this area include:

- Literature survey;
- Failure modes and effects analysis;
- Voluntary inspections;
- Empirical models.

The desired outcome of this R&D is a set of susceptibility assessment criteria that may be applied in order to evaluate the potential for CISCC on a canister specific basis. The criteria document will recommend a combination of models and monitoring systems that utilities can use to determine which of their canisters (if any) may become susceptible to CISCC. The criteria document will allow utilities to prioritize follow up actions for canisters which have the highest possibility of becoming susceptible in the near term. Knowledge gained during these follow up actions will provide improved understanding of the timeframe for CISCC initiation in spent fuel storage canisters.

This is an important first step that will bring closure to the RIRP. Other actions within the industry's overall approach to addressing this potential issue and leading to an aging management guideline are outside the scope of this document.

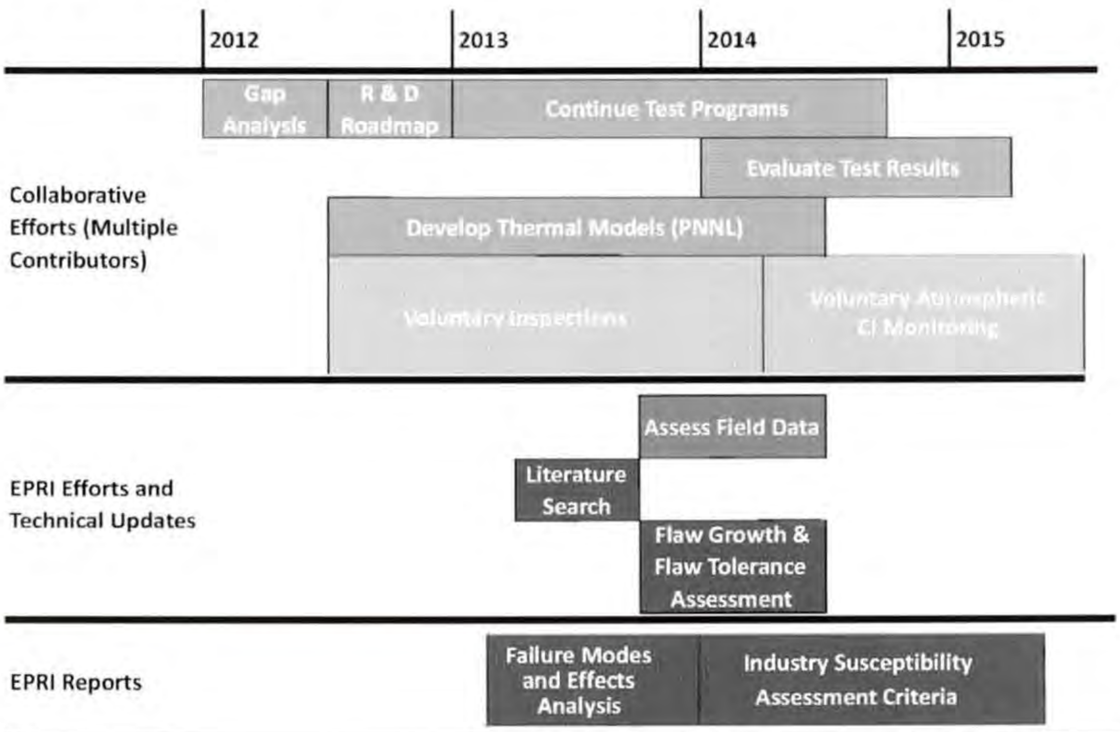
This R&D Roadmap is a living document to be updated as items are completed and new information becomes available. This document is divided into four sections, this section provides the introduction and purpose, the second section provides a high level outline of the recently completed, on-going, and near-term planned R&D activities, the third section provides

summary details of these R&D activities, and the final section discusses the desired additional R&D that could provide improved results in future revisions of the susceptibility assessment criteria.

2. R&D SUMMARY STATUS AND SCHEDULE

The elements of the R&D roadmap are summarized in Figure 1 with further detail listed below. In the figure, blue represents actions that are collaborative and led by national laboratories, green represents actions that involve participation of volunteer sites (utilities), red represents EPRI contractor activities, and purple represents EPRI sponsored work resulting in milestone reports.

Figure 1: Roadmap Timeline



- Literature Survey Report
  - This report provides data used as input to FMEA and Susceptibility Assessment Criteria reports.
  - A draft was developed by EPRI contractors in 2013 with review and comment by EPRI and industry advisors.
  - A final technical update report will be published by June of 2014.
- Failure Modes and Effects Analysis Document
  - This report evaluates potential degradation mechanisms and identifies CISCC as primary concern for potential through-wall cracking and provides context for the likelihood and consequences of CISCC in spent fuel canisters.
  - It was published in December 2013 (EPRI product 3002000815).
- Voluntary Inspections

    - Calvert Cliffs 2012
    - Hope Creek November 2013
    - Diablo Canyon January 2014
- Thermal models
    - PNNL modeling, benchmarked, and validation against INL casks and related systems (PNL) – 1983-1992
    - PNNL thermal model for the Calvert Cliffs canisters (PNNL-21788) – 2012
    - PNNL thermal model for Hope Creek canisters (pre-inspection predictions only, draft completed August 2013 – Final to be release in September 2014)
    - PNNL thermal model sensitivity study for Calvert Cliffs canisters (PNNL-22646) – 2013
    - PNNL thermal model for Diablo Canyon canisters (pre-inspection predictions only, draft completed December 2013– Final to be release in September 2014)
    - PNNL and ORNL are currently developing models for system and component temperature determination of modules existing for ISFSIs at the shutdown sites and will account for time of loading out to extended duration in time; completed models currently include
        - Rancho Seco (NUHOMS horizontal module, site-specific 24P DSCs with B&W 15x15 fuel)
        - Maine Yankee (NAC-UMS; site-specific fuel loadings with CE14x14 fuel, including configurations with failed fuel canisters)
        - Connecticut Yankee (NAC-MPC with CY-MPC 26 and 24 canisters)
        - NAC-UMS (design basis with WE 17x17 fuel)
        - HI-STORM100 (design-basis modules with MPC-24 and MPC-32 containing WE 17x17 fuel, and MPC-68 with GE 8x8 fuel)
    - NRC Research is working with CNWRA to develop a thermal model of the NUHOMS canister, expected completion in mid-2014.
    - NRC Research anticipates development of a thermal model for a vertical cask design to be completed in 2015.
- Weld residual stress models:
    - EPRI's contractors performed modeling which is published in the FMEA report; the results confirm sufficient stress for SCC concern.
    - The NRC published a report, *Finite Element Analysis of Weld Residual Stresses in Austenitic Stainless Steel Dry Cask Storage System,* in December 2013. (ML13330A512)
    - MIT has obtained flat plate welded specimens fabricated using materials and methods typical of canister fabrication and is currently performing residual stress measurements on these specimens.
- Thermodynamic Models
    - Sandia plans to assess the stability of salt assemblages corresponding to site-specific aerosols, as a function of waste package surface temperature, relative humidity, and ambient air acid gas concentrations.
- SCC crack initiation and propagation models:
    - Laboratory studies of SCC initiation were recently completed at SWRI with NRC support; results are published in NUREG/CR-7170, *Assessment of Stress*

Corrosion Cracking Susceptibility for Austenitic Stainless Steels Exposed to Atmospheric Chloride and Non-Chloride Salts, (ML14051A417).
    - MIT plans to conduct SCC testing on flat plate welded specimens once weld residual stress measurements are complete.
    - Sandia has near term plans for SCC initiation and propagation testing to be conducted on a canister mockup which will be full scale diameter.
    - EPRI will publish a stress corrosion crack growth rate models in a report, *Flaw Growth and Flaw Tolerance Assessment for Dry Cask Storage Canisters*, due in late 2014
- EPRI's contractors are utilizing a chloride deposition model to predict canister surface chloride concentration as a function of atmospheric chloride concentration, over pack airflow, surface orientation, and surface temperature (function of canister age and heat flux, varies with location on canister). This model will be described in the susceptibility assessment criteria report.
- Susceptibility Assessment Criteria Report
    - To be published by EPRI – Mid-2015

Aging Management Actions Related to CISCC (beyond scope of R&D Roadmap)

- ANL has developed a report, *Managing Aging Effects on Dry Cask Storage Systems for Extended Long-Term Storage and Transportation of Used Fuel*, which is currently in revision 1 (FCRD-UFD-2013-000294, ANL-13/15, 9/30/2013). Recent comments will be addressed over the next few months and a revision 2 report will be issued.
- NEI is developing guidance for ISFSI license renewal applications – estimated completion in November 2014
- NRC is revising Generic Guidance for Aging Management and developing guidance specific to spent fuel storage aging management.
- EPRI is developing Aging Management Guidance specific to the CISCC issue – plan to publish early 2016
- Additional monitoring is planned at sites that are likely susceptible and/or currently seeking license renewal:
    - Calvert Cliffs has specific commitments related to license renewal
    - EPRI plans to support atmospheric monitoring at three sites where surface samples were collected
- EPRI has begun efforts to develop non-destructive examination (NDE) technology for stress corrosion crack detection, this work will include investigation and development of delivery systems and is planned to continue through 2017
- Confirm/Refine Susceptibility Assessment Criteria based on results
- Confirm/Refine Aging Management Plan guidance based on continuing operating and implementation experience
- The Department of Energy has announced funding and is seeking proposals for potential cask monitoring applications.
- EPRI has proposed future work to develop CISCC mitigation guidance. Effective mitigation options may include use of coatings or filters to prevent chloride from depositing, or application of mechanical stress relief.

3. R&D ELEMENTS

This section outlines the R&D needed to develop susceptibility assessment criteria. Application of the criteria will determine which in-service canisters may be susceptible to SCC, where they are located, how their susceptibility to SCC changes over time, and the relative priority of actions in response to the susceptibility concern.

3.1 Literature Survey

A comprehensive literature review of past and current work relevant to the specific concerns related to CISCC of welded stainless steel canisters has been completed. This review identified the currently available information to define the necessary conditions for SCC in stainless steels and the available information regarding actual canister conditions. The review report also identifies limitations in the current state of knowledge.

The literature summary identified relevant operating experience and laboratory experiments for SCC in stainless steels.

- While CISCC has not been identified in spent fuel canisters, it has been observed on the outer diameter of un-insulated piping and tanks at nuclear plants. It is important to note that this operating experience is at ambient temperatures.
- Experiments were recently conducted by CRIEPI [2009-2011] in Japan and at the Center for Nuclear Waste Regulatory Analyses (CNWRA) at the Southwest Research Institute [2010-2013] (funded by NRC).
- Tests conducted by CNWRA found SCC initiation in sensitized specimens under controlled laboratory conditions with Cl surface areal density as low as 0.1 grams per square meter at 45°C under cyclic humidity conditions in heavily cold worked specimens.

In order for SCC on austenitic stainless steels to occur, all of the following conditions need to be present:

- A metal susceptible to SCC.
    - Austenitic stainless steels such as Grades 304, 316, and 316L are used in canister fabrication and have been found to be susceptible. Some laboratory experiments suggest that SCC initiation is delayed in 316 compared to 304.
- Sufficiently high tensile stresses in the SS.
    - Sources of tensile stresses in canisters include:
        - Shrinkage in the welds due to thermal contraction as the weld cools to room temperature. Residual stresses in welds are the largest when the welds are rapidly cooled rather than being thermally or mechanically annealed to relieve these tensile stresses ("stress relieved"). SS dry storage canisters currently in use do not have welds that have been stress relieved. This is true for the canister body longitudinal and circumferential wells and the lid closure welds.
    - Residual stresses were not typically calculated or measured for each lot of canisters produced by a particular fabricator. While the cask vendors specify particular welding standards for the fabricators to follow, there are differences in welding procedures between fabricators. In some cases, welding procedures for the same fabricator changed over time.
    - Weld residual stress calculations performed as part of the FMEA confirmed the expectation of sufficient stress in welded regions of spent fuel canisters.

- Presence of deliquescent salts on the SS surfaces.
    - Airborne salts and other contaminants can be drawn inside the concrete over pack of a canister due to natural air convection driven by used fuel decay heat.
    - Data found in the literature review indicates that airborne salt concentrations are highest for ISFSIs located near breaking ocean waves. The literature review investigated non-marine sources of chloride and found that deposition rates were typically lower than those in marine environments by factors ranging from about 10 to 100.
    - Existing Cl deposition models have been reviewed and will be modified and utilized to estimate Cl surface areal density [grams per square meter] as part of the EPRI susceptibility assessment criteria development and implementation.
- Humidity sufficient to cause deliquescence.
    - The amount of humidity required to cause deliquescence is a function of the temperature of the humid air, SS canister surface temperature and the type of salts present on the SS surface.
- Temperature Window
    - Temperature is an important parameter in evaluating the potential for CISCC in dry storage canisters.
        - In general, higher temperatures cause higher corrosion rates. However, higher dry storage canister surface temperatures could prevent the deliquescence of salt by reducing relative surface humidity levels, thus reducing corrosion rates.
        - Given these countervailing effects, there is a limited range of temperatures over which SCC can occur. Crack initiation and propagation are most likely to occur on surfaces that are *just cool enough* to sustain deliquescent brine.
    - Canister surface temperature varies significantly with location, with peak temperatures near the center of the active fuel length and lowest temperatures near the ends of the package.
        - Surface temperature distributions can be predicted with existing thermal models used by the cask vendors, but these thermal models use bounding assumptions that generally result in overestimates of temperatures, focused on the main concern in the licensing process of providing reasonable assurance that the 400°C peak cladding temperature limit is not exceeded in dry storage operations, including the drying process itself. Using these same models will likely result in overestimated canister surface temperatures in actual operation of a storage module.
    - In order to determine when SCC may initiate, it is necessary to determine the time interval during which the canister surface temperature is low enough to sustain deliquescent brine.
        - Very few direct measurements of in-service canister surface temperatures are available.
        - The modeling assumptions made in evaluations to ensure compliance with Regulatory-defined peak cladding temperatures limits generally result in non-conservative estimates of the time at which canister surface temperatures drop below a particular temperature. (That is, the canister surface is predicted to be hotter, for a longer period of time, than would likely be the actual case.)

- Modified calculations with more realistic boundary conditions and more accurate (rather than bounding) resolution of package geometries will improve the accuracy of consequence modeling and models for Cl deposition on canisters.

While some data are available that can help identify the conditions under which SS dry storage canisters may become susceptible to SCC, there are some important data gaps. Controlled laboratory conditions are likely to be significantly different from actual canister conditions. Key factors that are likely to affect SCC initiation can be very difficult to model. These include:

- The amount of non-salt surface deposits is expected to be significant on actual canisters and may interfere with formation of (or significantly reduce Cl concentration of) deliquescent brines on the canister surface.
- Atmospheric gases and non-Cl surface deposits can interact with any deliquescent brine formed, changing the chemical composition and corrosive capacity.
- The effects of continuous airflow over canister surface have not been modeled in laboratory testing to date.
- Actual canister Cl surface areal density may be very low; however there is no current laboratory data lower than 0.1 g/m^2.
- Actual material conditions and stress states may differ significantly from laboratory specimens used in most testing so far.

3.2 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 DCSSs, to identify which of these conditions are most likely to occur, and to identify the most likely consequences associated with loss of confinement function. While the FMEA process does not define susceptibility criteria, the results do point to the key factors for determining CISCC susceptibility and provide context for the safety significance of this issue.

The main body of the FMEA report includes six sections. The first and second are an introduction to the report and background information on the different DCSS designs. The third section covers the process, criteria, and terminology used in the FMEA. The fourth section discusses the technical details of the degradation mechanisms, canister failure modes, and the potential consequences of canister degradation. The fifth and sixth sections cover the implications of the FMEA and the conclusions of the report. An appendix includes calculations that consider the residual stresses resulting from canister shell rolling and from welding. The report also includes additional appendices that examine transportation, after the extended storage life, as a source of cyclical and accident stresses, and issues specific to fuel assemblies with stainless steel cladding.

The FMEA considered the following corrosion mechanisms:

- General (uniform);
- Pitting, crevice, and localized;
- Microbially-influenced corrosion (MIC);
- 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 also 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 induced corrosion (MIC) is limited where relative humidity (RH) is below 90%, and negligible where RH is below 60%. A review of MIC was performed for geological repository of spent fuel storage canisters and there is no operating experience for SS MIC under atmospheric conditions.

The FMEA determined that CISCC is the most likely degradation mechanism leading to a through-wall crack and should be the focus of aging degradation consideration. The FMEA went on to consider the likelihood and consequences of SCC in a canister. Chlorides are the most credible atmospheric species to cause degradation of austenitic stainless steels and chloride aerosol concentration decays rapidly moving inland. Establishment of conditions conducive to CISCC initiation is considered likely for small number of sites close to the open ocean. Likelihood of CISCC at sites farther from the ocean but still exposed to sources of chloride is expected to vary greatly and increase over multiple decades.

The FMEA determined that 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 presence of breached fuel rods outside damaged fuel cans. 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.

3.3 Voluntary Inspections

Data is needed to confirm the actual conditions (surface chloride concentration, temperature, etc.) that dry storage canisters experience. EPRI has recently completed an effort to gather an initial set of data through inspections of 6 in-service canisters at three volunteer sites located in or close to potentially marine environments. Two different storage systems (vertical and horizontal) were inspected.

EPRI anticipates publication of three reports in 2014 that will describe each inspection and the chemical analysis of the surface samples collected. These reports will detail the limitations of the inspection technologies used. Only a small portion of the surface area of each canister was analyzed for surface chemistry.

The inspections were completed using a truly collaborative effort involving EPRI, 2 cask vendors, 3 utilities and 3 national laboratories each providing funding and/or in-kind contributions.

The sites and systems inspected were:

Site	System	Years in service	Distance from water
Calvert Cliffs	NUHOMS® site-specific modules with 24P canister	16 - 19	0.8 km from the Chesapeake Bay
Hope Creek	Holtec HI-STORM 100S Version B	7	0.4 km from the Delaware Bay
Diablo Canyon	Site specific version of Holtec HI-STORM 100SA	2 - 4	0.6 km from the Pacific Ocean

These first set of inspections included:

- Visual examination of canister surfaces for signs of pitting and corrosion
    - Focus on shell welds, areas in contact with other surfaces where possible;
    - As much of the canister surface as practical, some areas with different air flows, canister surface temperatures, upper and lower surfaces;
- Temperature measurements: both ambient and on the canister surfaces at various locations to gauge the spatial temperature distribution. These data will be used to benchmark new thermal models so improved best-estimate predictions can be made of canister surface temperature spatial and temporal distributions;
- Canister surface contaminant measurements (through sample retrieval and analysis):
    - Composition;
    - Concentration;
    - Other characteristics (such as whether the material seems tightly bound to the surface or is fluffy such that much of it is not really contacting the surface)

In the context of the R&D needed for developing susceptibility criteria, the results from these first inspections were informative, but not complete.

- Visual
  No gross or unexpected degradation was observed. Some rust was seen on one of the canisters believed to be from external free iron contamination, as opposed to pitting initiation from atmospheric chlorides.
- Temperature
  Some anomalies between measured and predicted temperatures were seen, however these differences are nearly eliminated with more accurate design input information. No additional R&D is needed for calculating best estimate temperatures, rather adequate emphasis needs to be placed on detailed and accurate input data.
- Surface contaminants
  Very low chloride concentrations were measured on the canister surfaces and the compositions were found to more resemble inland rainwater than sea salt for the sites inspected. There is additional need to obtain samples at sites much closer to the ocean and breaking waves to understand the chloride concentrations at the most severe sites. Further testing at very low chloride concentrations would also be helpful to understand

when pitting and SCC may occur, since ~95% of sites appear to be non-marine based on the results of these voluntary inspections.

Current plans for additional surface exams and sampling are limited to site-specific commitments made by license renewal applicants. Calvert Cliffs has indicated repeat inspections will be planned on a ten year frequency.

It is anticipated that the susceptibility criteria will rely on a Cl deposition model that requires Cl atmospheric concentration as an input. This model will also rely on the canister heat flux modeling discussed in the next section. EPRI will work with the three volunteer inspection sites to implement atmospheric monitoring by installing additional equipment beyond that which typical utilities have in place. EPRI will benchmark the chloride deposition model based on results from the three volunteer sites and, using the experience gained in atmospheric monitoring at these three volunteer sites, will provide guidance for implementing atmospheric monitoring at additional sites in the future.

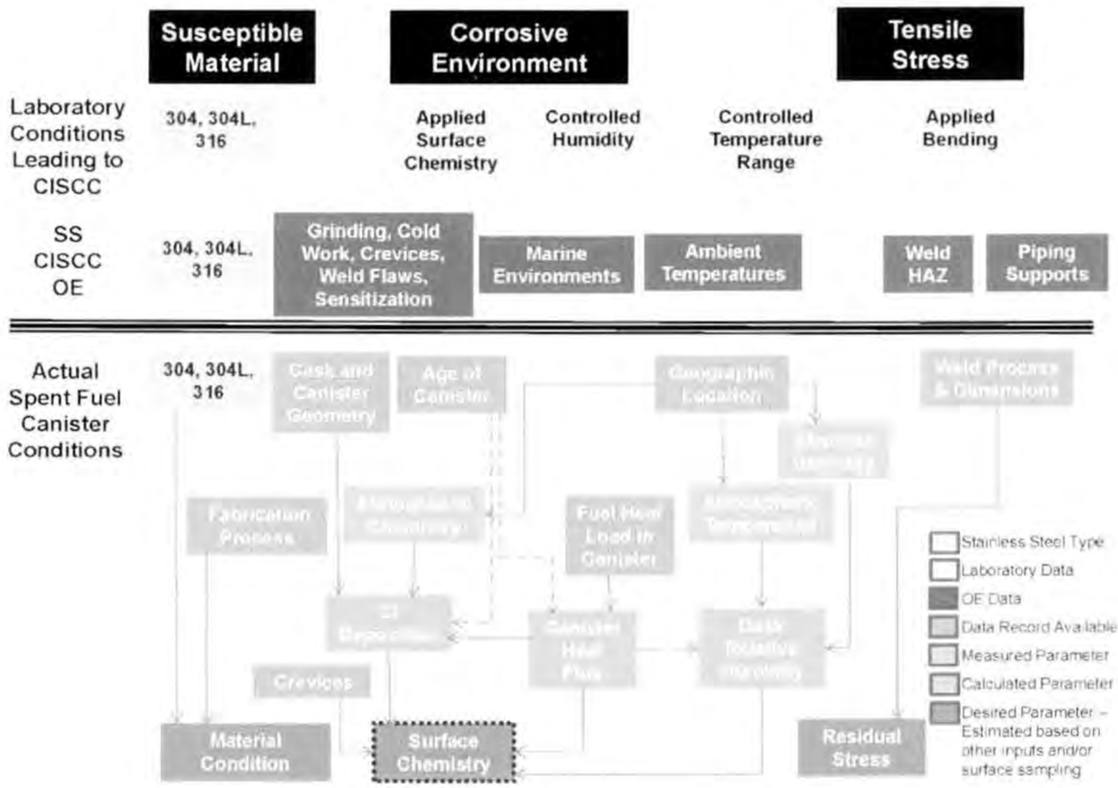
- Monitoring of ambient conditions at storage sites is planned to provide information on the temporal distribution of:
    - Site ambient temperature and humidity
    - Atmospheric salt and other pollutants/organics in the ambient air.
    - Wind and precipitation.

Many inland sites may be able to reduce the Cl atmospheric sampling frequency/duration or provide justification for use of nearest (or representative) atmospheric monitoring station data in lieu of site specific monitoring. Some marine sites may be able to rely on data collected at a "sister" site that is demonstrated to be bounding.

3.4 Empirical Models

The last phase of research and development that will lead to the goal of Susceptibility Assessment Criteria is the identification of empirical models that can be applied to estimate the likelihood and timeframe for SCC initiation and propagation in SS spent fuel storage canisters. These models will be based on the results of the R&D elements described in the previous three subsections. Figure 2 describes the key parameters for SCC susceptibility.

Figure 2: Susceptibility Parameters



As shown in Figure 2, SCC can occur in susceptible materials exposed to corrosive environments and subject to tensile stresses. Canisters have been manufactured from stainless steels (304, 304L and 316) that are susceptible to SCC. Fabrication processes including welding, grinding and cold work will impact the degree of susceptibility. Weld residual stress modeling predicts that sufficient tensile stress is present to support SCC. That leaves the environment as the key parameter to predicting SCC susceptibility of spent fuel canisters. As discussed earlier in this roadmap, there is a data gap between the known conditions where SCC has occurred in stainless steel piping in nuclear and other industries, the laboratory conditions applied for SCC testing, and the actual conditions of spent fuel canisters. Modeling will be used to estimate actual canister conditions for comparison to conditions known to cause SCC. Inputs to models will include parameters that are part of the cask fabrication and loading records, as well as parameters that will need to be measured at ISFSI sites.

The key models that will be utilized in the calculating susceptibility (calculations indicated in purple in Figure 2) parameters are:

- Thermal models have been developed to inform voluntary inspection efforts and will also be an input to estimating surface temperature and subsequently surface chemistry
- Atmospheric deposition models found in the literature survey report will be used to estimate chloride deposition and subsequently surface chemistry
- Residual weld stress models documented in FMEA report confirm the relevance of SCC to dry storage canisters.

- SCC crack initiation and propagation data and models from the literature survey are being utilized in EPRI's flaw growth and tolerance calculations. These calculations will provide better understanding of the timeframe under which SCC may be a concern for SS spent fuel canisters.

It is anticipated that the susceptibility assessment criteria may be revised based on data gathered and lessons learned in implementation, including subsequent implementation of aging management activities.

4. ADDITIONAL DESIRED DATA AND MODELING WHICH COULD BE USED TO REFINE SUSCEPTIBILITY CRITERIA

Inspection of in-service SNF storage canister surfaces is very difficult, and CISCC has never been directly observed. The potential occurrence of CISCC is inferred on the basis of three factors/data sets. First, the austenitic stainless steels used in the construction of typical storage containers (e.g., 304, 304L, etc.) are known to be susceptible to CISCC when a sufficiently aggressive environment is present in combination with significant tensile stress (either residual or imposed). Second, CISCC has been observed in other stainless steel components and structures at nuclear power plants in near-marine environments. Finally, experimental studies carried out using test conditions (i.e., chloride based salt deposit approximating a marine aerosol plus an appreciable tensile stress) potentially relevant to those seen by interim storage canisters resulted in CISCC.

However, both the environment and the specific materials used in the aforementioned laboratory studies may vary from those relevant to interim storage canisters within their over packs. In addition, the laboratory based SCC testing performed to date has focused on initiation and not crack growth. Thus, on-going flaw growth and tolerance assessments have relied on typical SCC crack growth models which do not include dependency on crack tip stress intensity or chloride loading.

For industry to refine CISCC susceptibility criteria and predict the timeframe of concern, a better understanding of the evolving environment on the surface of SNF interim storage canisters is required.

Development of the following data, tools, and models would constrain canister surface environments, inform SCC experimental studies with respect to materials and environment, and allow better prediction of SCC occurrence and propagation.

- Best estimate thermal and ventilation models using field data for validation;
- Higher fidelity measurements of the environment at the surface of SNF storage containers
  - Improved instrumentation for taking measurements of canister surface conditions (temperature, humidity, deposited materials);
  - Additional field data allowing evaluation of temporal and spatial variations in the composition and concentration of canister surface deposits (salt/contaminant/organic materials).
- Field data assessing the composition and abundance of atmospheric aerosols and reactive gases (e.g. HCl, HNO_3, NH_3, and SO_2), potentially allowing (through thermodynamic modeling) correlations with measured surface deposits.

- Thermodynamic models assessing the stability of deliquesced salt assemblages on the waste package surface, and the importance of particle-gas conversion reactions and brine-gas exchange reactions.

Additional repeatable laboratory experiments by multiple organizations need to be conducted to reduce the uncertainty in the conditions required to cause SCC in the SS materials used in dry storage canisters (base metal and welds). In addition to providing an improved understanding of the likelihood of CISCC in existing in-service interim storage canisters, these tests will identify modifications in the current manufacturing processes that might mitigate stress corrosion cracking.

The experimental parameters that should be considered are those that address the three criteria that must exist for SCC—susceptible material, an aggressive environment, and tensile stress.

<u>Material properties</u>

Surface treatments should match those currently in use in the manufacturing process (e.g., samples should not be polished), but might also include pickling to remove embedded iron or carbon steel fragments, if testing shows that such fragments provide loci for corrosion initiation. Specific considerations for future testing include the following:

- Composition of the base and weld filler metal used in the container
  - Use of 304 vs. 316
  - Use of L-grade versions
- Surface condition of the storage container prior to deployment
  - Critical surface orientation (horizontal, vertical)
  - Mechanical abrasion/grinding
  - Cleaning procedures
    - Pickling/passivation procedures
    - Contamination with carbon steel or tool steel
- Weld properties (input to characterize material microstructure and residual stress)
  - Weld type (longitudinal, circumferential, base plate, closure)
  - Welding process (GTAW, GMAW, SAW, etc.)
  - Weld joint design
    - Fitup requirements
    - Weld root design
    - Edge preparation
    - Number of passes
    - Heat input and interpass temperature control
    - In-process mechanical treatments (e.g., applying edge preparation following part of weld, repair procedures, etc.)
    - Degree of sensitization in heat affected zone
  - Surface profile (weld surface grinding, reinforcement)

<u>Environmental Conditions</u>

Environments used in SCC corrosion testing to date may not replicate actual conditions on canister surfaces. Deposited salts are generally sea salts or subsets of those salts (e.g., $MgCl_2$); salt compositions measured to date on canister surfaces, even those close to ocean shorelines, differ from these assemblages. Moreover, salt decomposition reactions, particle-gas conversion reactions, and deliquescent brine degassing are limited in experimental studies because of low

gas-phase flow rates relative to the high ventilation flow rates though canister over packs. Additional field sampling efforts to measure aerosol particle and gas-phase compositions at ISFSI sites will provide critical information to define the canister surface environment. Experimental work and modeling efforts are required to better understand the stability of salt assemblages as canister surface conditions evolve. The ultimate goal of this work is to define the relevant chemical and physical environments on the waste package surface for use in corrosion testing. The parameters of interest include the following:

- Temperature
- Airflow condition
  - Rate
  - Geometry of flow pathway,
- Humidity range
- Contaminant composition
  - Sea salts
  - Inland salt assemblages
  - $MgCl_2$
- Gas phase composition (e.g. HCl, HNO_3, NH_3, and SO_2)
- Contaminant transport, deposition, and removal mechanisms
- Salt surface loading
- Presence of pitting or crevices
- Periodic salt loading and wet-dry cycling
- Duration of corrosion tests—SCC initiation as a function of time in different environments

Tensile Stress

To ensure that residual stresses and sensitization in the heat affected zones around welds are typical of in-service canisters, weld geometries, joint design, and schedules should match those used in industry. Much current experimental work on SCC has been done thin U-bend specimens that fail to capture the stress fields the heat-affected zones of manufactured canisters. Post-weld treatments are not currently in use, but should be evaluated for potential future applications. Additional testing should be designed to closely match actual canisters conditions with the following considerations:

- Residual stress
  - Cold working (rolling)
  - Welding
- Post-weld annealing
  - To remove sensitization
  - To relieve residual stresses
- Stress mitigation
  - Heating
  - Shot peening
  - Laser peening
  - Low plasticity burnishing

Given the large number of parameters and test conditions necessary for crack initiation and growth development, a comprehensive test program would require preparation of a significant

number of samples and experiments. Also, the length of time required for crack initiation and growth under conditions more representative of dry cask storage may be considerable such that future testing should be on the duration of years rather than months.

5. REFERENCES

1. Cragnolino, G.A., 2008. "Corrosion Fundamentals and Characterization Techniques," Chapter 2 of *Techniques for Corrosion Monitoring* by Lietai Yang. Southwest Research Institute, CRC Press, New York.
2. DOE 2012. *Gap Analysis to Support Extended Storage of Used Nuclear Fuel, Rev. 0*, FCRD-USED-2011-000136 Rev. 0, US Department of Energy, Office of Nuclear Energy, Used Fuel Disposition Campaign, Washington DC.
3. EPRI 2005. *Effects of Marine Environments on Stress Corrosion Cracking of Austenitic Stainless Steels*, EPRI, Palo Alto, CA. 1011820
4. EPRI 2011. *Extended Used Fuel and High-level Waste Storage Collaboration Program – Progress Report and Review of Gap Analyses*, EPRI, Palo Alto, CA: 2011. 1022149.
5. EPRI 2012. *Extended Storage Collaboration Program International Subcommittee Report: International Perspectives on Technical Data Gaps Associated With Extended Storage and Transportation of Used Nuclear Fuel.* EPRI, Palo Alto, CA: 2012. 1026481.
6. Mintz et al. 2010. Mintz TS, L Caseres, DS Dunn, and M Bayssie, "Atmospheric Salt Fog Testing to Evaluate Chloride Induced Stress Corrosion Cracking of type 304, 304L, and 316L Stainless Steel", *NACE Corrosion 2010 Conference and Expo*. Paper 10232. NACE, Houston Texas.
7. Mintz et al. 2012. Mintz TS, L Caseres, X He, J Dante, G Oberson, DS Dunn, and T Ahn: "Atmospheric Salt Fog Testing to Evaluate Chloride-Induced Stress Corrosion Cracking of Type 304 Stainless Steel", *Corrosion 2012*. Salt Lake City, Utah.
8. Prosek, T., Iversen, A. and Taxén, C. (2009) Low temperature stress corrosion cracking of stainless steels in the atmosphere in presence of chloride deposits. Corrosion 65(2), 105-117.
9. NRC 2012. *Identification and Prioritization of the Technical Information Needs Affecting Potential Regulation of Extended Storage and Transportation of Spent Nuclear Fuel – Draft for Comment*, ML120580143, US Nuclear Regulatory Commission, June 2012.
10. NWTRB 2010. *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel.* US Nuclear Waste Technical Review Board, accessed on 27 August 2011 at: http://www.nwtrb.gov/reports/eds-final.pdf.
11. Shirai et al. 2011. Shirai K, J Tani, T Arai, M Wataru, H Takeda, and T Saegusa. 2011. "SCC Evaluation Test of a Multi-Purpose Canister", *Proceedings of the 13th International High-Level Radioactive Waste Management Conference (IHLRWMC) April 10-14, 2011, Albuquerque, New Mexico*, pp. 824-831. American Nuclear Society, La Grange Park, Illinois.
12. Tani JI, M Myuzumi, and N Hara. 2009. "Initiation and Propagation of Stress Corrosion Cracking of Stainless Steel Canister for Concrete Cask Storage of Spent Nuclear Fuel", *Corrosion*. Vol. 65 No. 3.
13. Overview of NUREG/CR-7170, "Assessment of Stress Corrosion Cracking Susceptibility for Austenitic Stainless Steels Exposed to Atmospheric Chloride and Non-Chloride Salts, Greg Oberson, Materials Engineer, U.S. Nuclear Regulatory Commission, Office of

Nuclear Regulatory Research Extended Storage Collaboration Program Meeting, Charlotte, NC – December 3-5, 2013

14. *Literature Review of Environmental Conditions and Chloride Induced Degradation Relevant to Stainless Steel Canisters in Dry Cask Storage Systems*. EPRI, Palo Alto, CA: 2013 (DRAFT)
15. *Failure Modes and Effects Analysis (FMEA) of Welded Stainless Steel Canisters for Dry Cask Storage Systems*. EPRI, Palo Alto, CA: 2013. 3002000815.
16. Calvert Cliffs Nuclear Power Plant Independent Spent Fuel Storage Installation Material License No. SNM-2505, Docket No. 72-8 Response to Request for Additional Information, RE: Calvert Cliffs Independent Spent Fuel Storage Installation License Renewal Application (TAC No. L24475), June 15, 2013.
17. Bates, JM, 1986. Single PWR Spent Fuel Assembly Heat Transfer Data for Computer Code Evaluations, PNL-5571, Pacific Northwest Laboratory, Richland, Washington.
18. Irino, M., M. Oohashi, T. Irie, and T. Nishikawa, 1986. Study on Surface Temperatures of Fuel Pins in Spent Fuel Dry Shipping/Storage Casks, IAEA-SM-286/139P. pp/ 585-598.
19. Fry, CJ, E. Livesey, and GT Spiller, 1983. Heat Transfer in a Dry, Horizontal LWR Spent Fuel Assembly, New Orleans, Louisiana. Oak Ridge National Laboratory, Oak Ridge, Tennessee. Packaging and Transportation of Radioactive Materials Symposium (PATRAM83), in Proceedings of Seventh International Symposium.
20. Creer, J.M., R.A. McCann, M.A. McKinnon, J.E. Tanner, E.R. Gilbert, R.L. Goodman, C. Dziadosz, E.V. Moore, D.H. Schoonan, M. Jensen, and C. Mullen. 1986. The CASTOR-V/21 PWR Spent Fuel Storage Cask: Testing and Analysis. EPRI NP-4887, Electric Power Research Institute, Palo Alto, CA.
21. Creer, J.M., T.E. Michener, M.A. McKinnon, J.E. Tanner, E.R. Gilbert, and R.L. Goodman, 1987. The TN-24P PWR Spent Fuel Storage Cask: Testing and Analyses, EPRI-NP-5128/PNL-6054, Electric Power Research Institute, Palo Alto, CA.
22. McKinnon, M.A., J.W. Doman, J.E. Tanner, R.J. Guenther, J.M. Creer, and C.E. King, 1986. BWR Spent Fuel Storage Cask Performance Test; Volume I: Cask Handling Experience and Decay Heat, Heat Transfer, and Shielding Data. PNL-5577, Vol. I, Pacific Northwest Laboratory, Richland, WA. (Note: cask is REA 2023)
23. McKinnon, M.A., L.E. Wiles, N.J. Lombardo, C.M. Heeb, U.P. Jenquin, T.E. Michener, C.L. Wheeler, J.M. Creer, and R.A. McCann, 1986. BWR Spent Fuel Storage Cask Performance Test; Volume II: Pre- and Post-Test Decay Heat, Heat Transfer, and Shielding Analyses. PNL-5577, Vol. II, Pacific Northwest Laboratory, Richland, WA. (Note: cask is REA 2023)
24. McKinnon, M.A., T.E. Michener, M.F. Jensen, and G.R. Goodman, 1989. The 24P PWR Spent Fuel Dry Storage Cask Loaded with Consolidated Fuel. EPRI-NP-6191/PNL-6631/UC-85, Electric Power Research Institute, Palo Alto, CA.
25. McKinnon, M.A., R.E. Dodge, R.C. Schmitt, L.E. Eslinger, and G. Dineen, 1992. Performance Testing and Analyses of the VSC-17 Ventilated Concrete Cask. EPRI-TR-100305/PNL-7839, Electric Power Research Institute, Palo Alto, CA.
26. Rector, D.R., R.A. McCann, U.P. Jenquin, C.M. Heeb, J.M. Creer, and C.L. Wheeler, 1986. CASTOR-1C Spent Fuel Storage Cask Decay Heat, Heat Transfer, and Shielding Analyses. PNL-5974, Pacific Northwest Laboratory, Richland, WA.

27. Lombardo, N.J., T.E. Michener, C.L. Wheeler, and D.R. Rector, 1986. COBRA-SFS Predictions of Single-Assembly Spent Fuel Heat Transfer Data. PNL-5781, Pacific Northwest National Laboratory, Richland, WA.
28. Cuta, J.M., D.R. Rector, and J.M. Creer, 1984. Comparisons of COBRA-SFS Calculations with Data from Simulated Sections of Unconsolidated and Consolidated BWR Spent Fuel. EPRI-NP-3764, Electric Power Research Institute, Palo Alto, CA.
29. Lombardo, N.J., J.M. Cuta, T.E. Michener, D.R. Rector, and C.L. Wheeler, 1986. COBRA-SFS: A Thermal-Hydraulic Analysis Computer Code: Volume III: Validation Assessments. PNL-6049, Vol. 3, Pacific Northwest National Laboratory, Richland, WA.
30. Rector, D.R., J.M. Cuta, and N.J. Lombardo, 1986. COBRA-SFS Thermal-Hydraulic Analyses of the CASTOR-1C and REA 2023 BWR Storage Casks Containing Consolidated Spent Fuel. PNL-5802, Pacific Northwest National Laboratory, Richland, WA.
31. Rector, D.R., T.E. Michener, and J.M. Cuta, 1998. Verification and Validation of COBRA-SFS Transient Analysis Capability. PNNL-11883, Pacific Northwest National Laboratory, Richland, WA.
32. Rector, D.R., T.E. Michener, 1989. COBRA-SFS Modifications and Cask Model Optimization. PNL-6706, Pacific Northwest Laboratory, Richland, WA.
33. Wheeler, C.L., R.A. McCann, N.J. Lombardo, D.R. Rector, and T.E. Michener, 1986. HYDRA and COBRA-SFS Temperature Calculations for CASTOR-1C, REA-2023, CASTOR-V/21, and TN-24P Casks. In Proceedings, Third International Spent Fuel Storage Technology Symposium and Workshop, Vol. 1, S77-S98, CONF-960417, National Technical Information Service, Springfield, Virginia.