Agenda

Public Meeting with Nuclear Energy Institute on Material Degradation

January 24, 2014
8:00 AM – 5:00 PM

8:00 – 8:10 AM	Welcome, Introductions, and Meeting Objectives (NRC, NEI, All)
8:10 – 8:25 AM	Update of RIRP Schedule/Tasks (NEI)
8:25 – 8:40 AM	CISCC Aging Management Advisory Panel (Constellation)
8:40 – 9:25 AM	Literature Review and Failure Modes and Effects Analysis (Dominion Engineering, Inc.)
9:25 – 9:40 AM	**Break**
9:40 – 11:00 AM	NRC Presentations on Testing Programs (NRC) • Overview of NUREG/CR-7170 • Dry Cask Storage System (DCSS) Canister Weld Residual Stress Finite Element Analysis • Review of Methods for DCSS Monitoring • Assessment of Methods for Detection of SCC in DCSS Canisters
11:00 – 11:30 AM	Update on In-Service Inspections (EPRI) • Schedule of Activities • Inspection Methods and Procedures
11:30 – 11:45 AM	Discuss Next Milestones and Anticipated Dates (All)
11:45 AM – 12:00 PM	Public Comments and Wrap Up
12:00 – 1:00 PM	**Lunch Break**
1:00 – 1:30 PM	NRC Presentation on Storage Renewal Team (NRC)
1:30 – 2:00 PM	Industry Presentation of License Renewal Guidance Document (NEI)
2:00 – 2:45 PM	Open Discussion (All)
2:45 – 3:00 PM	Public Comments and Wrap Up
3:00 – 3:15 PM	**Break**
3:15 – 4:00 PM	NRC Presentation on High Burnup Fuel Strategy (NRC)
4:00 – 4:30 PM	Open Discussion (All)
4:30 – 5:00 PM	Public Comments, Final Discussion, Wrap Up

AFTERNOON #1

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NRC Storage Renewal Team

Aladar A. Csontos, Ph.D

Chief, Structural Mechanics & Materials Branch
Division of Spent Fuel Storage and Transportation
Office of Nuclear Material Safety and Safeguards

CISCC RIRP & HBUF Public Meeting
January 24, 2014

Background

ISFSI License and Storage Cask Design Renewal

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- Renewal for a period not to exceed 40 years
- Time-limited aging analyses (TLAAs) that demonstrate that SSCs important to safety will continue to perform their intended function for the requested period of extended operation
- Description of the Aging Management Program (AMP) for issues associated with aging that could adversely affect SSCs important to safety
- Design bases information as documented in the most recently updated FSAR

Current Challenges

Current and Future License Renewals & Guidance

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- 3 ISFSI license and storage CoC renewal applications currently under staff review
- Currently, multiple year reviews & RAI cycles -one been @ NRC for 4 years.
- Staff review experience of renewal applications indicates that NUREG-1927 (SRP for Renewal of ISFSI licenses & CoCs) may need clarification in several areas, e.g. AMPs, TLAA's, etc.
- ~12 ISFSI license and storage CoC renewal applications expected within next 6 years

Current Challenges

Materials Degradation Modes

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- Storage & reactor operating experience indicate potential unanticipated degradation of SSCs:
  - IN 2013-07: Premature degradation of cask structures & components from environmental moisture
  - IN 2012-20: Cl-induced Stress Corrosion Cracking
  - Site-Specific License Renewal for the TMI Unit 2 ISFSI Public Meeting Presentation (ML13353A611)
  - NRC TIN Report (ML120580143)
- Unanticipated known vs. unknown degradation modes
- Difficult to define and assess all operable degradation modes for all potential chemistries for all locations

Future Approach

Storage Renewal Strategy Team

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- Established renewal strategy team from across NRC:
  - NMSS/SFST & SFAS
  - RES/DE
  - NRR/DLR
- Mission: assess current storage renewal regulatory framework and investigate guidance update needs
  - Interim Staff Guidance
  - NUREG-1927 Update
- Develop learning, proactive, and reactive regulatory approach to address current and future renewals
- Focused on operational experience loop providing data to support AMPs and TLAAs rather than RAI loop for extensive technical bases development

Future Approach

Storage Renewal Strategy Team

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- Focused on achievable operational methodologies:
  - Condition based monitoring and/or intelligent in-service inspections based on technically defensible criteria
  - Living AMPs feeding operational data to analyses
  - Analyses feeding prevention, mitigation, or repair decisions
- CISCC RIRP screening criteria and EPRI FMEA project results may provide defensible inspection/monitoring criteria
- Long term research incorporation into learning AMPs
- In turn, this may provide a basis for defining the appropriate lead canister(s)

Future Approach

Storage Renewal Strategy Team

- Phase I:
  - Team/Charter Development & Kickoff Meetings
  - October – December 2013
- Phase II:
  - Strategy Development
  - Dialogue, Review, and Consideration of Stakeholder Input
  - January – June 2014
- Phase III:
  - Publish Draft Guidance for Public Comment
  - Publish Final Guidance
  - 2014/2015

Industry Guidance for Operations-Based Aging Management for Dry Cask Storage

Nuclear Energy Institute

Presentation to
NRC Spent Fuel Storage and Transportation
Staff and Management

January 24, 2014

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STORIED HISTORY BRIGHT FUTURE

Background

- Three specific ISFSI licenses have been renewed
- NRC is currently reviewing renewal applications for two specific licenses and one CoC (used by general licensees)
- 12 applications expected over next 6 years
- Staff review guidance for renewal applications in NUREG-1927 issued in 2011 needs augmentation:
  - to reflect the current state of knowledge
  - Provide forward-looking , confirmatory approach
- Industry proposes to develop additional guidance and seek NRC endorsement

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STORIED HISTORY BRIGHT FUTURE

Vision of Industry Guidance

- Safety-focused
- Operations-based
- Built upon existing programs (OE, CAP)
- Risk-informed qualitatively via FMEA
- Forward-looking
- Proactive
- Responsive to condition-based monitoring

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Status of NEI Effort

- Issue team established
  - NEI project manager
  - Four CoC holders
  - General and specific licensees
  - Shutdown site licensees
  - EPRI
  - Independent advisor
- Project plan issued
- Guidance outline drafted

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Guidance Scope

- Augments NUREG-1927 Section 3.0 "Aging Management Review"
- Recognizes NUREG-1927 Section 1.0 and 2.0 "General Information Review" and "Scoping Evaluation" are sufficient
- Addresses practical considerations from CoC holders pertaining to lead canister inspections (LCI)
- Addresses 40-year renewal periods
- Focuses on storage only; understands linkage to transportation

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Guidance Foundation

- Current Part 72 regulations
- Current ISFSI/CoC licensing basis (CLB)
  - Regulations, orders
  - Specific license, as amended
  - Initial CoC and all approved CoC amendments
  - ISFSI or cask UFSAR, as modified by 72.48 and to reflect amendments
  - Specific revisions of guidance and standards committed to in CLB
    - RGs, NUREGs, ISGs, ASME, ACI, ANSI, ASTM, etc.

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Guidance Goals

- Assure aging management activities are safety-function focused and prioritized based on risk and timing of degradation mechanisms
- Provide for appropriate use of future operational experience, research, LCIs, and condition monitoring
- Provide a predictable regulatory environment
  - Avoid piecemeal submittals and renewals
  - Minimize multiple rounds of RAIs
  - Balance specificity and flexibility
  - Achieve alignment with NRC through endorsement

Guidance Approach

- Addresses known and potential age-related degradation mechanisms by applying established practices
- Uses operating experience, research, monitoring, and lead canister inspection results in a feedback loop to adjust aging management activities as appropriate
  - Operating experience and corrective action programs
  - Evaluate effectiveness of corrective actions
- Establishes "toll gate" milestones during renewed operating period to systematically evaluate the body of relevant information

Guidance Approach

- At each "toll gate", evaluate
  - Susceptibility criteria (e.g., canister CISCC)
  - Plant-specific, other plants, R&D (e.g., demo), LCI
  - Impact, if any, on storage safety functions
- Actions developed in accordance with existing licensee QA corrective action program
  - Based on risk-informed assessment
- Results of monitoring, inspections, and assessments will be maintained as plant records

Lead Canister Inspections

- The guidance will address conduct of lead canister inspections (revision to NUREG-1927, Appendix E)
- Canister inspections will be included in aging management activities in the renewed CoC
- Canister inspections (and other monitoring and inspections) may occur at a location/environment chosen to bound other sites

Monitoring and Inspections

- Techniques, acceptance criteria, and remediation actions need to be tied to maintaining a storage safety function and reasonable to accomplish
- Monitoring and inspection protocols for aging management need to be specific and appropriate for the component or variable being monitored
- Use existing industry codes and standards where possible

Use Sect XI for acceptance criteria if possible.

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Preliminary Guidance Outline

- Table of Contents
- Definitions
- 1.0 PURPOSE AND SCOPE
- 2.0 APPROACH
- 3.0 AGING MANAGEMENT REVIEWS
- 4.0 REFERENCES

- 3.1 Current Licensing Basis
- 3.2 TLAAs and AMPs
- 3.3 Operations-Based Aging Management
- 3.4 Key Technical Issues
- 3.5 Canister Inspections
- 3.6 Monitoring and Inspection
- 3.7 Toll Gates
- 3.8 Reporting
- 3.9 Records

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Guidance Development Milestone Schedule

TASK	DATE
Submit Guidance Outline to NRC	2/10/14
Presentation at Regulatory Information Conference	3/12/14
Draft NEI Guidance Report	4/28/14
Presentation of Guidance Status at NEI Used Fuel Management Conference	5/8/14
Project Team Review and Comment	5/30/14
Project Team Comment Resolution and Report Revision	6/23/14
DSTF Steering Group Review and Comment	7/31/14
DSTF Steering Group Comment Resolution and Report Revision	8/29/14
Final NEI Editorial Proof	9/12/14
Submit to NRC for Endorsement	9/19/14
NRC Endorsement	11/30/14

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Draft Certification/Licensing Approaches for High Burnup Spent Fuel

Huda Akhavannik
Project Manager
Division of Spent Fuel Storage and Transportation
Office of Nuclear Material Safety and Safeguards

January 24, 2014

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Overview

- Purpose
- Challenges with Meeting Regulatory Requirements
- Draft Storage Licensing/Certification Approach
- Draft Transportation Certification Approach
- Research and Other Activities

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Purpose

- Develop certification/licensing approaches for high burnup spent fuel storage and transportation applications while on-going research and other activities continue

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High Burnup Fuel – Hydride Reorientation

- At the high drying temperatures, the normally circumferential hydrides in the cladding will go into solution. As the fuel cools down, this soluble hydrogen may precipitate to form radial hydrides.
- When the temperature of the fuel drops below the ductile to brittle transition temperature (DBTT) the radial hydrides provide an additional embrittlement mechanism which may make it difficult to meet Part 71 and 72 with respect to the structural integrity of the fuel.

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Geometric Form – Storage

- Confinement barriers and systems
  - Maintain cladding integrity 10 CFR 72.122(h)
- Retrievability
  - Be able to readily retrieve fuel per 10 CFR 72.122(l)
- Guidance
  - ISG-11, "Cladding Considerations for the Transportation and Storage of Spent Fuel"
  - ISG-2, "Fuel Retrievability"

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Geometric Form – Transport

- Maintain criticality safety, most reactive credible configuration – 10 CFR 71.55(b),(d), and (e)
  - Package contents cannot be substantially altered during NCT - 10 CFR 71.55(d)(2).

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Draft Licensing and Certification Approaches

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Theme for approaches

- We believe that research activities will **confirm** the position that HBF which has undergone the hydride reorientation will **be able to meet** the regulatory requirements necessary for licensing

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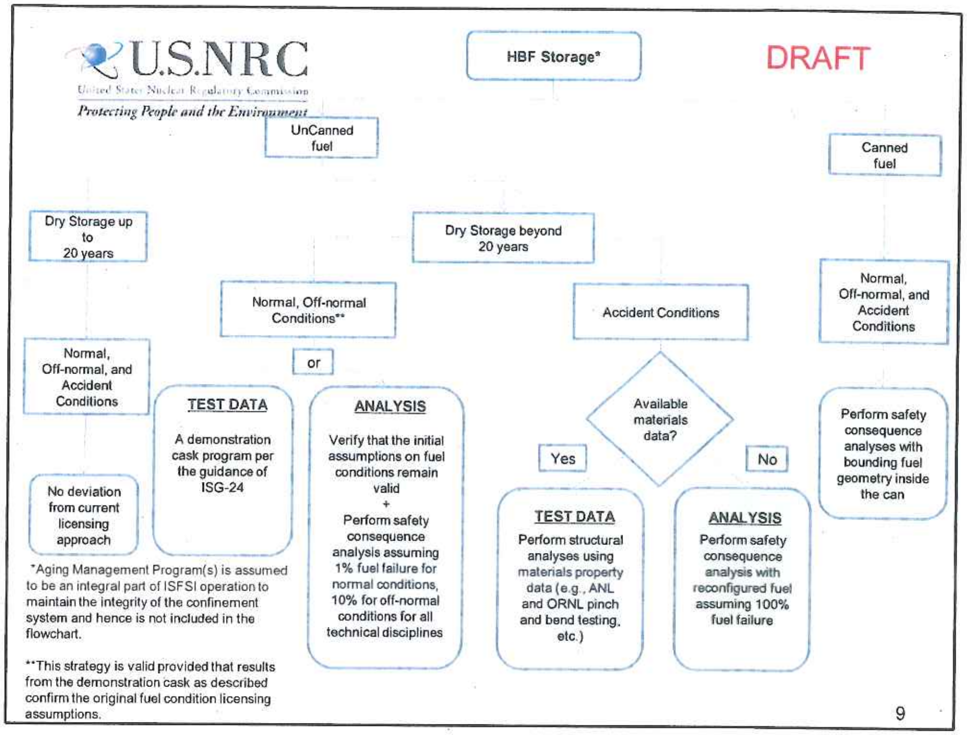
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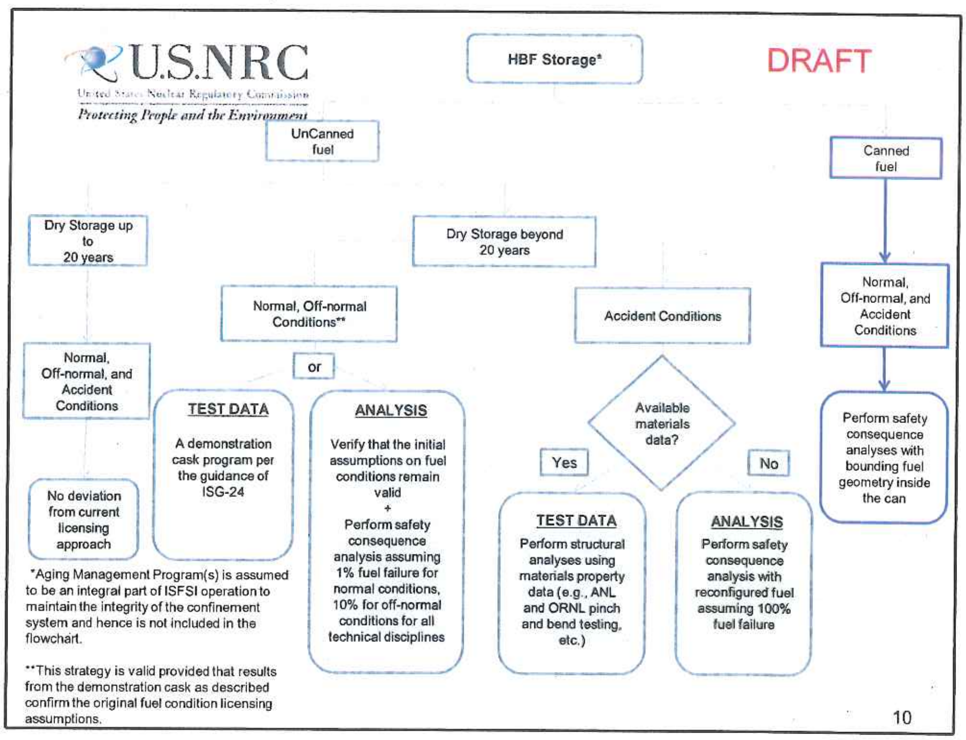
HBF Storage*
DRAFT
UnCanned fuel
Canned fuel
Dry Storage up to 20 years
Dry Storage beyond 20 years
Normal, Off-normal Conditions**
Accident Conditions
Normal, Off-normal, and Accident Conditions
Normal, Off-normal, and Accident Conditions
or
TEST DATA
A demonstration cask program per the guidance of ISG-24
ANALYSIS
Verify that the initial assumptions on fuel conditions remain valid
+
Perform safety consequence analysis assuming 1% fuel failure for normal conditions, 10% for off-normal conditions for all technical disciplines
Available materials data?
Yes
No
TEST DATA
Perform structural analyses using materials property data (e.g., ANL and ORNL pinch and bend testing, etc.)
ANALYSIS
Perform safety consequence analysis with reconfigured fuel assuming 100% fuel failure
Perform safety consequence analyses with bounding fuel geometry inside the can
No deviation from current licensing approach
*Aging Management Program(s) is assumed to be an integral part of ISFSI operation to maintain the integrity of the confinement system and hence is not included in the flowchart.
**This strategy is valid provided that results from the demonstration cask as described confirm the original fuel condition licensing assumptions.
9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Canned Fuel

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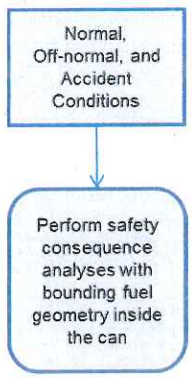

Canned fuel will require safety consequence analyses to be completed with bounding fuel geometry inside the can

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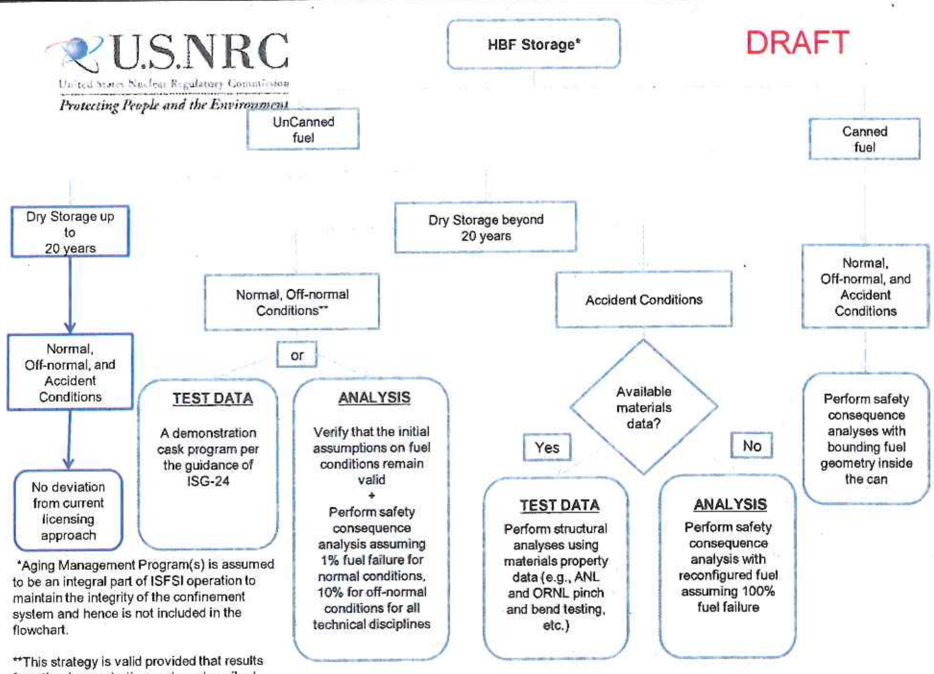

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UnCanned Fuel

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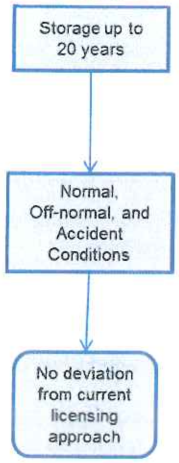

Fuel that is not canned and will be in dry storage for a period below 20 years will follow the current licensing approach (currently fuel is licensed up to 20 years)

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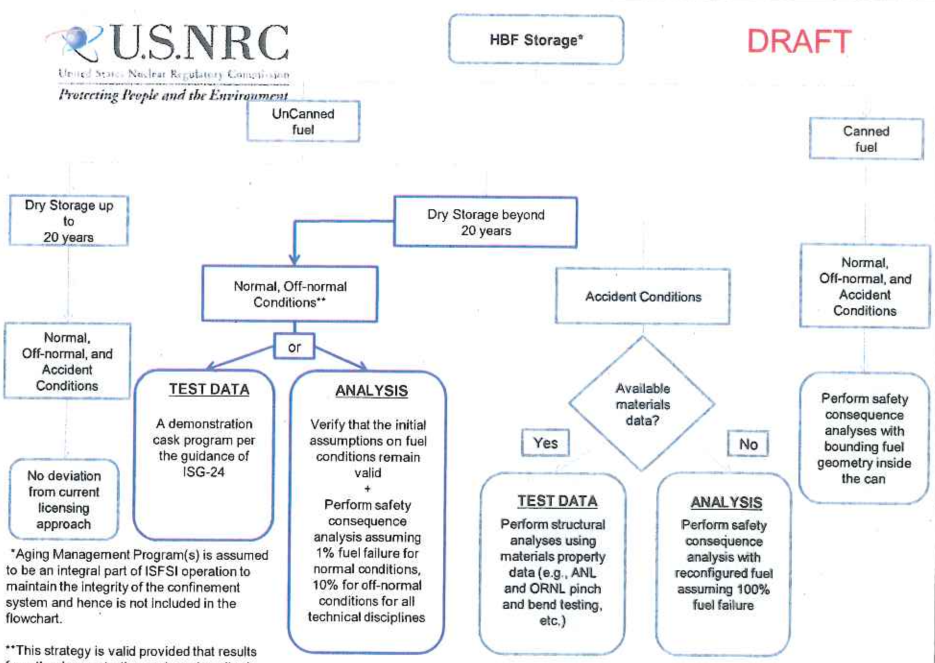

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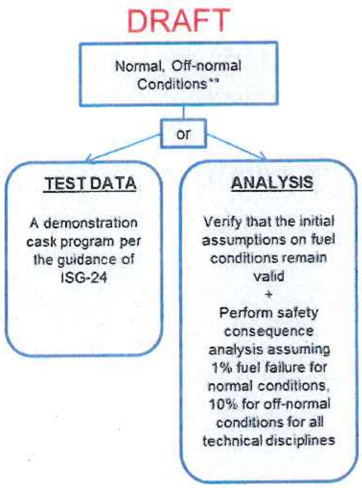
UnCanned Fuel – beyond 20 years, Normal and Off-normal Conditions



- Test Data
  - Relies on ISG-24 guidance to use a cask demonstration as confirmation of integrity for continued dry storage of HBF beyond 20 years
  - The ** highlights that this strategy is valid provided that results from the demonstration cask as described confirm the original fuel condition licensing assumptions
- Analysis
  - Confirmation that initial assumptions on the fuel condition are still valid
  - Consequence analyses assuming 1% and 10% fuel failure
    - Values taken from confinement analysis
    - Previous studies completed regarding fuel failures of all fuel types consider 1% to be a bounding value

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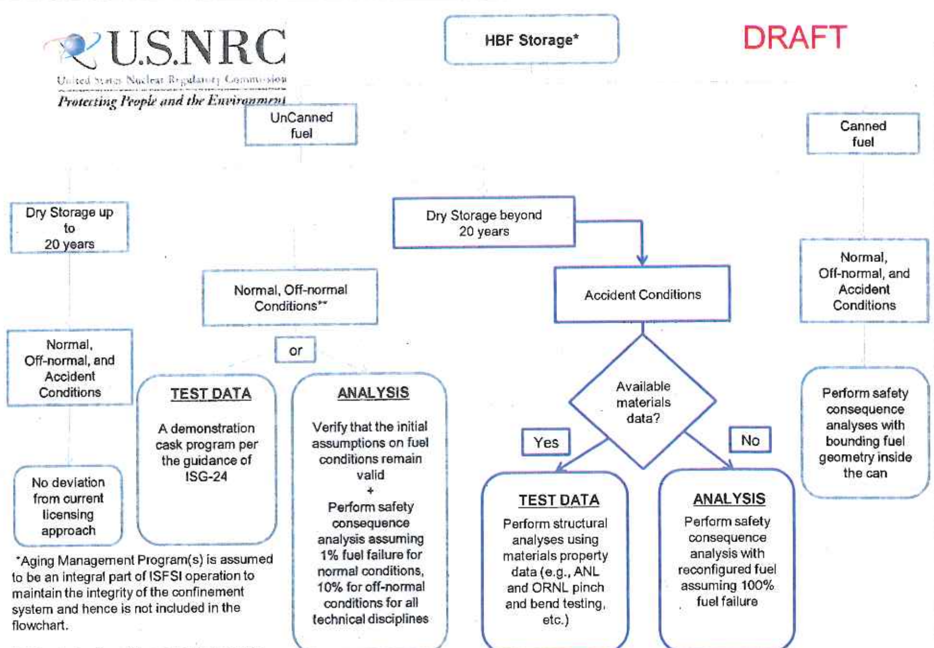

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UnCanned Fuel – beyond 20 years, Accident Conditions

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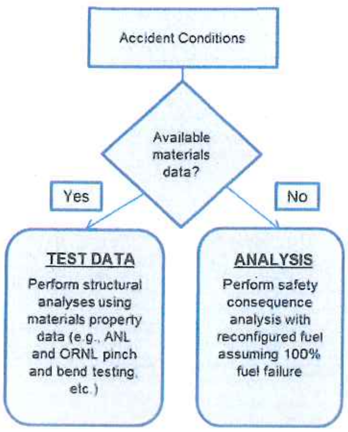

- Test Data
  - Relies on available and applicable cladding materials data
  - Possible data that can be used are results from ANL and ORNL pinch and bend tests, or applicant provides own data
- Analysis
  - Perform consequence analysis assuming 100% fuel failure

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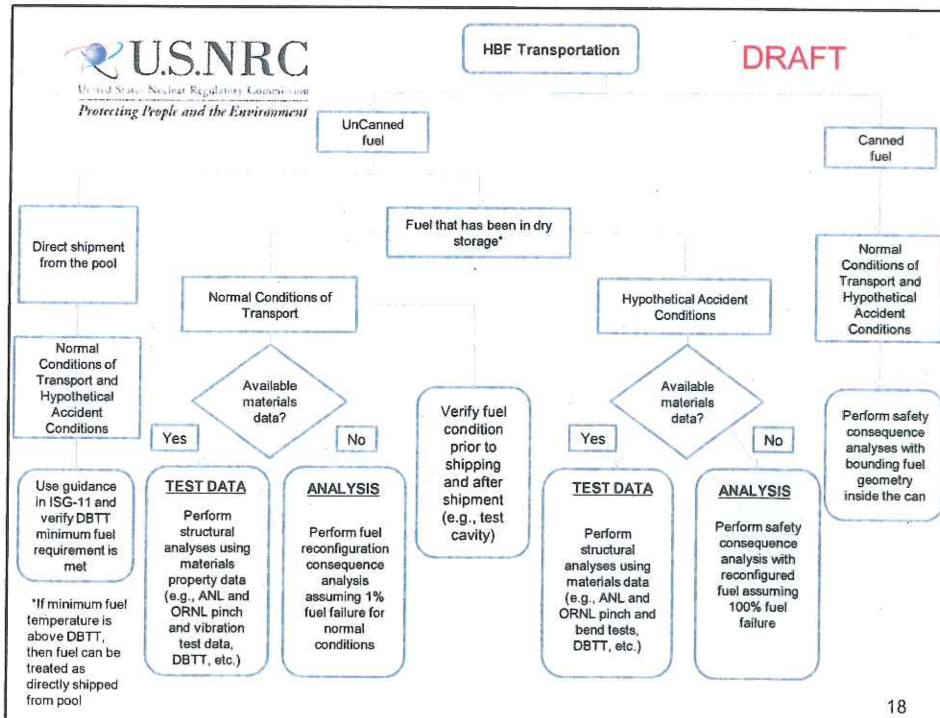

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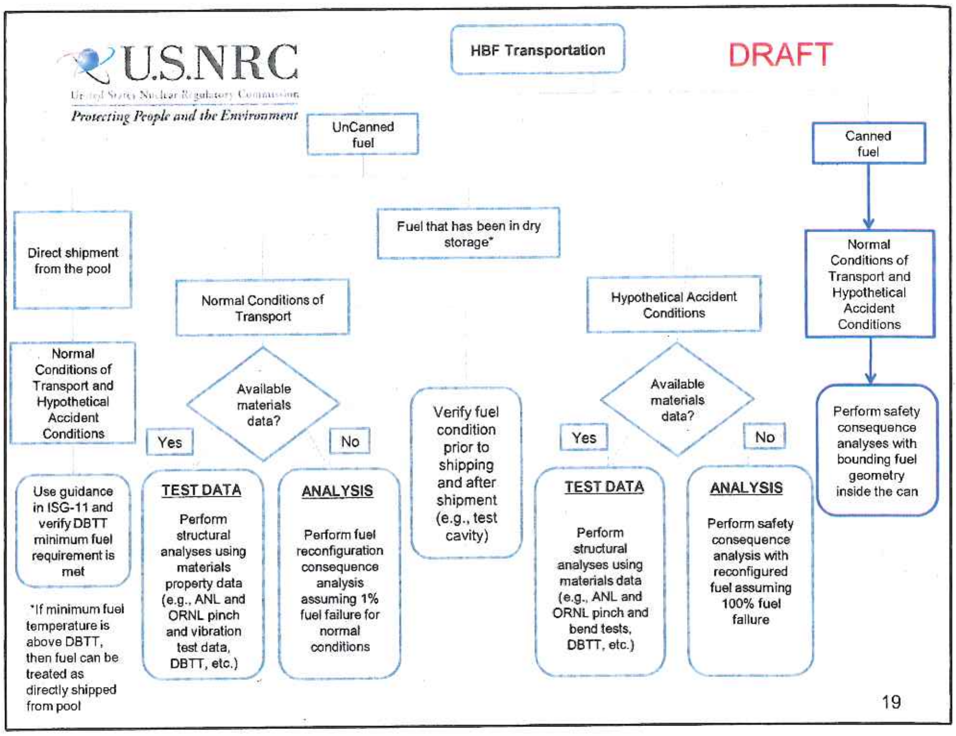

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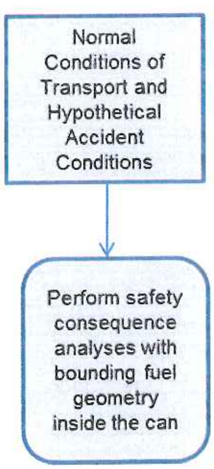
Canned Fuel



Similar to storage, if fuel is canned, safety consequence analyses are performed with bounding fuel geometry inside the can

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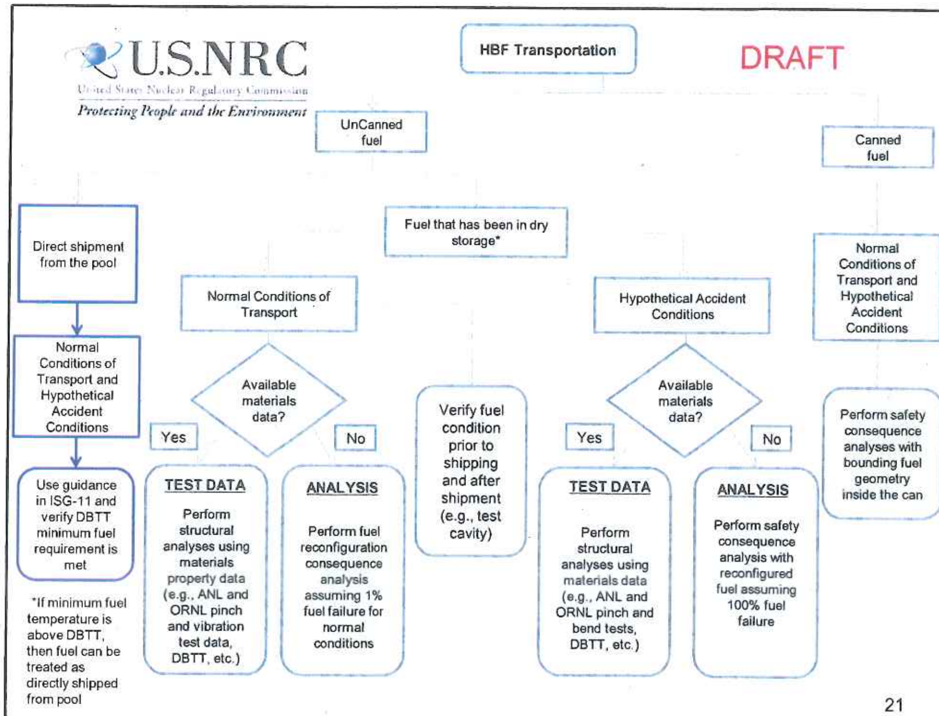

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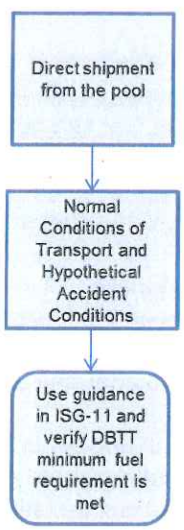
UnCanned Fuel – Directly Shipped from pool



Fuel shipped from the pool must confirm that the minimum fuel DBTT is met and can use guidance in ISG-11

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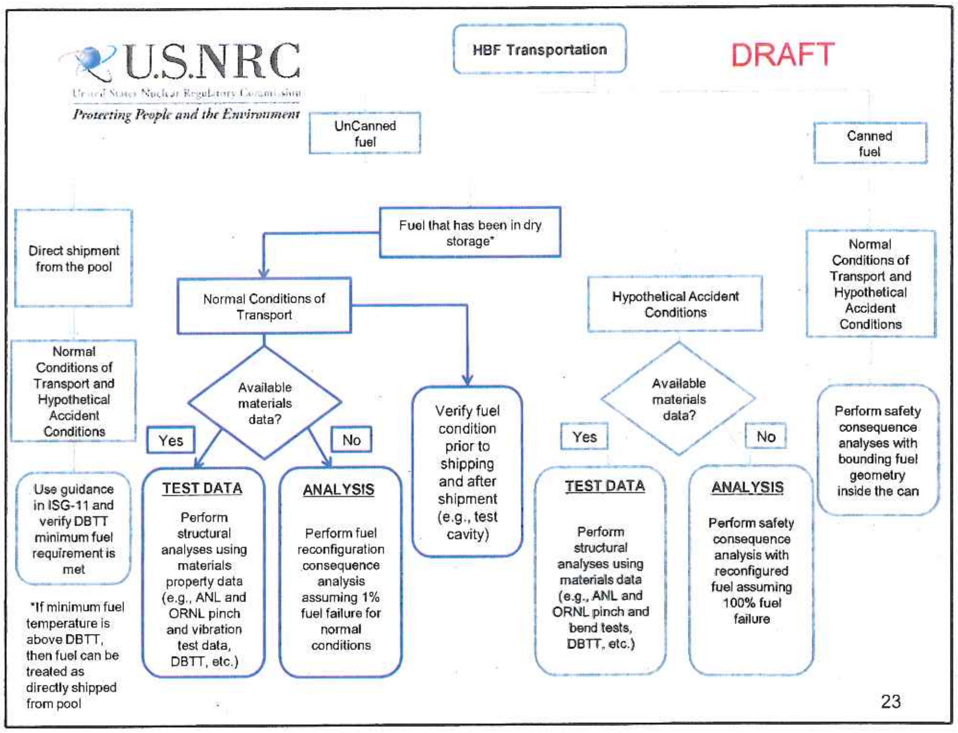

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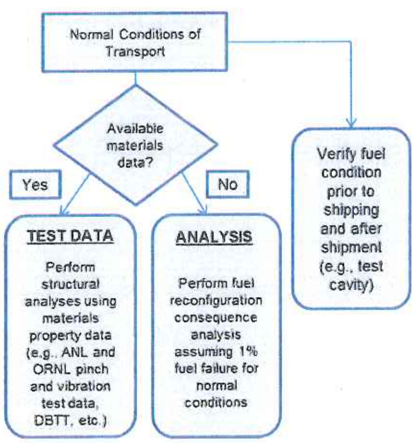
UnCanned Fuel – From Storage – Normal Conditions of Transport



- Test Data
  - Structural analysis relies on available cladding materials data
  - Possible data that can be used are results from ANL and ORNL pinch and vibration tests, or applicant provides own data
- Analysis
  - Confirmation that initial assumptions on the fuel condition are still valid
  - Consequence analyses assuming 1% fuel failure
- Fuel condition must be confirmed before and after shipment to ensure licensing assumptions are still valid

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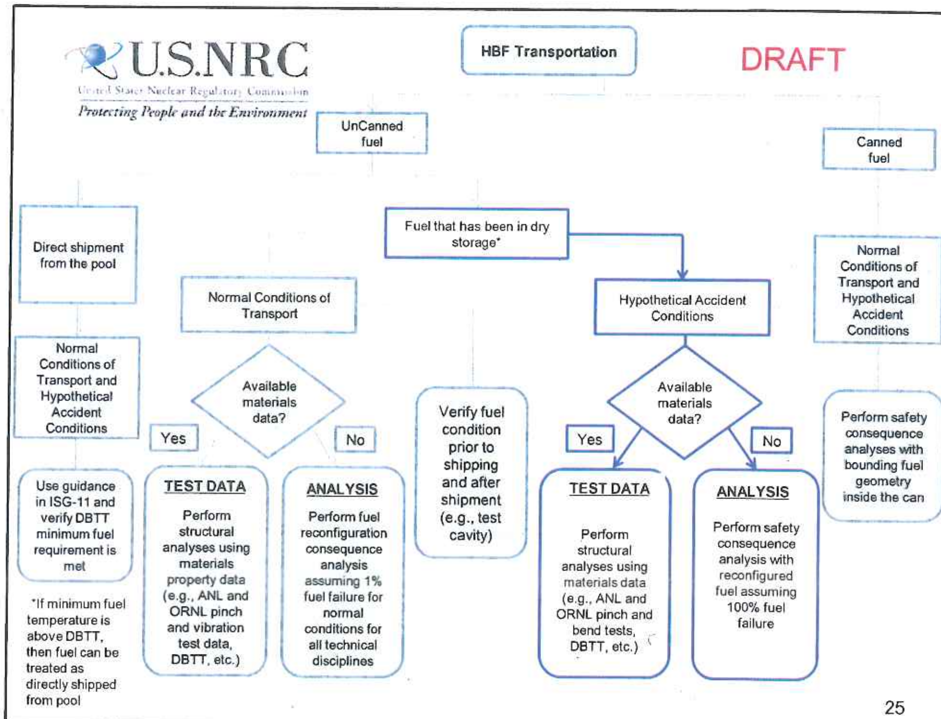

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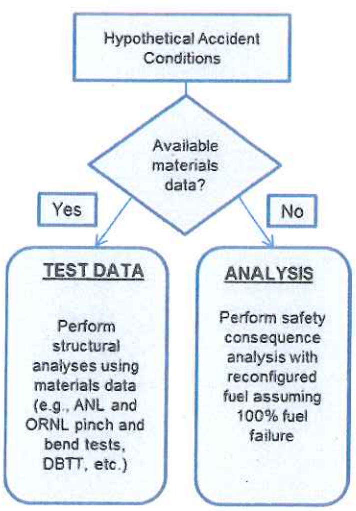
UnCanned Fuel – From Storage – Hypothetical Accident Conditions



- Test Data
  - Relies on available cladding materials data
  - Possible data that can be used are results from ANL and ORNL pinch and bend tests, or applicant provides own data
  - If fuel can reasonably be expected to reconfigure, perform safety consequence analysis
- Analysis
  - Consequence analyses assuming 100% fuel failure

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Research and Other Activities on High Burnup Fuel

- Argonne National Laboratory has performed ring tests on HBF to develop stress-strain curves most appropriate for the pinch mode failure.
  - Cask tip over and HAC side drops
- Oak Ridge National Laboratory is performing vibration tests on HBF to determine the cladding endurance limit. Additionally, Oak Ridge National Laboratory has performed consequence analyses assuming different percentages of failed fuel.
- A DOE sponsored cask demonstration project will provide data on the normal conditions of storage for HBF.
- Staff believes that these research activities will validate the position that HBF which has undergone the hydride reorientation will be able to meet the regulatory requirements necessary for licensing

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Contact Information

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- 301-287-9241 (Office No.)

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Industry CISCC Aging Management Program Overview

John Massari
Constellation Energy

NRC Public Meeting with Nuclear Energy Institute on Material Degradation
January 24, 2014

Background
Potential Issue Identified; Industry and NRC Engaged

- Over 1500 welded stainless steel (SS) dry storage canisters loaded with spent fuel in the U.S.
- Canisters provide the primary confinement barrier to prevent release of radionuclides into the environment
- Operating experience of ODSCC for stainless steel piping, particularly sheltered piping at marine locations (near the ocean)
- Laboratory testing has identified the possibility for stress corrosion cracking (SCC) of stainless steels with deposited chlorides and sufficient relative humidity
- Utilities, Cask Vendors, and EPRI volunteered to perform in-situ inspections of actual canisters
  - Data collection and data analysis is on-going with DOE support

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Background
Welded SS Canister Types

- Horizontal canisters – NUHOMS family
- Vertical canisters – HI-STORM family, UMS, MPC, MAGNASTOR, FuelSolutions

Horizontal Storage Overpacks (NUHOMS Pictured)
[ML113120566]

Vertical Storage Overpacks (HI-STORM Pictured)
[ML113120566]

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Project Overview
Approach

- Developed to address RIRP N-10-01 and the potential issues discussed in NRC IN 2012-20
- Project is designed to identify any additional potential degradation mechanisms, prioritize industry activities, determine the timeframe for degradation, and develop susceptibility assessment criteria for the canisters during an extended storage period
- Susceptibility criteria will allow ISFSIs to assess themselves for the potential for material degradation during an extended storage period
- Project will culminate with development of Aging Management Plan Guidelines to support license renewal commitments

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Project Overview
Advisory Panel – Reviews Key Deliverables

- Arizona Public Service
- Constellation
- Exelon
- Nextera/Florida Power& Light
- Pacific Gas & Electric (PG&E)
- Public Service Electric and Gas Company (PSE&G)
- Tennessee Valley Authority
- Three Yankees

- Areva-Transnuclear
- Holtec
- NAC

- Dominion Engineering Inc. (contracted authors)
- Nuclear Energy Institute
- Structural Integrity Associates
- Transware

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Project Overview
Recently Completed / Ongoing Work

- Failure Modes and Effects Analysis (FMEA) Report of Welded Dry Storage Canisters
  - Reviewed by Advisory Panel and HLW TAC
  - Publicly available product ID = 3002000815
- Literature Review of CISCC (Mid 2014)
  - Drafts submitted to Advisory Panel for review
  - Provided to HLW TAC
- Flaw Growth and Flaw Tolerance Assessment (Late 2014)
  - Based on results of the literature review and FMEA
  - Considers establishment of a susceptible environment, modeling of through-wall crack growth, and establishes critical flaw sizes
  - Includes models that affect initiation and growth: deposition, residual stress, deliquescence

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Project Overview
Future Work and Deliverables

- Industry Susceptibility Assessment Criteria (Mid 2015)
  - Based on results of prior work (e.g., FMEA, Flaw Growth and Flaw Tolerance)
  - Develop a set of criteria to determine susceptibility of stored canisters to materials aging degradation
- SS Canister Confinement Integrity Assessment (Late 2015)
  - Further development of models from Flaw Growth and Tolerance Assessment to probabilistic framework
- Aging Management Plan Guidance Document (Early 2016)
  - Recommendations on inspection locations, inspection intervals, inspection and monitoring technologies, and flaw evaluation and acceptance criteria
  - Potential mitigation techniques
  - Will include learning aspects

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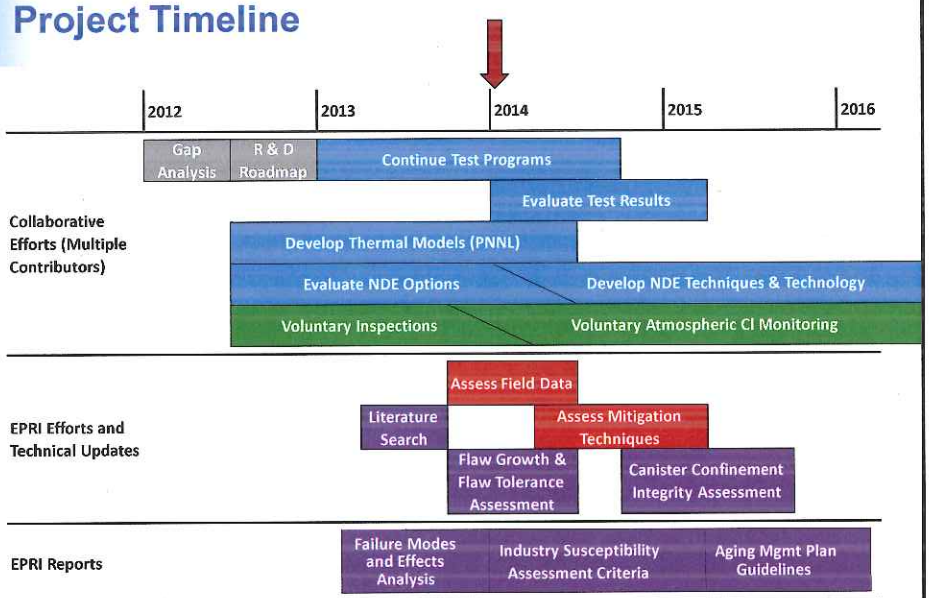
Project Timeline



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Eizinger Comments: what about 2 transports. (one interim; one Final)

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EPRI Literature Review and Failure Modes and Effects Analysis (FMEA) for Welded Stainless Steel Canisters in Dry Cask Storage Systems

Kevin Fuhr
John Broussard
Glenn White
Jeff Gorman
Dominion Engineering, Inc.
Shannon Chu
EPRI Nuclear Power Sector – High Level Waste Group

NRC Public Meeting with Nuclear Energy Institute on Material Degradation
January 24, 2013

Agenda

- Literature review
  - Major findings and summary
- FMEA
  - Methods
  - Results
  - Implications
- Project Continuation

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Literature Review

- Approach
- Operating experience
- Surface conditions
- CISCC initiation and growth
- Other mechanisms
- Testing priorities

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Literature Review
Approach

- Building on previous EPRI work, perform a comprehensive literature review of past and current work relevant to chloride-induced stress corrosion cracking (initiation and propagation) in 304 and 316 SS
- Review literature on other corrosion mechanisms relevant to conditions at canister surface
  - Initial stages included review of ASM Materials Handbook chapters on atmospheric corrosion and corrosion of stainless steel to identify relevant corrosion mechanisms
- Seek to identify available information to better define the actual environmental conditions of DCSS installations in the U.S.
- Identify any knowledge gaps in available test data and characterization of canister environments

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Literature Review
Operating Experience

- CISCC on the OD of uninsulated piping and tanks at nuclear plants has been observed near ambient temperatures
  - San Onofre, Turkey Point, St. Lucie, Koeberg (S. Africa), Ohi (Japan), etc.
    - All these plants essentially on the ocean and near breaking waves
    - Despite differences in conditions, OE supports the possibility of CISCC occurrence for canisters
- CISCC on the OD of insulated piping in containment (under pipe clamps) considered less relevant
  - Insulation would trap moisture and could add to concentrating effects

Literature Review
Surface Conditions – Chloride Aerosols

- Chloride aerosol concentration is measured by dozens of EPA sites across the U.S.
- Empirical models predict that the aerosol concentration decays rapidly over the first km from the shoreline[1]
  - Source term is controlled by breaking waves and whitecaps
  - Larger particulates dominate deposition
- Potential non-marine sources of chloride investigated
  - Cooling tower drift, road salt, etc.
  - Much lower deposition rates (likely factor of 10 to 100 lower) than locations in marine environments

1. G. R. Meira, "Modeling Sea-Salt Transport and Deposition in Marine Atmosphere Zone – A Tool for Corrosion Studies," *Corrosion Science*, Vol. 50, No. 9, p. 2724–2731, 2008.

Literature Review
Surface Conditions – Deposit Behavior

- Deposition may be dominated by gravitational settling (i.e. horizontal surfaces will have much higher deposition rates than vertical)
- Deliquescence of sea salt appears to occur at a similar RH to that for $MgCl_2$; CISCC sometimes initiates slightly below the typical DRH, i.e. in the range of 25-35%
  - Cyclical deliquescence and efflorescence exposes canisters to highest brine concentrations twice per cycle
- Deposits will likely be mixtures of organic and inorganic materials
  - High volume fraction dust could sequester brine from surface

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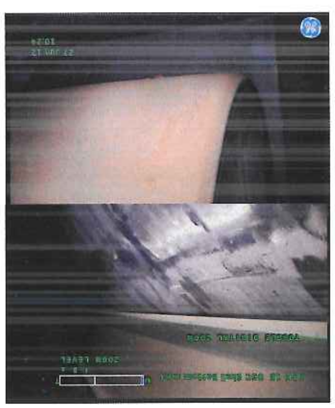
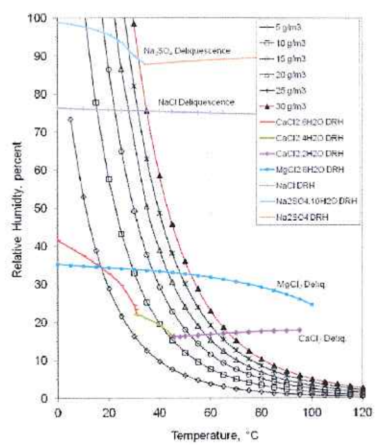
Literature Review
Surface Conditions – Deposit Behavior



Visible Deposits on Top; Metallic Underside
[ML13022A316]



Deliquescence vs. RH and AH
[ML12275A352]

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Literature Review
SCC of Stainless Steel – Initiation

- Combination of aqueous conditions (e.g. deliquescence), chloride concentration, and tensile stress needed for CISCC
- Some cracking has been observed at 0.1 g/m^2 salt[1] in heavily cold worked specimens; few experiments below this value
- Initiation observed only at higher surface loadings in lower cold work specimens
- Laboratory testing to date has generally been short duration (i.e., less than 2 years)
- At ambient temperatures, TGSCC typically occurs. IGSCC can occur for sensitized material

1. G. Oberson, D. Dunn, T. Mintz, et al., "US NRC-Sponsored Research on Stress Corrosion Cracking Susceptibility of Dry Storage Canister Materials in Marine Environments," *WM2013 Conference*, 2013.

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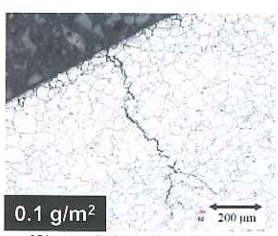
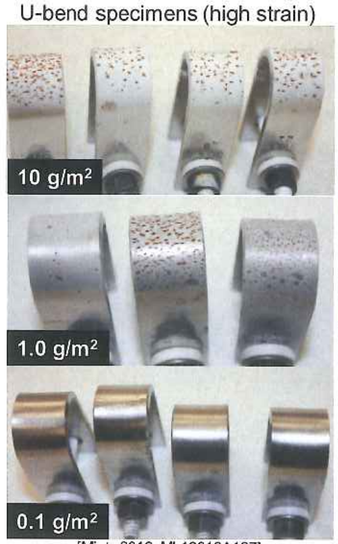
Literature Review
SCC of Stainless Steel – Initiation Testing Samples

T= 45°C; AH= 15 ↔ 30 g/m^3
U-bend specimen (high strain)
Sensitized material



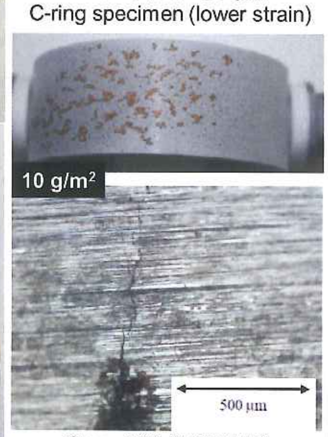
[Oberson 2013, ML13241A391]

T= 35 or 45°C; AH= 15 ↔ 30 g/m^3
U-bend specimens (high strain)



[Mintz 2013, ML13016A127]

T= 52°C; AH= 30 g/m^3
C-ring specimen (lower strain)



[Oberson 2013, ML13051A152]

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Literature Review
SCC of Stainless Steel – Growth

- Crack growth rate (CGR) dependence on stress intensity factor (SIF) appears weak and generally lost within data scatter[1]
- Substantial dependence on temperature[2]
- CGR for sea salt is lower than for $MgCl_2$
- Some existing data are time to specimen failure (initiation + growth) which are less useful as growth data

1. A. Kosaki, "Evaluation Method of Corrosion Lifetime of Conventional Stainless Steel Canister under Oceanic Air Environment," *Nuclear Engineering and Design,* Vol. 238, No. 5, p. 1233–1240. 2008.
2. K. Shirai, et al., "Research on Spent Fuel Storage and Transportation in CRIEPI (Part 2 Concrete Cask Storage)," *16th Pacific Basin Nuclear Conference (16PBNC)* held in Aomori, Japan, Paper No. P16P1215, October 13-18, 2008.

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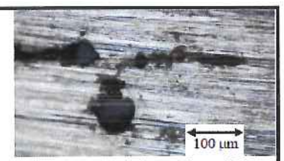
Literature Review
Other Mechanisms



Example of Superficial Pit
[ML13022A314]

- Other SS degradation mechanisms were investigated (pitting, crevice corrosion, MIC, etc.)
- In stainless steels exposed to ambient conditions, aqueous chloride also the most common aggressive contaminant for pitting and crevice corrosion
- Pitting 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 similarly more likely to facilitate SCC rather than penetrate through-wall by bulk material dissolution

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Literature Review
Other Mechanisms

- Microbiologically induced corrosion (MIC)
  - Limited at RH < 90%, negligible at RH < 60%
  - Review of MIC was performed for geological repository
  - No OE for SS MIC under atmospheric conditions
- Intergranular attack (IGA)
  - Limited attack only a few grains deep observed in weld region of specimen in pure deliquescent NH_4HSO_4 [1]

1. X. He, R. Pabalan, T. Mintz, G. Oberson, D. Dunn, and T. Ahn, "Scoping Study of Effect of Salts in Non-Coastal Particulate Matter on Stress Corrosion Cracking of Type 304 Stainless Steel," CORROSION 2013, NACE, 2013. (Available with NRC Accession No. ML13018A120)

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Literature Review
Testing / Data Gaps

- If additional test data becomes available, it could be used to reduce conservatism
- *Crack growth rate testing* – most testing has focused on initiation; relatively little testing has been conducted to determine crack growth rates
  - Data at more combinations of RH & T, also Cl^- concentrations
  - CGR data for welded plate specimens to investigate most realistic material conditions
- *Site specific data* – e.g., airborne concentrations of contaminants
- *Additional deposit sampling* – detailed ionic analysis of deposit samples from canister surfaces to determine the chloride concentration and that of other species
- *Crack initiation thresholds and rates* – initiation at low Cl^- concentrations for welded specimens
- *Deposition behavior and modeling* – for expected conditions

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Failure Modes and Effects Analysis (FMEA)

- Approach
- Degradation Mechanisms and Failure Modes
- Consequences
- Implications

Failure Modes and Effects Analysis (FMEA)
Approach (1/3)

- FMEA process is structured to systematically identify the potential failure modes of a system, their relative likelihood, and their consequences to the system
- Used existing FMEAs for reactor systems as an example
- Scope limited to welded stainless steel canisters exposed to air
  - Considers aging-related degradation during the lifetime of extended storage plus consequences of such degradation
  - Considers mechanisms caused by the environmental conditions surrounding the canister
- Focused on identifying credible failure modes for welded SS canisters under design basis conditions
- Leveraged information acquired by literature review

Failure Modes and Effects Analysis (FMEA)
Approach (2/3)

- Reviewed general literature on corrosion of stainless steels and on atmospheric corrosion to identify potential mechanisms
  - Focused on mechanisms judged to be more likely to occur under canister conditions
  - Not all mechanisms reviewed were explicitly discussed in FMEA
- Incorporated results from gap analyses and topical reports (EPRI, ESCP, DOE, NRC/CNWRA, NWTRB)
- Existing design basis documents for general license DCSS and plant specific DCSS reviewed and factored into the failure modes considered

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Failure Modes and Effects Analysis (FMEA)
Approach (3/3)

- Identified range of potential effects for failure modes
  - FMEA table provides rankings of potential degradation modes
  - A Fault Tree Analysis (FTA) of the canister failure modes to evaluate combinations of initiating events
- Because of the common mode of canister failure, the FMEA was broken into two phases:
  - Mechanisms and modes leading to confinement penetration
  - Consequences stemming from confinement penetration
- Degradation mechanisms and effects were categorized in terms of detectability, severity, and likelihood based on engineering judgment and available literature
  - Permits focusing of resources on most important items

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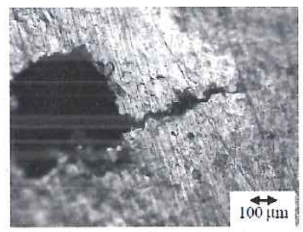
Failure Modes and Effects Analysis (FMEA)
Mechanisms – CISCC

- CISCC most likely of potentially active degradation mechanisms to lead to TW penetration
- Development of conditions conducive to CISCC expected to dominate the time to initiation
  - Susceptibility of a region on the canister is influenced by chloride surface load, tensile stresses at the canister OD, and the local surface RH
  - Sensitization and surface cold work (e.g. grinding) also increase susceptibility
- Time to develop significant risk of initiation expected to be governed by local chloride surface loading



Cracking on surface of specimen immersed in $MgCl_2$

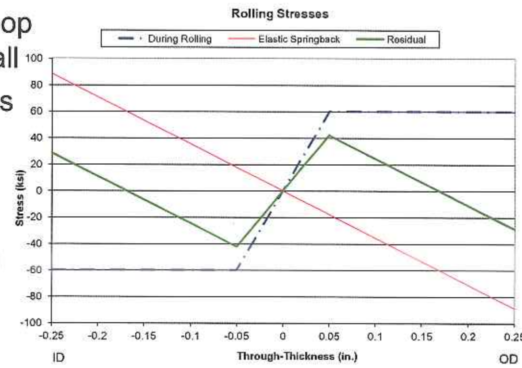
[ML13051A152]

Failure Modes and Effects Analysis (FMEA)
Mechanisms – CISCC

- Source of chlorides most likely to be marine aerosol from breaking waves and whitecaps on the ocean
  - Concentration of larger particles from breaking wave decays very rapidly over first hundred meters
  - Total concentration decays rapidly over first kilometer from exposed shore
- Deposition rate of aerosols on canister is much greater on horizontal surface and is reduced in areas with higher heat flux
- Aqueous conditions may develop by rain ingress or deliquescence of deposits in the cooler regions
  - Local RH limited by ambient AH and local temperature

Failure Modes and Effects Analysis (FMEA)
Residual Stress Analysis – Plate Rolling

- Scoping calculation of residual hoop stresses due to cold rolling of the shell from a plate
  - Material plastically deforms during rolling then relaxes elastically until the moment about the neutral axis is zero
  - Compressive residual hoop stress in outer 15% of wall
- For comparison, hoop stress due to 110 psig internal pressure is about 8 ksi
  - Max of all design types
  - Some designs are 7 psig internal pressure



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Failure Modes and Effects Analysis (FMEA)
Residual Stress Analysis – WRS

- Performed scoping analyses for different weld configurations
  - Seam weld, girth weld, shell to baseplate butt weld
  - Girth weld analyzed as single V, double V (ID and OD first)
- Residual stress analysis results indicate short through-wall cracks across the weld are more likely
  - Elevated through-wall tensile residual stresses oriented parallel to the weld bead
    - Elevated stress region limited to about two wall thicknesses from weld CL
  - Much lower stresses, in many locations compressive, oriented transverse to weld bead
- General trends are not sensitive to specific weld configurations
  - Changing the order of welding the double-V grooves and using a single-V geometry did not significantly change the trends reported here

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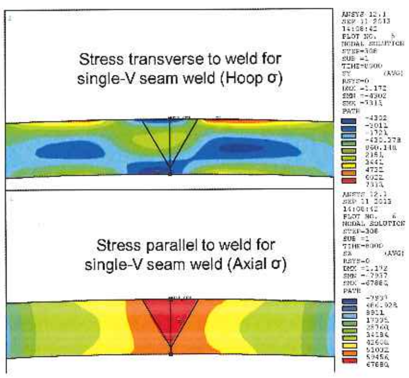
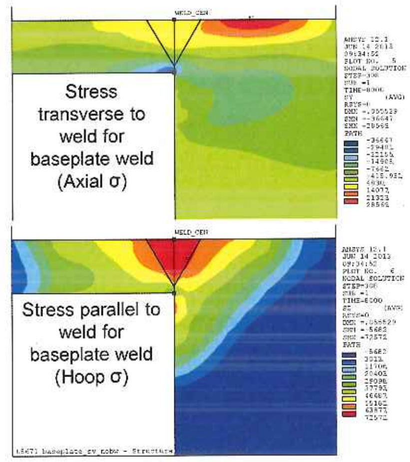
Failure Modes and Effects Analysis (FMEA)
Residual Stress Analysis – WRS





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Failure Modes and Effects Analysis (FMEA)
Failure Modes

- Tight through-wall crack is most likely mode of canister penetration (CISCC/crevice)
  - Would release helium overpressure, then allow air ingress over time; likely to not release particulates
  - Reliable detection of degradation prior to release of helium backfill likely requires non-visual NDE
  - Time for growth of an initiated CISCC crack to TW depth is expected to take a number of years
- Growth of a flaw to critical flaw size would have higher consequences; this is very unlikely or not credible
  - Even under accident pressure and lifting loads, the critical flaw length is multiple feet long

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Failure Modes and Effects Analysis (FMEA)
Consequences of Canister Wall Penetration

- Penetration results in release of helium backfill and ingress of air
  - Timescale varies greatly depending on crack size
  - Release of higher backfill pressures can raise the peak cladding temperature
  - Ingress of air by diffusion and ambient temperature cycles raises temperatures and provides oxidizing conditions
  - Loss of over pressure expected to be relatively rapid (minutes to a month) compared to air ingress (weeks to years)
- Release of helium backfill provides driving force to potentially expel radioactive gasses, if breached fuel is stored
- Operating experience from REA 2023 leaking cask
  - Air ingress – canister at 7% O2 after three months, 16% O2 after twenty months (vs 20% O2 in air)
  - No radioactive contamination reported at leak despite damaged fuel

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Failure Modes and Effects Analysis (FMEA)
Consequences of Canister Wall Penetration

- Release of fuel particulates from canister stored on pad would require sequential occurrence of individually unlikely events
  1. Penetration of canister confinement must grow larger than tight crack (to provide path for particles)
     - Would release backfill pressure before any fuel particles are generated
  2. Oxidation of fuel pellet on rod with breached cladding causes fuel pellet swelling leading to cladding unzipping
  3. Unzipped cladding releases some grains of fuel (generation of fine fuel particles in canister plenum)
  4. Significant disturbance required to entrain particles in air and provide a driving force for release of particulates
     - Backfill pressure has long since been released

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Failure Modes and Effects Analysis (FMEA)
Implications – Locations of Higher Susceptibility

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 Location	Support rail contact region	Under baseplate
Material Condition	Areas of grinding or mechanical abuse (e.g. gouges)	Areas of grinding or mechanical abuse (e.g. gouges)
Greatest Combination of Factors	Shell welds at canister ends (top surface); support rail interface near welds	Canister sides near welds at the bottom of the canister

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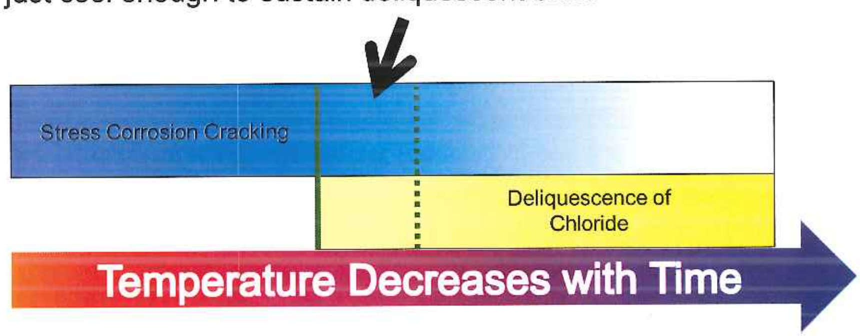
Failure Modes and Effects Analysis (FMEA)
Implications – Susceptibility Temperature Window

- Low surface temperatures may lead to aqueous conditions due to deliquescence at high local humidities
- Higher surface temperatures are likely to cause reduced time to CISCC initiation and higher CISCC propagation rates
- Fastest propagation would tend to occur on surfaces that are just cool enough to sustain deliquescent brine



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Failure Modes and Effects Analysis (FMEA)
Summary

- FMEA confirms that CISCC leading to a TW crack should be the focus of aging degradation consideration
  - Crack releases helium and any fission gasses in the canister cavity; allows air to enter
  - Cracks are concerns for through-wall penetration and leakage but not concerns for rupture
- Chlorides are most credible atmospheric species to cause degradation of austenitic stainless steels
- Chloride aerosol concentration decays rapidly moving inland
  - Establishment of conditions conducive to CISCC initiation considered likely for small number of sites close to the open ocean
  - For other sites farther from the ocean but still exposed to sources of chloride, the probability could vary greatly, with the probability tending to increase over multiple decades

Failure Modes and Effects Analysis (FMEA)
Summary

- Investigation of consequences informs the level of tolerance for confinement penetration
  - Depends on cladding temperature with air as a cover gas and presence of breached fuel rods outside damaged fuel cans
    - Burnup, time in storage, and initial enrichment affect the cladding temperature over time
    - For low enough cladding temperature in air (i.e. after long storage times), no assembly degradation expected as consequence of canister penetration
- Effective mitigation or detection options may include:
  - Prevent species from depositing (e.g., filter inlet air)
  - Monitor chloride surface concentration
  - Monitor cover gas properties, if tolerant of confinement penetration

Project Continuation
Progression of Modeling

- FMEA
  - Qualitative judgments of frequency/probability, detectability, and severity over time based on literature and limited calculations
  - Define boundaries of the degradation problem and guide approach to subsequent assessments
- Canister Flaw Growth and Flaw Tolerance
  - Model the process of canister degradation based on the pathways identified in the FMEA
  - Model flaw growth to through-wall and consequential flaw sizes
- Canister Confinement Integrity Assessment
  - Probabilistic analysis to determine the benefit of various monitoring, mitigation, and inspection regimes

Susceptibility Criteria Process

- Process of prioritization based on susceptibility and implementing aging management is likely to be iterative (learning program)
  - New testing/monitoring/inspection results will enhance screening criteria and evaluations
  - Inspection/monitoring/mitigation techniques under development to be implemented when available and where needed
- FMEA process has identified CISCC as the most likely form of canister degradation to lead to through-wall penetration
- Initial focus of susceptibility criteria will be based on CISCC factors

Susceptibility Criteria – Primary Factors

- Literature review and FMEA have identified three primary factors related to CISCC susceptibility
  - **Absolute humidity**: depends on ISFSI site location
  - **Cl surface load**: depends on atmospheric concentration of Cl, overpack air flow, local surface orientation (horiz/vert)
  - **Surface temperature**: depends on location on canister, canister age, and initial thermal power
- Primary factors identified assume that:
  - Residual stress sufficient to lead to through-wall cracking cannot be ruled out
  - At sufficient conditions, initiation of SCC will be relatively rapid
- Primary factors will be used to assess relative priority of inspection for different sites

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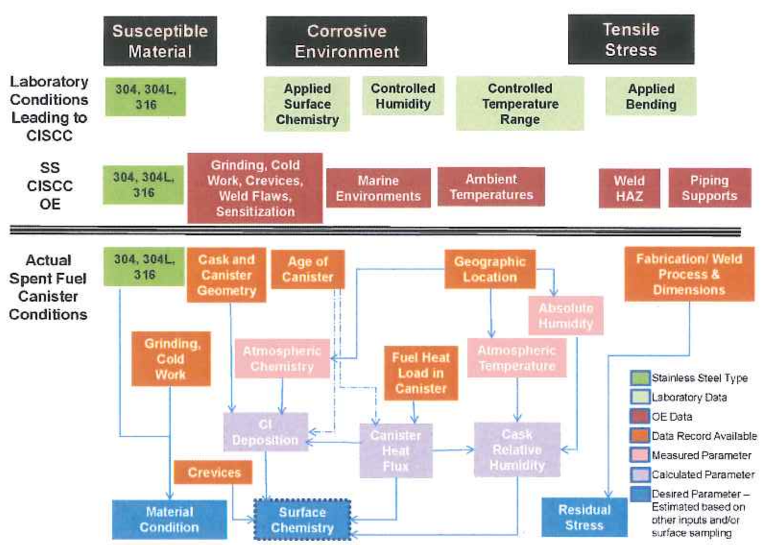
Susceptibility Criteria – Parameters



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Assessment of NDE Methods for Detection of SCC in DCSS Canisters

Bruce Lin
NRC

Chloride Stress Corrosion Cracking
Regulatory Issue Resolution Protocol Meeting

January 24, 2014

NDE of DCSS Canisters

- Purpose:
  - To identify and assess potential NDE methods for detection of stress corrosion cracking in DCSS canisters
- Scope and Approach:
  - Focus on HI-STORM 100 and NUHOMS HSM to represent vertical and horizontal systems
  - Considers access and deployment, environmental compatibility, and NDE methods and techniques
  - Focus on Ultrasonic Testing (UT) and Eddy Current Testing (ECT)

NDE of DCSS Canisters

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- Report Layout (ML13276A196)
  - Chapter 1 – Introduction
  - Chapter 2 – Atmospheric Stress Corrosion Cracking
  - Chapter 3 – Description of HI-STORM 100 and NUHOMS
  - Chapter 4 – Accessibility and Deployment
  - Chapter 5 – Environmental Compatibility
  - Chapter 6 – Ultrasonic Testing Performance
  - Chapter 7 – Eddy Current Testing Performance
  - Chapter 8 – Discussion
  - Chapter 9 – Summary

NDE of DCSS Canisters

U.S.NRC
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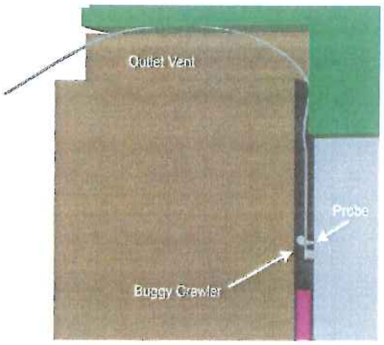
- Environmental Compatibility
  - NDE sensors should be able to withstand temperature and radiation exposure for inspections
  - Permanently mounted sensors could degrade due to cumulative radiation dose
- Accessibility and Sensor Deployment
  - The inlet and outlet vents provide potential access to the canister surfaces, but access is restricted by other structures and narrow annulus between the canister and the overpack
  - Various options may be available for deployment of NDE sensors

NDE Sensor Deployment Concepts



NDE Sensor Deployment Concept Utilizing a Spring-Loaded Wheeled Buggy on End of Flexible Wand

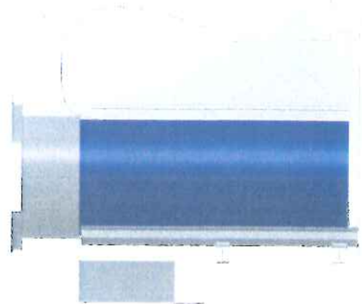


Illustration of Insertion of NDE Probe Mounted to Spring Steel Probe Through HSM Outlet Vent

Summary

- Assessment of UT and ECT
  - The performance data (based on previous studies) indicates that both UT and ECT may be capable of detecting flaws that do not fully penetrate DCSS canisters with good reliability
  - NDE performance could be affected by the surface conditions of the canisters and the challenges associated with the deployment of the sensors
  - Effectiveness of the NDE techniques needs to be verified through performance assessment accounting for specific factors such as delivery method, environmental conditions and configuration/geometry constraints

Review of Methods for Dry Cask Storage System Monitoring

Darrell Dunn
NRC

Chloride Stress Corrosion Cracking
Regulatory Issue Resolution Protocol Meeting

January 24, 2014

U.S.NRC
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Protecting People and the Environment

Outline

- Background
  - Dry cask storage systems
  - Technical information needs
  - Possible advantages of monitoring
  - Challenges to monitoring
- Parameters of interest
  - Environmental conditions
  - Degradation processes
- Monitoring system attributes
- Summary of methods reviewed

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Dry Cask Storage Systems

- Dry Cask Storage Systems (DCSS) were necessary because of limited space in spent fuel pools
- DCSSs used at many currently operating and decommissioned commercial nuclear power plants
- DCSSs will likely be called upon for longer than originally planned
  - Uncertain timing for an available repository
  - Lack of an alternative storage facility

Safety of DCSSs currently in service and during subsequent license renewal periods

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Technical Information Needs

- Multiple specific recommendations in the NRC Technical Information Needs Report
- The NRC Technical Information Needs Report also recommends that first priority be given to the following crosscutting areas:
  - Thermal calculations
  - Effects of residual moisture after normal drying
  - Development of in-service monitoring methods for storage systems and components

Reference: U.S. NRC, “Identification and Prioritization of the Technical Information Needs Affecting Potential Regulation of Extended Storage and Transportation of Spent Nuclear Fuel,” May 2012, (ML120580143)

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Possible Advantages of Monitoring

- Identify the onset of environmental conditions conducive to component degradation
- Detect degradation processes
  - Corrosion and stress corrosion cracking
  - Environmental effects and material aging
- Basis for inspection programs and maintenance schedules

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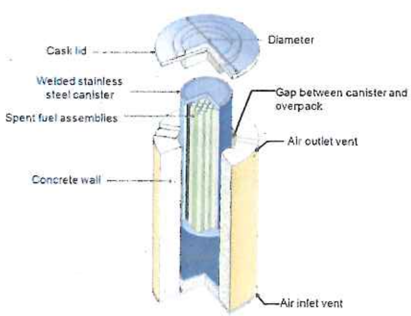
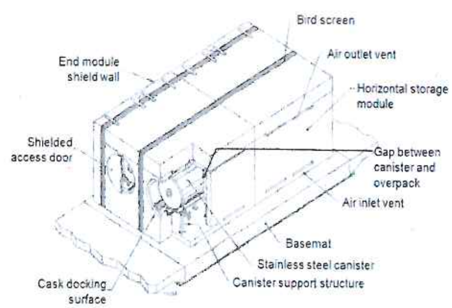
Monitoring Challenges





- DCSSs not designed to incorporate monitoring
- Access restrictions and challenging environments
- Limitations of available methods
- Worker dose considerations

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Parameters of Interest

- External environmental conditions
  - temperature and humidity
  - chloride ion and atmospheric deposits
- Component degradation
  - Microbially influenced corrosion (MIC)
  - SCC of welded stainless steel canister
  - Concrete overpack aging and degradation
  - cask bolt degradation, corrosion and SCC
- Canister/cask internal conditions and components
  - Temperature and humidity/residual water content
  - Helium
  - Cladding integrity

01/24/2014 Chloride SCC RIRP Meeting 7

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Monitoring System Attributes

- Maturity
- Measurement range and sensitivity
- Power requirements
- Longevity

- Monitoring area
- Data collection
- Temperature tolerance
- Radiation tolerance

↓

DCSS monitoring needs

↓

System Strengths, Weaknesses and Unknowns

01/23/2014 Chloride SCC RIRP Meeting 8

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Summary of Methods Reviewed

- External environmental conditions
  - Temperature and RH sensors developed for nuclear applications
  - Chloride/deposition monitoring methods are limited
- External component degradation
  - Microbially influenced corrosion (MIC): sensors available
  - SCC: sensors have been developed
  - Concrete aging and degradation: typically performed using manual methods but some sensors have been developed and deployed in civil engineering structures
  - cask bolt degradation: some monitoring methods may be applicable; inspection methods in use in nuclear applications
- Internal conditions and component degradation
  - Development necessary to overcome access limitations and the challenging environment inside the DCSS canisters/casks

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Director, Used Fuel Programs

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NUCLEAR ENERGY INSTITUTE

May 31, 2013

Mr. David W. Pstrak
Chief, Structural Mechanics and Materials Branch
Division of Spent Fuel Storage and Transportation
Office of Nuclear Materials Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Subject: Regulatory Issue Resolution Protocol Screening Form and Resolution Plan for Chloride-Induced Stress Corrosion Cracking (RIRP-N-10-01)

Project Number: 689

Dear Mr. Psrtak:

On behalf of the nuclear energy industry, the Nuclear Energy Institute (NEI) is transmitting updated versions (Revision 3) of the Regulatory Issue Resolution Protocol (RIRP) Screening and Resolution Plan forms for the Chloride-Induced Stress Corrosion Cracking (CISCC) issue (RIRP-N-10-01). These forms have been updated in accordance with industry verbal commitments made at a recent NRC public meeting held on April 4, 2013.

The updated forms reflect the latest revision of the Electric Power Research Institute (EPRI) *Integrated Plan for Addressing Potential Chloride-Induced Stress Corrosion Cracking of Austenitic Stainless Steel Dry Cask Storage System Canisters*. As discussed at the aforementioned meeting, the specific focus of this RIRP is to complete the Susceptibility Assessment Criteria described in the EPRI plan and updated RIRP Resolution Plan form. The industry is committing to have these criteria finalized by June 15, 2015. The industry will further keep the NRC informed of subsequent plans to apply the criteria as also described in the EPRI plan.

I would be happy to address any feedback the NRC may have on the updated RIRP forms. If you have any questions, please do not hesitate to contact me.

Sincerely,

Rodney McCullum

Attachments

c: Ms. Catherine Haney, NMSS, NRC
Mr. Mark D. Lombard, NMSS/DSFST, NRC
Ms. Sara DePaula, NMSS/DSFST, NRC

USED FUEL STORAGE AND TRANSPORTATION ISSUE SCREENING FORM
Issue Number: N-10-01

Title: Dry Spent Fuel Storage Canister Chloride Induced Stress Corrosion Cracking

I. a. Problem Statement (Provide a clear, concise description of the issue.)

There is insufficient data to determine the minimum conditions (environmental and cask), and the associated time scales, necessary for potential initiation of stress corrosion cracking (SCC) in stainless steel dry spent nuclear fuel (SNF) storage canisters deployed at ISFSIs located in chloride containing atmospheres.

b. Background Information (Summarize industry events, licensing actions, inspection information, correspondence, and other documents germane to the issue. Attach documents as appropriate)

Austenitic stainless steels (304, 304L and 316L) used for confinement boundary in SNF storage canisters may be susceptible to SCC when exposed to a chloride containing atmosphere (References 1 through 4). Fog and spray aerosols from salt water bodies can contain airborne chlorides that may deposit on canister surfaces, potentially leading to SCC. Degradation from this phenomenon may impact the ability of the storage system confinement boundary to perform its safety function over an extended operating period. SCC, if present, may also impact the future transportation performance (if the system or component is dual-purpose certified and the canister is used as a second watertight barrier for moderator exclusion during transport). The chloride induced SCC (CISCC) phenomenon has historically not been the subject of NRC review of applications for dry spent fuel storage system Certificates of Compliance for initial 20 year licenses, but has been the subject of some RAIs issued since 2012 regarding applications for renewal beyond 20 years.

References 1 through 4 contain descriptions of laboratory experiments performed to simulate the CISCC phenomenon. However, the laboratory conditions do not accurately represent in-situ conditions at ISFSI sites. This difference between the laboratory and the in-situ conditions makes it impossible to determine the condition-based time scales under which SCC of stainless steel dry cask storage canisters could potentially occur.

References:

1. "Research Program on Stress Corrosion Cracking of Stainless Steel Canister for Concrete Cask," Central Research Institute of Scientific Power Industry (CRIEPI), Japan, January 16, 2007.
2. NUREG/CR-7030, "Atmospheric Stress Corrosion Cracking Susceptibility of Welded and Unwelded 304, 304L, and 316L Austenitic Stainless Steels Commonly Used for Dry Storage Containers Exposed to Marine Environments," USNRC, October 2010.
3. Report 1011820, "Effects of Marine Environments on Stress Corrosion Cracking of Austenitic Stainless Steel," Electric Power Research Institute, September 2005.
4. Report 1013524, "Climatic Corrosion Considerations for Independent Spent Fuel Storage Installations in Marine Environments," Electric Power Research Institute, June 2006.

II. Screening Criteria (Provide an explanation as to how the issue meets each of the screening criteria to be considered for generic issue resolution.)

1. **Does the proposed issue involve spent fuel storage or transportation and affect multiple 10 CFR 71 and/or 10 CFR 72 regulated entities** (provide basis)**?**
Yes. There are multiple ISFSIs located at sites in the United States which could potentially be affected by chloride containing atmospheres.

2. **Does the proposed issue warrant generic resolution** (provide basis)**?**
Yes. A consistent approach is needed to determine the conditions under which chloride induced SCC of austenitic stainless steel initiates and over what time frame SCC could cause deleterious effects to the SNF

canister's confinement boundary.

3. **Does the issue warrant engagement between the industry and NRC** (provide basis)**?**
Yes. The NRC believes industry involvement would provide a better understanding regarding the extent of the condition and/or provide additional data to identify systems susceptible to this phenomenon . This effort would inform future licensing requirements for spent fuel storage systems as well as actions that may be taken to mitigate potential CISCC at presently licensed systems.

4. **Will generic resolution of the issue produce tangible benefits** (provide basis)**?**
Yes. The beneficial outcomes of resolving this issue using this protocol are a consistent licensee and CoC holder approach to addressing the issue and a stable, predictable licensing and inspection protocol.

5. **Is the issue already adequately covered by another process** (provide basis)**?**
No. This issue has not reached a level of urgency or safety significance to qualify it for the NRC's generic safety issue process because testing is inconclusive (laboratory conditions do not accurately represent in-situ conditions at ISFSI sites), actual conditions (atmosphere and cask) vary from site to site and from model to model and cask to cask; and actual field data is insufficient. Since there is not an immediate safety concern, use of this protocol permits a deliberate yet timely approach to understanding the issue and creating the necessary tools for licensing and implementing prevention and mitigation strategies, as necessary. On November 14, 2012 NRC issued Information Notice 2012-20 to inform addressees of recent issues and technical information concerning the potential for CISCC of austenitic stainless steel dry cask storage system canisters. The efforts being undertaken in this RIRP will be carried out consistently with industry's understanding of the information conveyed in Information Notice 2012-20.

POC: Are all screening criteria satisfied ("Yes" responses to questions 1-4 and "No" to question 5) **?**
Yes ___X___ **No**__________

III. Success Criteria (Describe the criteria to be used to define success for resolving this issue.)

Consistent with the data acquired, the following are determined and documented:

1. The conditions of canister materials and environment under which CISCC could potentially initiate.
2. The time scales under which CISCC could occur, based upon actual atmospheric and cask conditions.
3. Agreed upon Susceptibility Assessment Criteria that can be used by licensees to evaluate the potential for CISCC to occur on canisters at their site.

IV. Date: 05/28/2013

USED FUEL STORAGE AND TRANSPORTATION ISSUE RESOLUTION PLAN
Issue Number: N-10-01

Title: Dry Spent Fuel Storage Canister Chloride Induced Stress Corrosion Cracking

I. Summary of Resolution Plan

Industry and NRC will interact in public meetings and through letters to achieve the following:

Consistent with the data acquired, the following are determined and documented:

1. The conditions of canister materials and environment under which CISCC could potentially initiate.
2. The time scales under which CISCC could occur, based upon actual atmospheric and cask conditions.
3. Agreed upon Susceptibility Assessment Criteria that can be used by licensees to evaluate the potential for CISCC to occur on canisters at their site.

II. Actions and Due Dates

ACTION	RESPONSIBLE PARTY	DUE DATE/STATUS
1. Public meeting to discuss the data acquired in NRC and EPRI research	NRC/Industry	Completed – 3/14/2011
2. Industry develop draft criteria for the minimum conditions defining a chloride atmosphere under which SCC of canister confinement boundary made of austenitic stainless steel (304, 304L, 316L) could occur (e.g. relative humidity, chloride concentration in air, distance from salt water, cask surface temperature), and a method for determining the condition based time scale under which CISCC could occur (e.g. screening criteria)	Industry	Completed – February 2012
3. Public meeting for industry to present plans for acquiring field data.	NRC/Industry	Completed – 2/14/2012
4. Public meeting for 1) NRC to present technical data and regulatory questions, and 2) Industry to present conceptual screening criteria identifying the minimum conditions necessary for potential initiation of CISCC and a method for determining the condition based time scale under which CISCC could occur.	NRC/Industry	Completed – 4/12/2012
5. Perform pilot acquisition of field data (e.g. cask surface temperature, relative humidity, chloride content, and atmospheric parameters) at Calvert Cliffs Nuclear Station. This pilot will demonstrate the feasibility of acquiring certain data, be used to inform development of a more robust program, and provide useful data for addressing information gaps. which will support the basis of the condition based time scales under which SCC could occur; future plans to acquire field data will be based in part on the need for information to inform the screening criteria	EPRI/Industry	Completed – 6/27&28/2012
6. Public meeting to provide update on industry's plans/actions including: 1) proposed update to	Industry/NRC	Completed – 12/18/2012

RIRP resolution plan, 2) R&D Roadmap, and 3) pilot data acquisition results and plans for future inspections. Discussion to obtain NRC feedback on industry's plans. NRC update of related activities.		
7. Develop an draft R&D roadmap (referred to as Master Plan at 4/12/2012 meeting) for acquiring data necessary to fill-in gaps for understanding the condition based time scales under which SCC could occur. R&D Roadmap will start with the gaps identified in the Conceptual Screening Criteria, and will identify R&D being performed by industry, NRC, DOE, and others; as well as how/when this R&D is projected to result in data sufficient to close the RIRP.	EPRI/Industry	Completed – 1/31/2013
8. Submit draft R&D Roadmap for NRC feedback.	EPRI/Industry	Completed – 1/31/2013
9. Submit proposed update to RIRP screening form and resolution plan (Revision 2) to NRC, which incorporates feedback from public meeting.	NEI/Industry	Completed – 1/31/2013
10. Provide comments on proposed update to RIRP screening form and resolution plan for industry to incorporate. OR If NRC agreement on proposed forms, RIRP screening form and resolution plan Revision 2 are finalized.	NRC	Completed - March 2013
11. If NRC comments on proposed screening form and resolution plan, incorporate and finalize RIRP resolution plan Revision 3.	NEI/Industry	Completed – 5/28/13
12. Provide comments on draft R&D Roadmap.	NRC	June 2013
13. Finalize R&D Roadmap, incorporate NRC comments.	EPRI/Industry	June 2013
14. Collect/consolidate data per R&D Roadmap (including EPRI acquisition of actual canister data). Evaluate/update conceptual screening criteria as additional data becomes available. Monitor all R&D and update Roadmap as necessary. Assess when sufficient data exists to resolve RIRP.	EPRI/Industry	TBD – Based upon R&D Roadmap
15. Review NRC sponsored research at SwRI/CNWRA to identify and evaluate any data that may be relevant to this RIRP.	NRC	TBD.
16. Periodic NRC/Industry public meetings to: 1) present updates on R&D and discuss development of data sufficient to close RIRP (including updates to conceptual screening criteria), 2) exchange information to increase the value of R&D activities (e.g. industry provide NRC with weld data for typical canisters), 3) discuss whether the RIRP resolution plan needs to be updated, and 4) discuss whether sufficient data exists to close the RIRP.	NRC/Industry	TBD. (e.g. every 6 months). Tentatively: March and September every year for as long as identified in R&D Roadmap
17. Finalize, and send to NRC, Industry Susceptibility Assessment Criteria that can be used by ISFSI licensees to evaluate the potential for CISCC to occur on canisters at their site.	NEI/EPRI/Industry	June 2015

18. NRC review and provide written comments on Industry Susceptibility Assessment Criteria	NRC	60 days after receipt of Industry's Screening Process
19. Industry address NRC comments and finalize Industry Susceptibility Assessment Criteria.	Industry	30 days after receipt of NRC comments
20. Submit proposed RIRP closure form to NRC.	NEI/Industry	Upon finalization of Susceptibility Assessment Criteria
21. Provide comments on proposed closure form for industry to incorporate. OR If NRC agreement on proposed closure form, RIRP closure form is finalized.	NRC	30 days after submission
22. Finalize RIRP closure form (if necessary to address NRC comments).	NEI/Industry	Upon resolution of comments
23. Once the RIRP is closed, industry will define the path forward for applying the Susceptibility Assessment Criteria. This path forward will address any procedures and capabilities needed to implement the criteria. Industry will seek NRC feedback on the implementation of the criteria in a public meeting or meetings.	NEI/Industry	TBD

III. Date: 05/28/2013

#1

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Update on In-Service Inspections of Stainless Steel Dry Storage Canisters

Keith Waldrop, Senior Project Manager

Presented by **John Kessler**, Program Manager

NEI-NRC Meeting on Spent Fuel Dry Storage Cask Material Degradation

January 28, 2014

Overview

- **Context**
- **Calvert Cliffs**
- **Hope Creek**
- **Diablo Canyon**
- **Conclusions from initial inspections**

Initial In-Service Inspections - Context

- They provided the first look at canister condition:
  - Visual look at canister condition for signs of gross change or any unexpected condition
  - *Initial* data collection to understand the actual canister conditions important to CISCC (temperature, surface compositions)

- They are not:
  - Perfect
  - The final step
  - Intended to find CISCC cracks

Calvert Cliffs

Calvert Cliffs – Visual Inspections

- No gross degradation
- Light surface corrosion
- Top covered in dust

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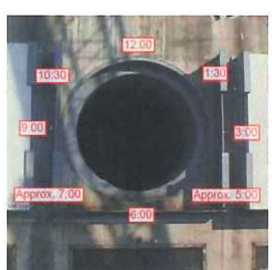
Calvert Cliffs - Temperature Measurement

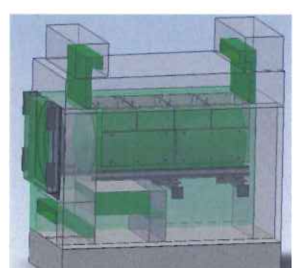
Measurement

- Insert tool, rotate to surface, wait for reading to stabilize, rotate and remove tool

Results

- Measured temperatures ranged from 40°C (104°F) to 51°C (124°F)
- Calculated temperatures ranged from 38°C (100°F) to 143°C (290°F)





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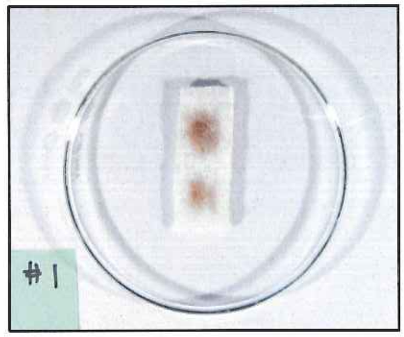
Calvert Cliffs - Samples Collected from Surface of Canister

- Dry (scraping, brushing, vacuum)
  - Best for upper surfaces to collect "dust"
  - Insert tool, rotate to surface, turn on vacuum, scrape back and forth, rotate and remove tool
- Wet - SaltSmart™
  - Qualification testing for temperature and range of concentrations expected (measurement taken on-site)
  - Insert tool, engage SaltSmart™, deliver water, wait, disengage SaltSmart™, remove tool



SaltSmart Device (Strip)

Calvert Cliffs Sample Chemical Composition - Evans Analytical Group Analysis

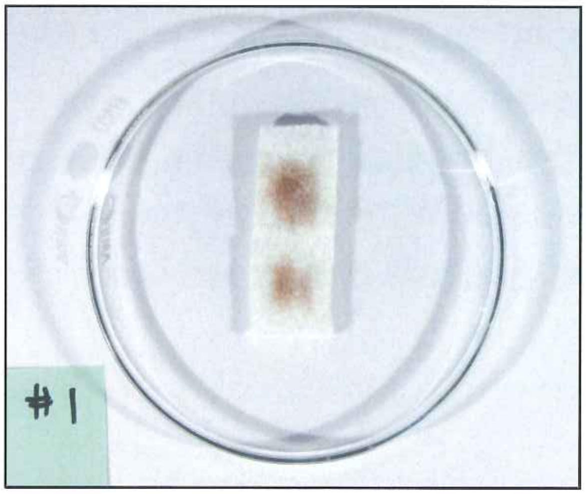
- Methods Applied
  - X-ray Fluorescence, X-ray Diffraction, Gas Chromatography Mass Spectrometry (GC-MS), Ion Chromatography
- Key Observations
  - SaltSmart™ meter not properly calibrated
    - Use only to collect soluble salts
  - Laboratory analysis found very little Cl present in samples
    - **Surface composition looks like "inland" (low chloride) rainwater – not seawater**

Sandia Analysis of Calvert Cliffs Samples

- SEM imaging and energy dispersive system (EDS) element maps
  - Provide textural and mineralogical information , Identification of floral/faunal fragments in dust
- X-ray fluorescence
  - Microanalytical technique—chemical mapping of filter/pad surfaces, resolution of ~50 μm
  - Semi-quantitative chemical analyses—yields element ratios that can be used in mass balance calcs
  - Cannot detect elements lighter than sodium
- X-ray diffraction
  - Analysis of pads/filters for mineralogical information (not useful—only quartz distinguished)
- GC-MS
  - Stepwise thermal decomposition to drive off volatile, semi-volatile components in the dust
  - Only components that are driven off prior to decomposition of the filter/pad matrix can be observed.
- Raman Spectroscopy
  - Microscopic technique provides mineralogical/compositional information of individual dust grains, if sufficiently large.
- FTIR analysis
  - Samples treated with solvents, and the solvents analyzed to determine volatile, semi-volatile organic components leached from the sample.
- Chemical Analysis
  - Blanks, filter, and pad samples leached with DI water, and the leachate analyzed to determine soluble salts in the dust
  - Insoluble fractions digested and analyzed to determine bulk chemistry

Sandia Analysis of Calvert Cliffs Samples

- Results confirm key observation, very little Cl present in samples
  - Brown stain on filter consists mostly of pollen



Calvert Cliffs Inspection Results

Thermal

- "Thermal Modeling of NUHOMS HSM-15 and HSM-1 Storage Modules at Calvert Cliffs Nuclear Power Station ISFSI," PNNL-21788

Surface samples

- Evans Analytical results available in ML13119A242, ML13119A243 and ML13119A244
- Sandia results will be available in "Data Report on Corrosion Testing of Stainless Steel SNF Storage Canisters," FCRD-UFD-2013-000324

Comprehensive EPRI report will be published March 2014

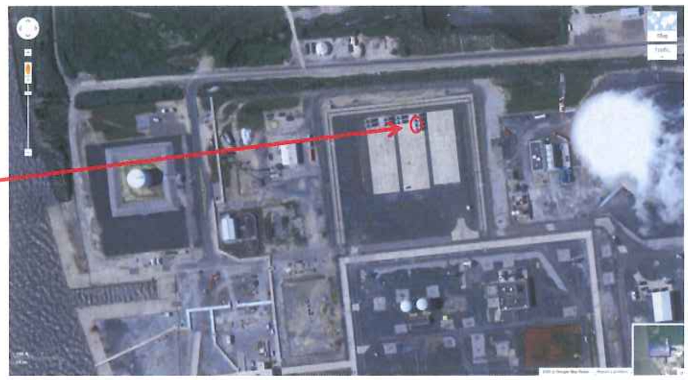
Lessons Learned, Implemented in Additional Inspections

- Better handling protocol of samples collected
  - To be stored in sterile lab containers
  - To be cooled ASAP
  - To be shipped and analyzed quickly (days to weeks)
- Contact pressure for thermocouple
- SaltSmart™ tool believed to provide reasonable collection efficiency - coupled with lab analysis
- Collection and analysis confirmed low Cl

Hope Creek Canister Inspection

- Inspect 2 canisters
  - Loaded 2006
  - Heat load 11-12 kW (loading), 9 kW (inspection)
  - Directly facing water (unobstructed)

Delaware Bay



Hope Creek Canister Inspection

- Inspection tooling
  - Developed by Holtec
  - Two Tools:
    - SaltSmart, Thermocouple, Camera
    - Dry scraper pad, Thermocouple, Camera
    - Tool attached to rod and deployed to canister lid
  - Lower tool into annulus, deploy tool to canister side surface
  - Tool development included mock-up testing prior to site deployment

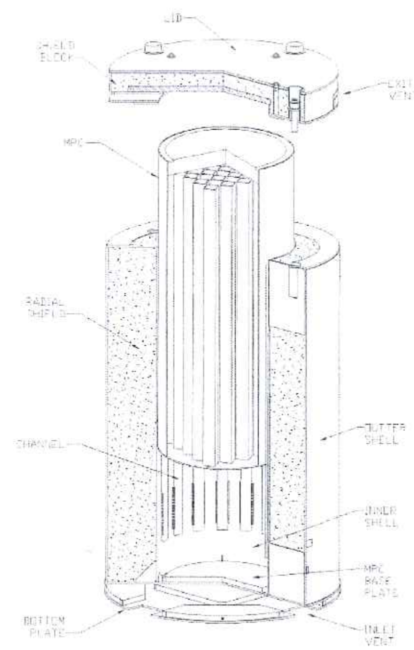
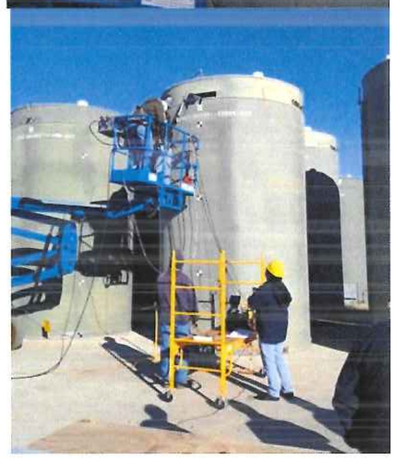


FIGURE 1.1.1B; HI-STORM 100S VERSION B OVERPACK WITH MPC PARTIALLY INSERTED

ML081350147

Hope Creek Canister Inspection

- Inspection sequence
  - Remove outlet screen and shield
  - Slide tool in vent on mounting assembly, position, push tool down to inspection location
  - Actuate tool
    - Sample collector (dry or wet)
    - Thermocouple
  - Retrieve tool and sample
  - Store sample
  - Repeat for remaining samples
  - Replace screen and shield
  - Ship samples for analysis



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Hope Creek Canister Inspection

- Completed 11/22/13
- *Preliminary* results
  - Thermal
    - Measured temperatures ranged from 21°C (71°F) to 57°C (134°F)
    - Calculated temperatures ranged from 28°C (83°F) to 56°C (133°F)
    - Lid - measured temperatures ranged from 54°C (129°F) to 79°C (174°F)
  - Samples
    - **Not much chloride**
    - **Composition looks like "inland" rainwater rather than "seawater"**
- Comprehensive EPRI report will be published June 2014

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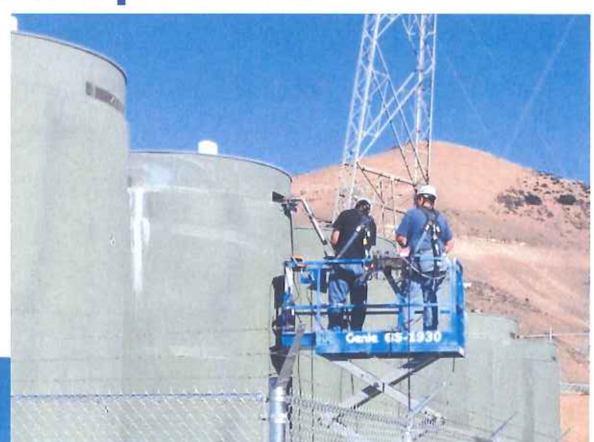
Diablo Canyon

Diablo Canyon Canister Inspection

- Inspect 2 canisters
  - Range from 2 to 3.5 years in service
  - 15 to 20 kW at time of loading
  - Directly facing water (unobstructed) until recently
- Follow similar process as Hope Creek



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Diablo Canyon Canister Inspection

- Completed 1/16/14
- Preliminary results
  - Thermal
    - Measured temperatures ranged from 49°C (120°F) to 118°C (245°F)
    - Calculated temperatures ranged from 60°C (140°F) to 105°C (221°F)
    - Lid - measured temperatures ranged from 87°C (188°F) to 97°C (207°F)
  - Samples
    - No results yet
- Comprehensive EPRI report will be published September 2014

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Conclusion – Much Learned from Initial Inspections

- First visuals of canister surfaces
  - No signs of gross degradation
  - Limited surface corrosion
- As expected, canister surface temperatures are age- and position-dependent
  - Older ~ colder
    - Calvert Cliffs: >19 years (coldest)
    - Diablo Canyon: <3.5 years (hottest)
  - Predictable areas of the canisters have the lowest temperatures
    - Coldest near air inlets
- Calvert Cliffs, Hope Creek: much less chloride on canister surfaces than anticipated
  - Cation/anion composition more like inland rainwater
  - Implication: less "marine" ISFSI sites than anticipated

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Chloride Induced Stress Corrosion Cracking

Aladar A. Csontos, Ph.D

Chief, Structural Mechanics & Materials Branch
Division of Spent Fuel Storage and Transportation
Office of Nuclear Material Safety and Safeguards

CISCC RIRP Public Meeting
January 24, 2014

Background

Chloride Induced Stress Corrosion Cracking

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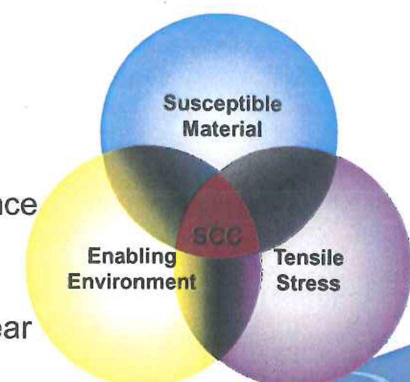
- Three necessary conditions must exist simultaneously:
  - Susceptible Material
  - Enabling Environment
  - Tensile Stresses
- Reactor operational experience indicate austenitic stainless steels susceptible to CISCC
- SCC typically occurs at or near welds or other high tensile stress locations:
  - Fit-up/Cold Work/Repairs, etc.



CISCC RIRP Results

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Industry & NRC Updates with Potential Path Forward

- Industry efforts to screen and resolve CISCC technical and regulatory issues worthwhile
- Focus on the potential susceptibility conditions and time scales necessary for potential initiation of CISCC in stainless steel dry spent nuclear fuel storage canisters deployed at ISFSIs
- NRC staff presenting following analyses:
  - SCC Susceptibility NUREG
  - WRS Analysis Report
  - NDE Assessment Report
  - Monitoring Report
  - Storage Renewal Strategy Team

#3

Overview of NUREG/CR-7170, "Assessment of Stress Corrosion Cracking Susceptibility for Austenitic Stainless Steels Exposed to Atmospheric Chloride and Non-Chloride Salts"

Darrell Dunn and Greg Oberson

Regulatory Issue Resolution Protocol
Public Meeting
Rockville, MD – January 24, 2014

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Report Layout

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- Chapter 1 – Introduction
- Chapter 2 – Experimental approaches
- Chapter 3 – Tests with chloride salts
  - Section 3.1 – Deliquescence testing
  - **Section 3.2 – Cyclic humidity SCC testing**
  - Section 3.3 – Elevated temperature SCC testing
  - Section 3.4 – High humidity SCC testing
  - **Section 3.5 – SCC testing at different specimen strain levels**
- Chapter 4 – Tests with non-chloride-rich species
  - Section 4.1 – Literature survey of atmospheric species
  - Section 4.2 – Deliquescence testing
  - Section 4.3 – SCC testing with non-chloride-rich species
  - Section 4.4 – SCC testing with chloride and non-chloride species mixtures
- Chapter 5 – Conclusions

Cyclic Humidity SCC Testing

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- Test objectives:
  - Identify whether SCC can initiate at an absolute humidity (AH) limited to about 30 g/m^3, which is reference point for natural conditions (not assumed as a limit for canister in the field)
  - Investigate effects of surface salt concentration and material condition on SCC susceptibility
- Test methodology:
  - Deposited 0.1, 1, or 10 g/m^2 of sea salt on ASTM G30 U-bend specimens
    - o Expose to salt fog for various times
    - o Quantity determined by control specimen weight gain
  - Specimens were Type 304 in as-received or furnace sensitized (2 hours at 650°C) conditions
  - Specimens were exposed in air to cyclic AH between about 15 and 30 g/m^3 at various temperatures
  - Specimens were not contacted by liquid water during exposure so SCC would only occur by salt deliquescence

Test Results

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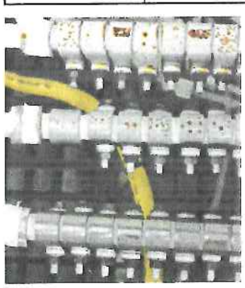
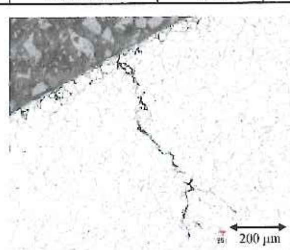
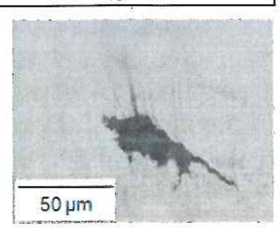
Temperature (°C)	RH Range (%)	Exposure Time	SCC Observed?	Lowest salt concentration at which SCC was observed
27	56-100	8 months	No	N/A – salt deliquesced and drained off
35	38-76	4 – 12 months	Yes	0.1
45	23-46	4 – 12 months	Yes	0.1
52	16-33	2.5 – 8 months	Yes	1
60	12-23	6.5 months	Yes	10



Pitting on specimens at 10 g/m^2 (top), 1 g/m^2 (middle), and 0.1 g/m^2 (bottom)



Cross section of sensitized, 0.1 g/m^2 specimen at 45°C after 4 months



Top view of sensitized, 10 g/m^2 specimen at 60°C for 6.5 months

C-Ring SCC Testing

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- Test objective: U-bend specimens represent a highly strained state, 13-14% at the apex. These may not be representative of canister conditions. SCC initiation at lower strain levels was evaluated using C-ring specimens.
- Test methodologies:
  - Specimens fabricated following ASTM G38-01 and deposited with 1 or 10 g/m^2 of salt
  - Specimens were strained to slightly above yield stress (~0.4% strain) or 1.5% strain, as measured by strain gage
  - Specimens were exposed at conditions of 35°C and 72% RH, 45°C and 44% RH, and 52°C and 32% RH (AH ~ 30 g/m^3 at each temperature)

Test Results

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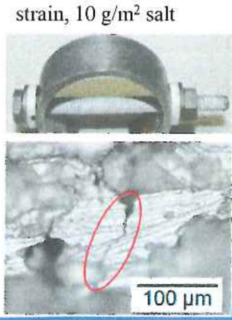
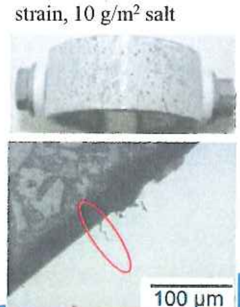
Temperature (°C)	RH (%)	AH (g/m^3)	Salt Concentration (g/m^2)	Strain (%)	Exposure Time (months)	Crack Initiation
35	72	29	1	0.4	2	No
			10	0.4	3	Sensitized only
45	44	29	1	0.4	3	No
			10	0.4	3	No
				1.5	2	Sensitized and as-received
52	32	29	1	0.4	2	Sensitized and as-received
			10	0.4	3	Sensitized only
				1.5	2	Sensitized and as-received

Sensitized, 35°C, 0.4% strain, 10 g/m^2 salt



As-received, 45°C, 1.5% strain, 10 g/m^2 salt



Sensitized, 52°C, 0.4% strain, 1 g/m^2 salt

Conclusions from Chloride Salt Tests

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- Between 35 and 80°C, SCC initiated by deliquescence of sea salt is observed on Type 304 stainless steel when RH is higher than about 20 to 30%, which is slightly above measured DRH for $CaCl_2$. At lower temperatures, this RH may be reached at AH well below 30 g/m^3.
- SCC initiation is observed at salt quantity as low as 0.1 g/m^2, but seems more extensive at higher amounts. The quantity of 0.1 g/m^2 is not considered to be a threshold, but only the lowest value tested.
- SCC initiation is observed at strain as low as 0.4%, where the stress is thought to be close to the yield stress. The extent of cracking increases with increasing strain.
- Sensitized material seems more susceptible to SCC than material in as-received condition.

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Backup

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TESTS WITH CHLORIDE SALTS

Chloride Salts Deliquescence Testing

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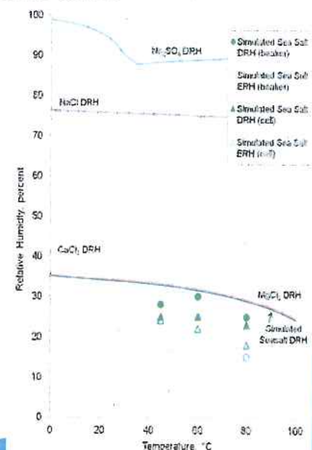
- Test objective: Confirm humidity above which sea salt and constituents will deliquesce (DRH) and compare to calculated values
- Test methodologies:
  - Salt in beakers
  - Conductivity cell impedance

45°C, 25% RH

45°C, 31% RH

- Test result: Measured DRH for simulated sea salt was between about 20 and 30% from 45 to 80°C, slightly above that of $CaCl_2$ and close to calculated values



Sea Salt Composition (wt. %)				
NaCl	$MgCl_2$	Na_2SO_4	$CaCl_2$	Others
58.5	26.5	9.8	2.8	2.4

Elevated Temperature SCC Testing

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- Test objective: Evaluate SCC susceptibility in the temperature range of 60 to 80°C
- Test methodology:
  - Deposited 10 g/m^2 of sea salt on ASTM G30 U-bend specimens
  - Exposed specimens in air at different humidity levels

Test Conditions			
Temperature (°C)	Relative Humidity (%)	Absolute Humidity (g/m^3)	Maximum Test Duration (Months)
60	22	29	1
	25	33	2.75
	30	39	5.75
	35	46	1
	40	52	1.5
80	28	82	2.5
	35	102	2.25
	40	117	1

Test Results

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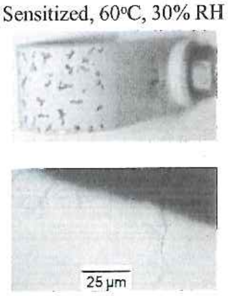
- SCC initiation observed at RH as low as 25% at 60°C and 28% at 80°C
- Sensitized specimens showed greater extent of cracking

Sensitized, 60°C, 30% RH

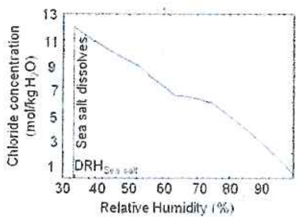


As-received, 80°C, 35% RH

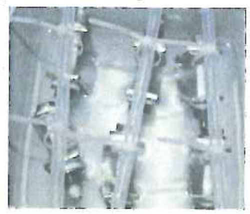
Sensitized, 80°C, 28% RH

High Humidity SCC Testing

- Test objective: Equilibrium chloride concentration in saturated solution decreases with increasing RH. Dilution of chlorides at high RH could reduce SCC susceptibility. Tests were performed at high RH to determine whether SCC could initiate.
- Test methodologies:
  - Immersed U-bend specimens in prepared saturated solutions at 30°C and 90% RH
  - Deposited 10 g/m[2] of sea salt on U-bend specimens for exposure at 30°C and 90% RH



Calculated chloride concentration in saturated sea salt solution as function of RH at 30°C



U-bend specimens immersed in solution

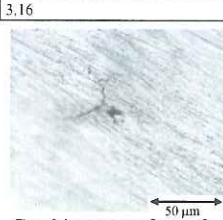
Test Results

- For specimens with deposited salt, salt quickly deliquesced and ran off sides of specimens with no SCC observed
- For immersed specimens in sea salt, NaCl, $MgCl_2$ and $CaCl_2$, pitting and SCC were observed within 5 weeks

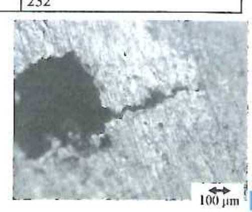
Chloride and Salt Concentrations in Saturated Solutions at 30°C and 90% RH

		Chloride Concentration (mol/kg H_2O)	Salt Concentration (g/kg H_2O)
Solution	Sea salt	2.71	203
	NaCl	2.79	163
	$MgCl_2$	3.01	306
	$CaCl_2$	3.16	232

Specimens immersed in sea salt after 5 weeks, as received (L); sensitized (R)



Cracking on surface of specimen immersed in sea salt



Cracking on surface of specimen immersed in $MgCl_2$

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TESTS WITH NON-CHLORIDE-RICH SPECIES

Literature Survey

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- Besides chloride salts, other atmospheric species could arise from industrial, agricultural, and commercial activities near ISFSI sites
- Survey of atmospheric monitoring data in U.S. identified common species containing ammonium, sulfate, and nitrate ions
- Representative set of species were selected for testing:
  - Ammonium sulfate – $(NH_4)_2SO_4$
  - Ammonium bisulfate – NH_4HSO_4
  - Ammonium nitrate – NH_4NO_3
  - Fly ash – class F, mostly alumina, silica, and iron, less than 20% lime
- Tests were also performed with chloride and non-chloride-rich salt mixtures: NH_4NO + NaCl

Deliquescence Testing

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- Beaker and impedance cell methodologies, similar to chloride salt testing
- Measured results are consistent with calculations made by thermodynamic software
- $(NH_4)_2SO_4$ and fly ash have very high DRH. DRH for other species is lower but still somewhat higher than that of sea salt

DRH in Temperature Range of 35 – 60°C (%)									
Pure Salts and Salt Mixture	NH_4HSO_4	NH_4NO_3	$(NH_4)_2SO_4$	Fly Ash	$(NH_4)_2SO_4 + NH_4NO_3$ Mole Ratio			NH_4NO_3 + NaCl Mole Ratio	
					0.5	1.0	3.0	3.0	6.0
Calculated DRH, percent	35-40	45-55	75-80	N/A	50-65	50-65	50-65	N/A	N/A
DRH by Conductivity Cell, percent	35-45	40-55	~80	No deliq.	50-60	50-60	50-60	N/A	N/A
DRH by Beaker, percent	30-45	40-60	~80	No deliq.	50-70	50-70	50-70	30-35	30-35

SCC Testing – Non-Chloride Species Only

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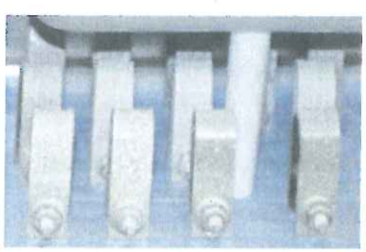
- Test objective: Determine if SCC could initiate for austenitic stainless steel exposed to the non-chloride-rich species
- Test methodology:
  - Deposited large quantities (>100 g/m^2) of species on ASTM G30 U-bend specimens by spray bottle. Other specimens were buried in bins of solid salt.
  - Exposed specimens in air at 45°C and 44% RH for 6 weeks followed by 35°C and 72% RH for 1 month (AH ~ 30 g/m^3 at both temperatures)



Test Results

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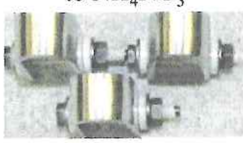
- No cracking observed on specimens exposed to any species, even above measured DRH
- Most specimens appeared near pristine after removing salt, except for extensive general corrosion on specimens exposed to NH_4HSO_4
  - Deliquescent solution pH for most species is in range of about 4 to 5
  - Deliquescent solution pH for NH_4HSO_4 is about -1 to -2

Specimens exposed to NH_4NO_3



Specimens exposed to $NH_4NO_3 + (NH_4)_2SO_4$ mixture

Specimens exposed to NH_4HSO_4

SCC Testing – Chloride and Non-Chloride Salt Mixtures

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- Test objective: Determine if SCC could initiate for austenitic stainless steel exposed to chloride-rich and non-chloride-rich mixed salts
- Test methodology:
  - Deposited NH_4NO_3 + NaCl mixtures on ASTM G30 U-bend specimens by spray bottle. Solution pH was about 3.5 to 4.
  - Amount of chlorides on specimens were less than 10 g/m^2.
  - Exposed specimens in air at 45°C and 44% RH for up to 4 months

Specimen Type	Molar Ratio of NH_4NO_3 to NaCl	Amount of NH_4NO_3 and NaCl Deposited (g/m^2)	Calculated Amount of NaCl Deposited (g/m^2)
As-Received	3	54	6.4
	6	74	4.9
Sensitized	3	62	7.4
	6	83	5.5

Test Results

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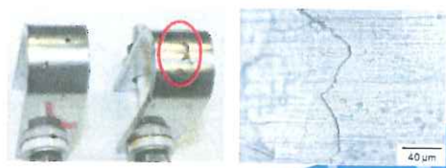
- Extensive cracking on specimens, larger cracks than any other specimens in test program
- Presence of nitrate does not appear to inhibit cracking in these test conditions

Specimens exposed to NH_4NO_3 + NaCl with NO^{3-}:Cl^- mole ratio of 3.0

Specimens exposed to NH_4NO_3 + NaCl with NO^{3-}:Cl^- mole ratio of 6.0



Conclusions from Non-Chloride Species Tests

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- Austenitic stainless steel did not appear susceptible to SCC when exposed to the ammonium, sulfate, and nitrate bearing species or fly ash evaluated in this test program, even above the species' DRH.
- Crack initiation was observed for mixtures of the chloride and non-chloride species, even with the presence of a large quantity of nitrate.

#4

Dry Cask Storage System Canister Weld Residual Stress Finite Element Analysis

Technical Letter Report: ML13330A512

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CISCC RIRP January 24, 2014

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Outline

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- Purpose:
  - Assess fabrication stresses for potential impact on chloride-induced stress corrosion cracking (CISCC)
- General weld residual stress (WRS) analysis:
  - FE modeling procedure
- Canister-specific WRS analysis:
  - Representative canister geometry and fabrication
  - Weld residual stress analysis
- Summary

Weld Residual Stress FE Modeling Procedure

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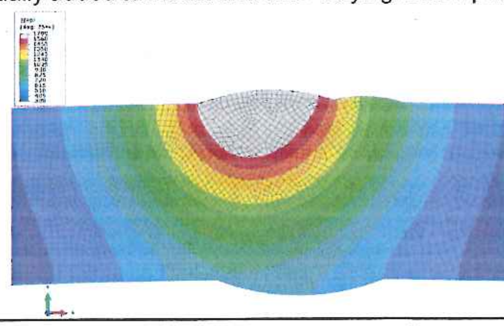
- 2-D, sequentially coupled thermal-structural analysis in Abaqus Standard version 6.11
- Circumferential Welds: Axisymmetric quadrilateral elements
- Longitudinal Weld: Plane-strain quadrilateral elements
- **Thermal Analysis**:
  - Weld beads sequentially added to model and time-varying heat input applied
  - Used typical heat energy input parameters for stainless steel SAW



Weld Residual Stress FE Modeling Procedure

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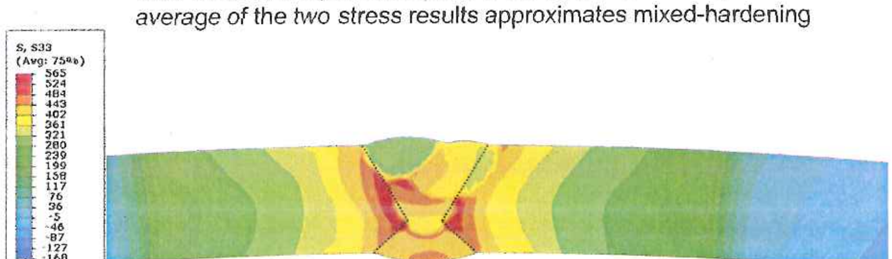
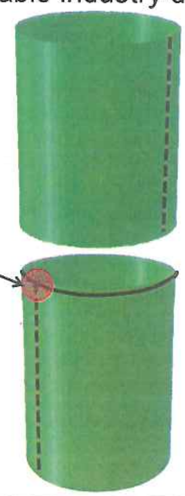
- **Structural Analysis**
  - Temperature results from heat transfer solution mapped to a structural model to calculate the strain due to thermal expansion/contraction and the resulting stress field
  - Both Isotropic and kinematic hardening rules were applied (separately) for each weld analyzed
    - Real materials experience a mix of these two behaviors; the *average of the two stress results* approximates mixed-hardening



Canister Geometry and Fabrication

- Specific data not available – dimensions and procedures applied based on assumptions from publicly available industry data
  - OD: 1.7 m
  - Length: 4.7 m
  - Thickness: 15.875 mm (5/8")
  - Material (base and weld): Austenitic stainless steel
- Welds modeled:
  - Longitudinal canister weld
  - Circumferential canister weld
  - Base plate weld
    - Not in presentation
  - Lid closure weld
    - Not in presentation

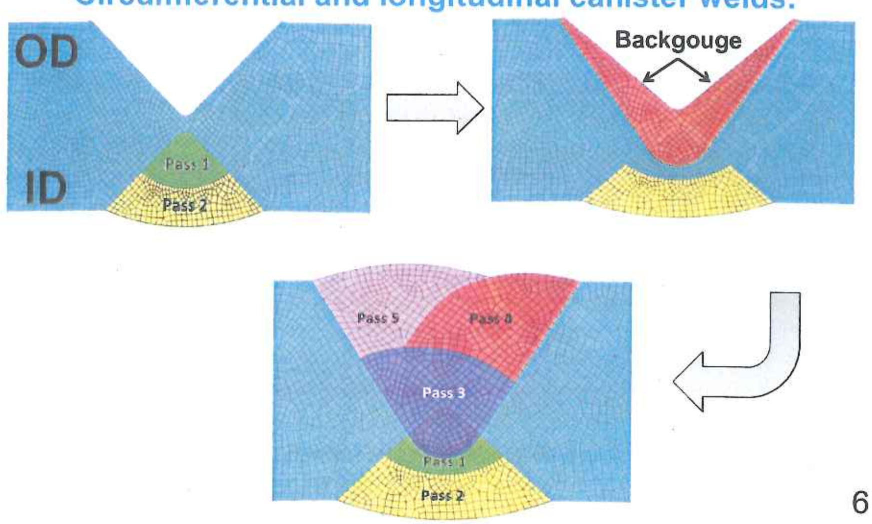
No interaction modeled between welds



Note:
3D representation for illustration only.
All analyses are 2D

Weld Geometry & Sequence

Circumferential and longitudinal canister welds:



Circumferential Weld – Hoop Stress

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Isotropic Hardening

Kinematic Hardening

Outside surface of canister

Circumferential Weld Through-Wall Residual Stress

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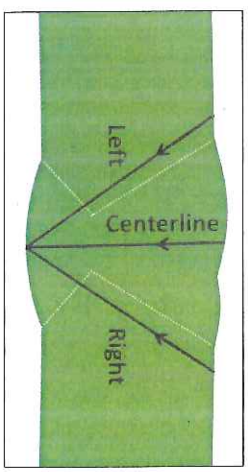

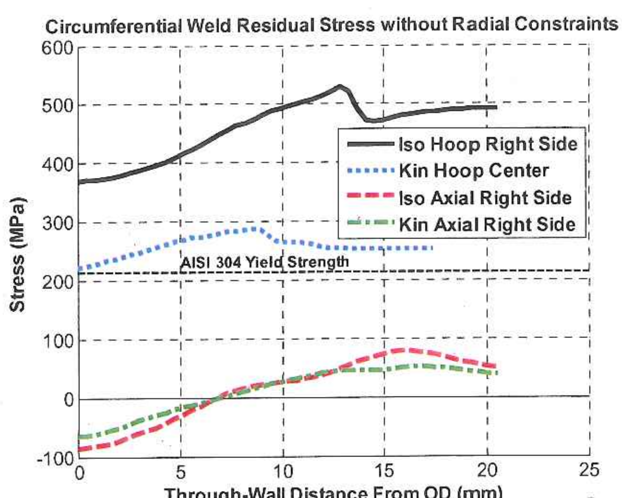

Longitudinal Weld – Axial Stress

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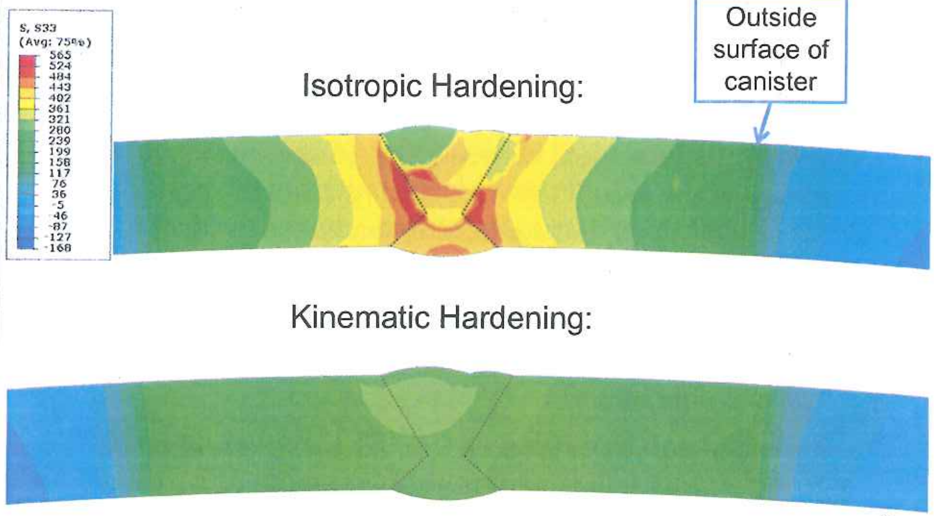

Longitudinal Weld – Through-Wall Residual Stress

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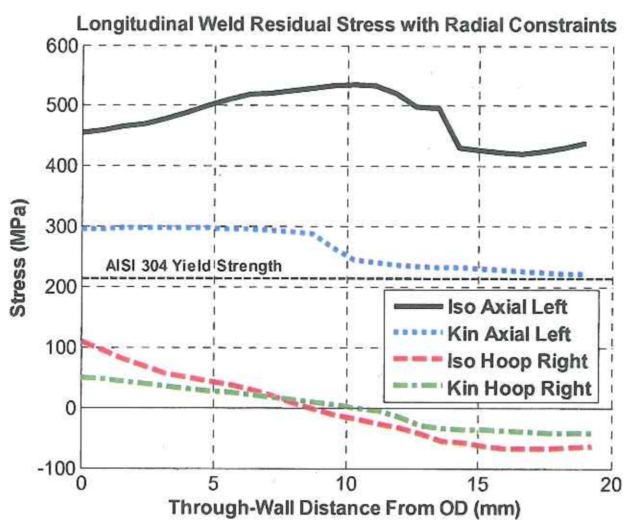

Summary

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- The **circumferential** storage canister weld resulted in high tensile **hoop** stresses in the weld and HAZ, remaining **near or above yield stress throughout the thickness**
- The **longitudinal** weld induced high tensile residual stresses in the **axial** direction, also remaining near or above yield stress throughout the thickness of the canister
- Results for both welds suggest:
  - A potential CISCC flaw would grow perpendicular to the weld direction
  - No indication through-wall CISCC crack would arrest or slow growth (no compressive stress region in/near the weld)

Summary, cont'd

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- Hardening laws influence stress
  - Average isotropic/kinematic results may be better approximation
- There may be sufficient stress for CISCC to occur in DCSS canisters in susceptible environments
- A more extensive 3D moving arc analysis that considered fabrication stresses and assessed the interaction between welds would refine the understanding of residual stresses
- A corresponding experimental program could provide validation of these results