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Investigations of Stress Corrosion Cracking of Spent Fuel Dry Storage Canisters Used for Long-Term Storage

IAEA International Conference on Management of Spent Fuel From Nuclear Power Reactors

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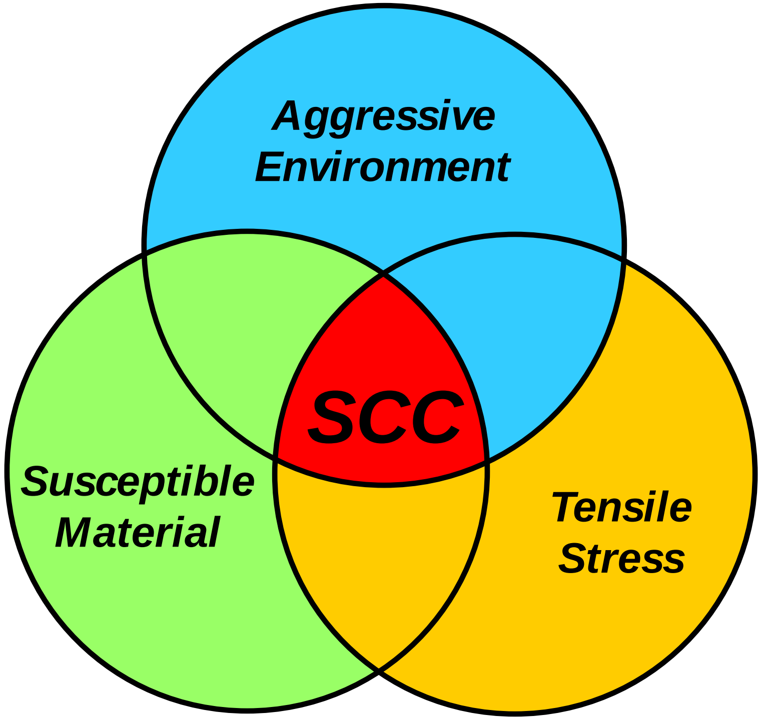
19 June 2015
Vienna, Austria

SAND2015-4430 C

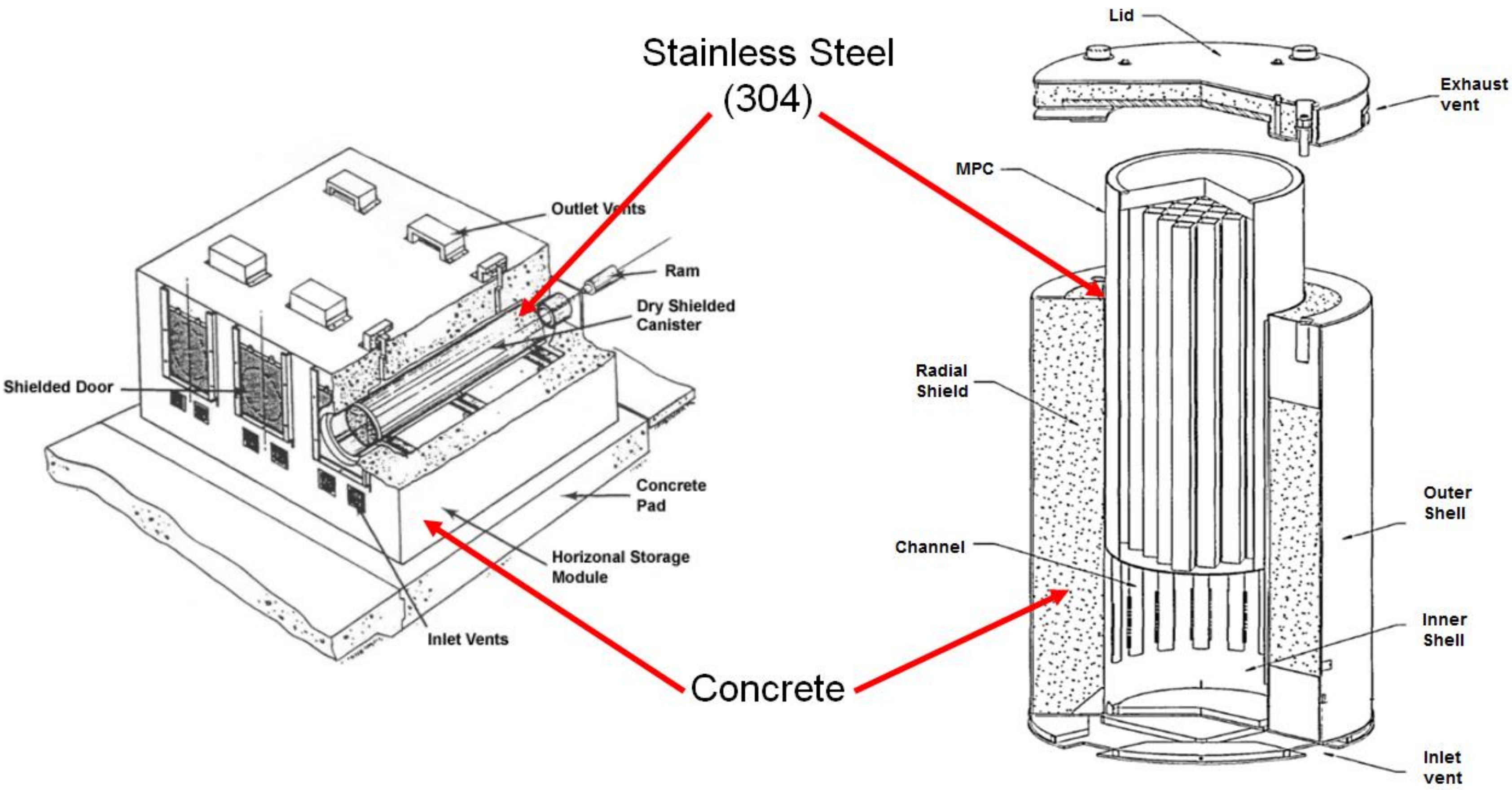
Degradation Mechanism of Concern: Stress Corrosion Cracking (SCC)



<u>Questions that need to be answered</u>:

1. Is the material of construction for fielded interim storage containers susceptible?
2. Will a chloride bearing environment form on the surface of the containers?
3. Is there a sufficiently large tensile stress to support crack initiation and propagation in fielded interim storage containers?

We Have Numerous Types of Dry Cask Systems.



Horizontal (e.g., Areva TN) **Vertical (e.g., Holtec)**

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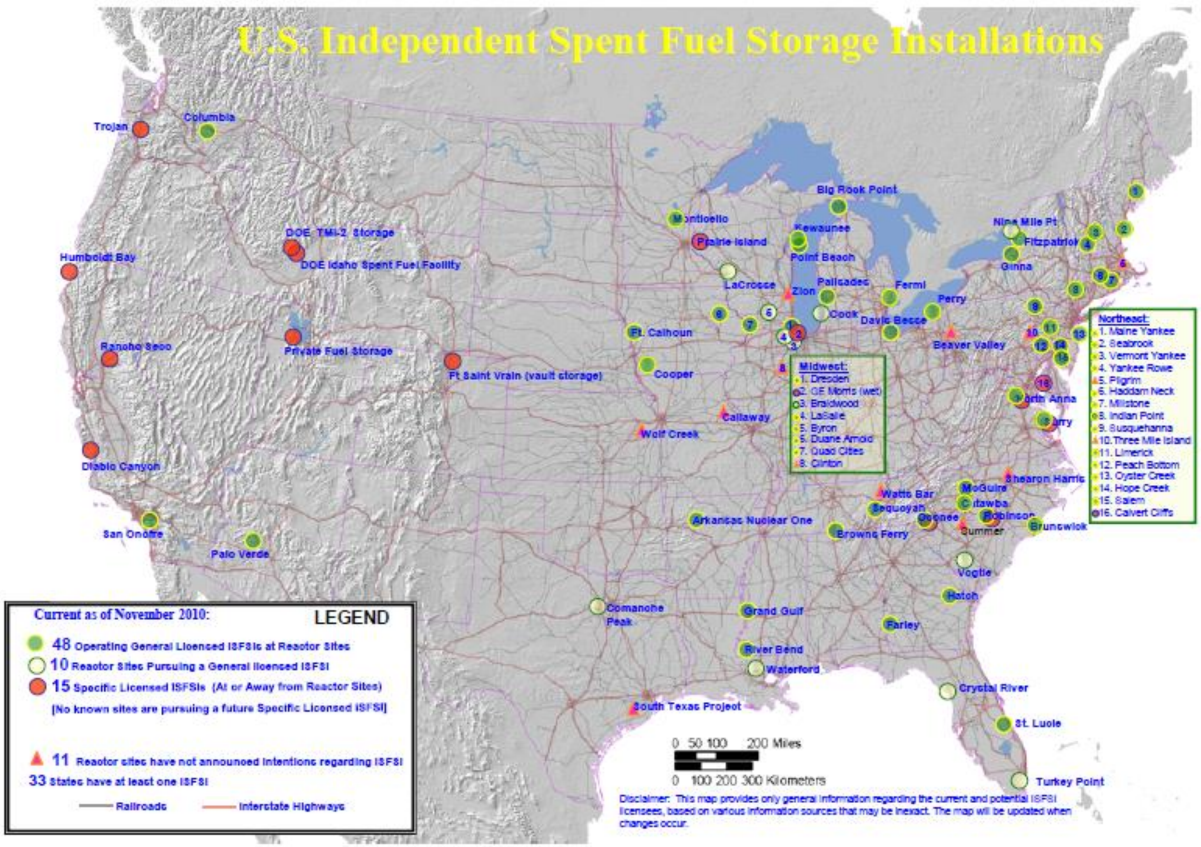
Dry Casks are Located in Diverse Environments.

- **Many interim storage sites are located in marine environments where significant deposition of marine aerosols is anticipated**



What is on the Surface Of Fielded Containers?

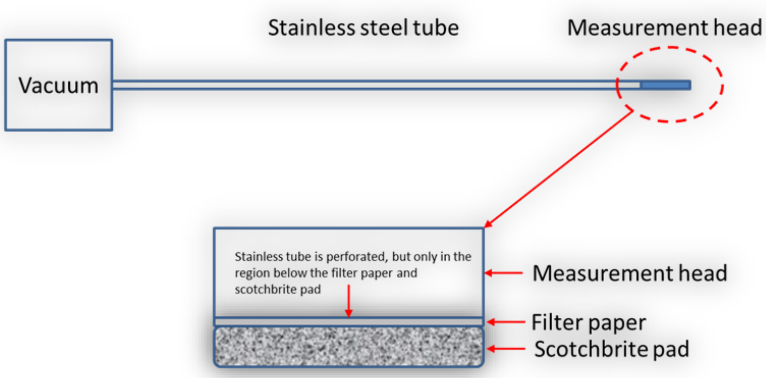
- **EPRI and the DOE have cooperated in an effort to view and sample the dust on the surface of the containers at three ISFSI sites**
  - Calvert Cliffs (with support from Areva TN) – Brackish water
  - Hope Creek (with support from Holtec) – Brackish water
  - Diablo Canyon (with support from Holtec) – Marine (Ocean)

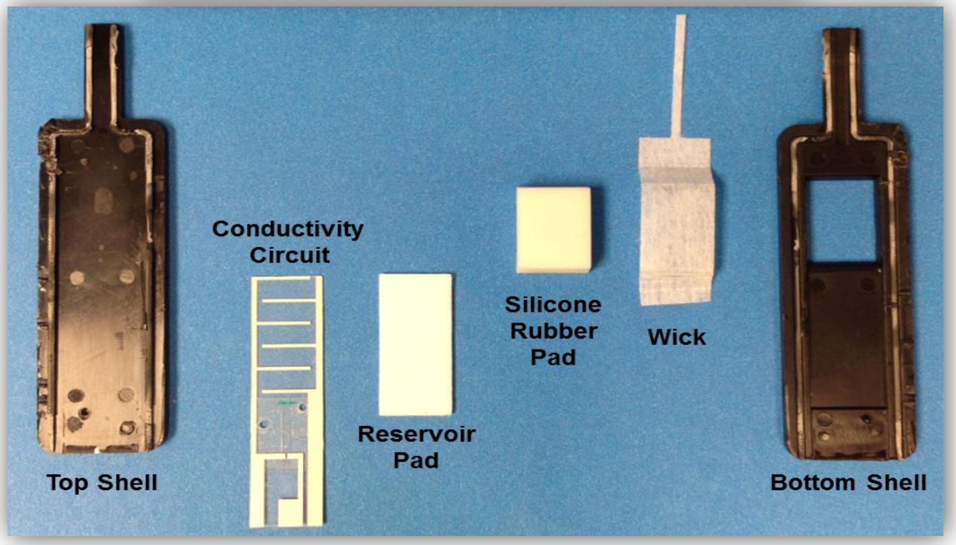
Surface of 19.5 yr old container at Calvert Cliffs

Images from July 27, 2012, supplemental information letter submitted from CENG to the NRC (Adams document no. ML12212A216)

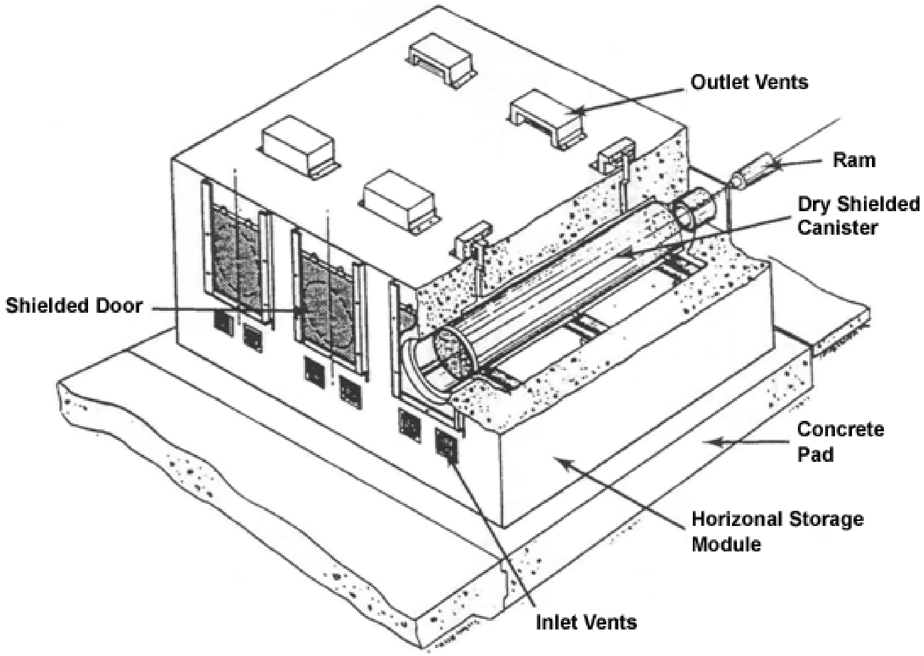
Both Wet And Dry Sampling Techniques Were Employed

- Similar procedures were used at all three utilities
- Dry sampling was accomplished via an abrasive pad rubbed on the container surface
- Wet sampling was performed using a device known as the SaltSmart™





Calvert Cliffs – Horizontal Storage System



Calvert Cliffs

Water soluble salts:

- 30 minute leach with deionized water
- Cations: Ca_2^+ >> Na^+, Mg_2^+, K^+
- Anions: SO_4^{2-} >> NO_3^- > Cl^-

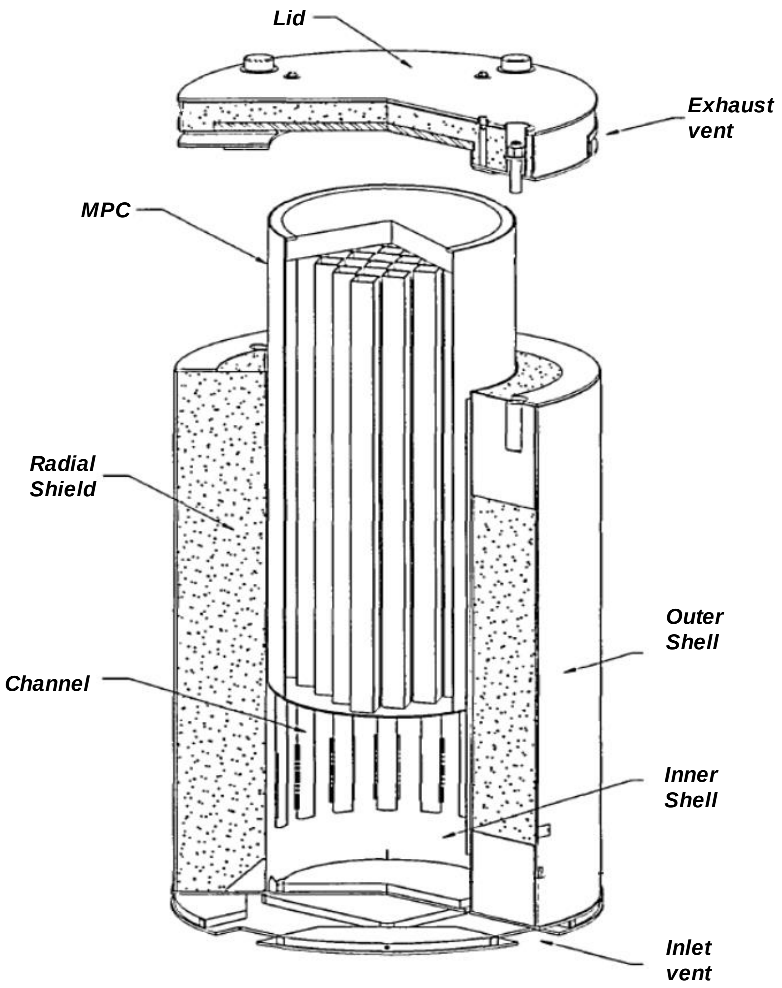
Salts do not appear to have a large marine component:

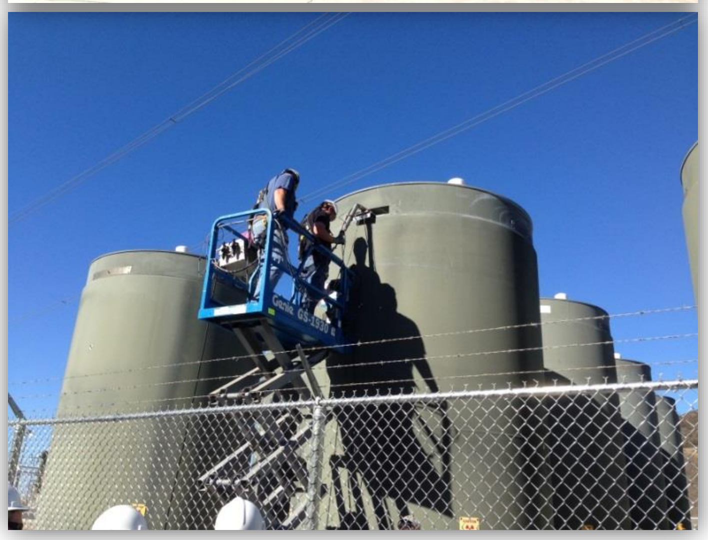
- Low Na^+, Cl^-, high Ca^{2+}, SO_4^{2-}
- Conversion after deposition via particle-gas conversion reactions? Does not explain low Na.
- Preferential deposition of deliquesced Ca-Cl salts, followed by conversion to sulfates and chloride-loss?

Ion	EPRI #1 filter	EPRI #1 pad	EPRI #4 filter	EPRI #4 pad
Na^+	19.2	14.8	n.d.	11.3
K^+	18.1	13.7	1.05	7.75
Ca^{+2}	77.1	20.6	24.1	153
Mg^{+2}	16.9	6.0	1.95	17.6
F^-	0.30	0.61	n.d.	n.d.
Cl^-	5.64	n.d.	n.d.	3.10
NO_3^-	21.3	9.09	4.34	14.2
SO_4^{-2}	89.7	51.5	48.0	291
PO_4^{-3}	6.68	2.05	0.45	n.d.
Total mass, µg	255	118	80	498

From: *C.R. Bryan, D.G. Enos "Understanding the Environment on the Surface of Spent Nuclear Fuel Interim Storage Containers", SAND2013-8487C, October, 2013*

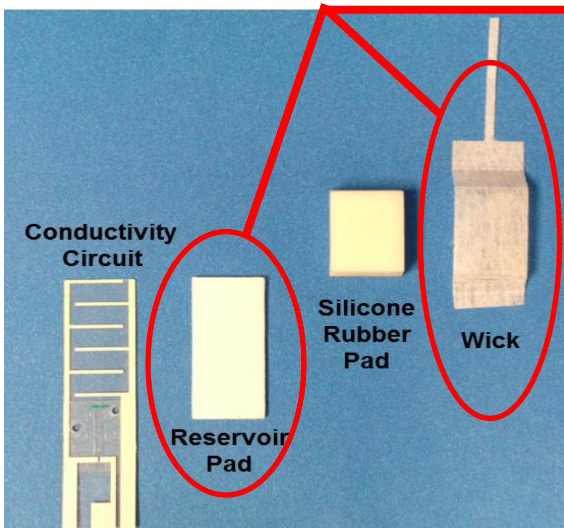
Hope Creek and Diablo Canyon – Vertical Storage System





Typical Wet Sample Results Hope Creek

- **Solutions extracted from SaltSmart reservoir pads**
  - Soluble components largely calcium, sulfate, and nitrate
  - Little chloride
- **Complicating factors**
  - Extraction efficiency in the field
  - Pad to container contact patch variation



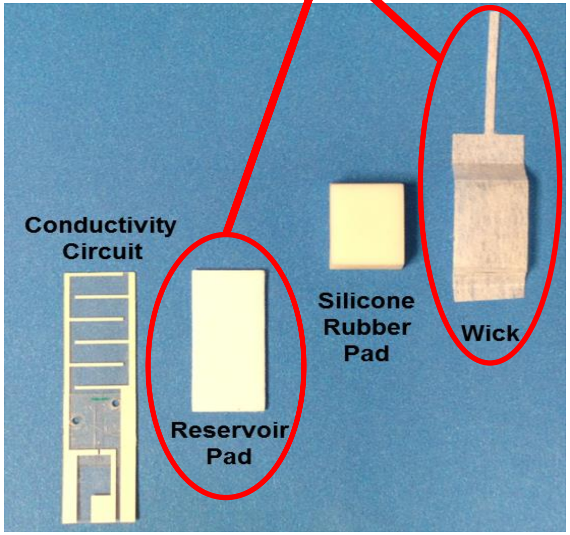
Sample #	Location	Depth (cm)	Temp (°C)	[Cl⁻] (mg/m²)
144-008	Side	396	34	3
144-009	Side	229	47	2.9
144-010	Side	30	57	3.9
144-013	Top	0	59	14
144-014	Top	0	61	60
144-003	G.S	--	--	1.6
144-004	G.S	--	--	2.5
145-006	Side	396	21	7.3
145-007	Side	229	38	7.1
145-014	Side	30	55	4.1
145-013	Top	0	79	7.5
145-002	G.S	--	--	2.2
145-011	Blank	--	--	2.5

G.S. = Gamma Shield

From: *C.R. Bryan, D.G. Enos "Analysis of Dust Samples Collected from Spent Nuclear Fuel Interim Storage Containers at Hope Creek, Delaware and Diablo Canyon, California", SAND2014-16383, July, 2014*

Typical Wet Sample Results Diablo Canyon

- **Solutions extracted from SaltSmart reservoir pads**
  - Sea salt aerosols of NaCl and Mg sulfate with trace amounts of K and Ca
- **Complicating factors**
  - Extraction efficiency in the field
  - Pad to container contact patch variation



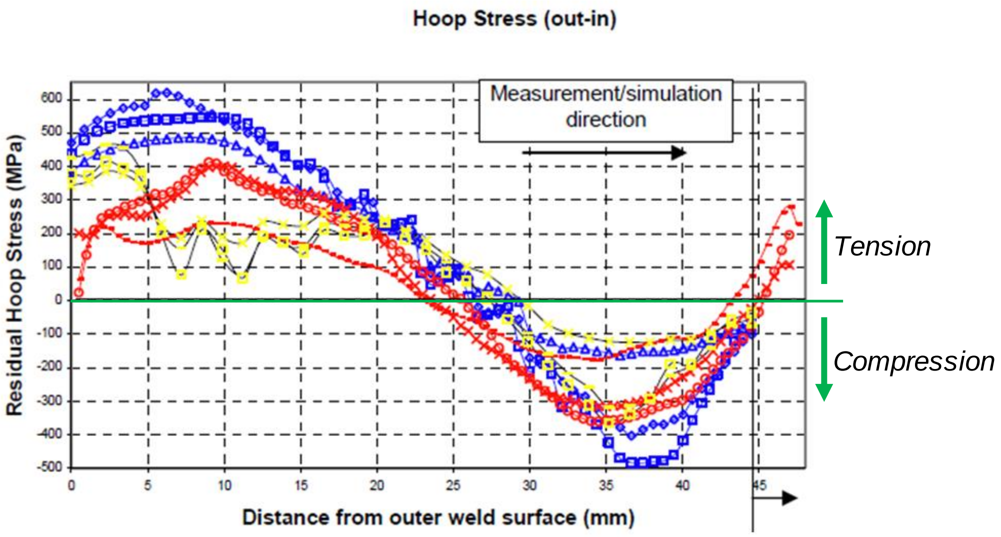
Sample #	Loc.	Depth (cm)	Temp (°C)	Cl^- (mg/m^2)
123-003	Side	426	49	4.8
123-004	Side	350	79	3.6
123-005*	Side	320	87	2
123-002	G.S.		—	58
123-010	Blank		—	25
170-007*	Side	320	81	4.2
170-008*	Side	289	84	2.9
170-009*	Side	274	87	2.5
170-002	G.S.	—	—	13
Blank	—	—	—	4.2
Blank	—	—	—	2.3
Blank	—	—	—	3.8
Blank	—	—	—	1.5

**Wick adhered to silicone pad, and reservoir only partially saturated*

From: *C.R. Bryan, D.G. Enos "Analysis of Dust Samples Collected from Spent Nuclear Fuel Interim Storage Containers at Hope Creek, Delaware and Diablo Canyon, California", SAND2014-16383, July, 2014*

Is There Going to be Sufficient Tensile Stress?

- **Is there sufficient residual stress within the container wall to support propagation of a through-wall crack?**
- **Many complicating factors**
  - Weld procedure (start/stop, technique, etc.)
  - Weld repairs



K. Ogawa, et al, "Measuring and Modeling of Residual Streses in Stainless Steel Girth Welds", PVP 2008 61542, July 27-31, 2008, Chicago, IL.

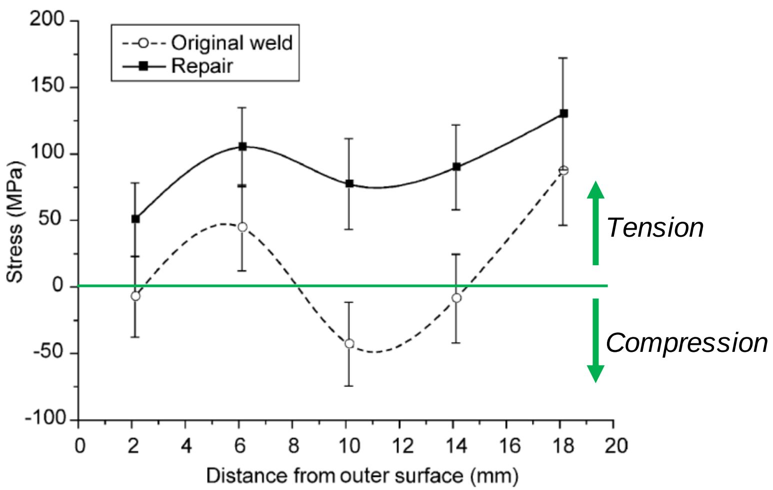
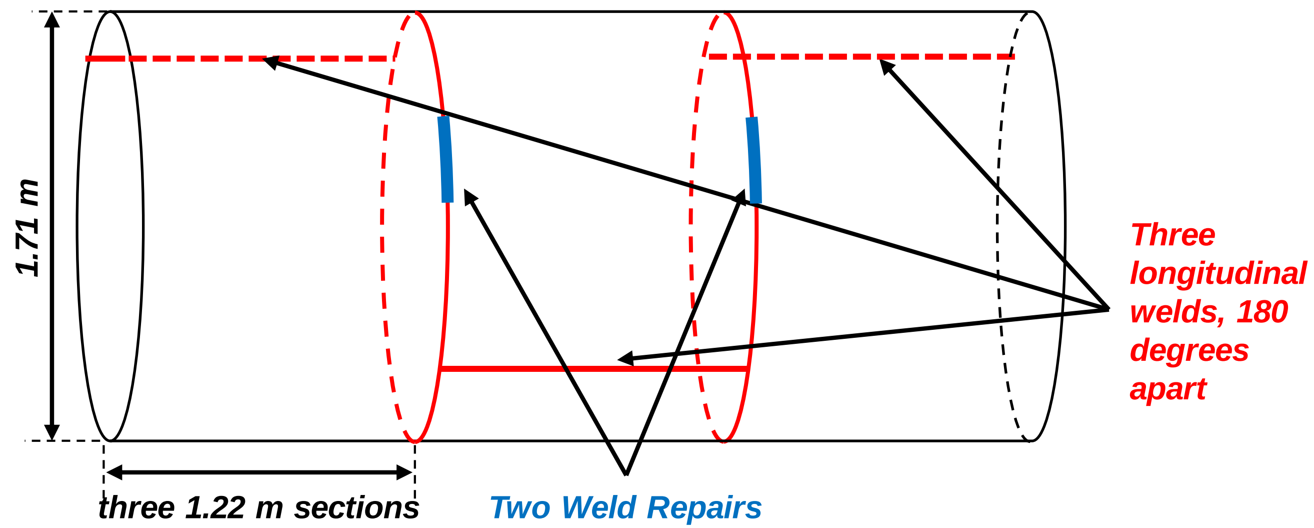


Fig. 14. Hydrostatic residual stress profile (17.5 mm from weld centre-line).

L. Edwards, et al, "Direct Measurements of the Residual Stresses near a "Boat-Shaped" repair in a 20mm Thick Stainless Steel Tube Butt Weld", International Journal of Pressure Vessels and Piping, 82 (2005), pp. 288-298

Full Scale Diameter Mock-Up Assembled to Directly Measure Residual Stresses



- ***Wall material: 304 SS welded with 308 SS***
- ***Wall thickness, overall diameter, weld joint geometry: standard geometry for NUHOMS 24P***
- ***Welds:***
  - *Full penetration and inspected per ASME B&PVC Section III, Division 1, Subsection NB (full radiographic inspection)*
  - *Double-V joint design, Submerged Arc welding process*
- ***What are we going to measure?***
  - *Weld residual stress state (deep hole drilling, contour measurement, x-ray diffraction)*
- ***Once analyzed, the container will be cut and used as samples for further analysis***

Summary and Future Direction:
Understand When and Where SSC may Occur

- **Large existing fleet of storage containers made from welded 304SS, located at both marine and inland sites**
  - Material known to be susceptible to SCC
  - Chloride bearing salts likely in some locations
  - Residual stresses at welds could be significant and tensile in nature

- **Moving Forward, research will focus on**
  - Understanding potential brine chemistry on container surface
  - Quantifying residual stress state at welds and weld repairs in full scale mock-container
  - Identify the most important parameters for evaluating canister SCC penetration times
  - Develop Non-Destructive Analysis tools detect cracks.
  - Exploring susceptibility of welded material to both localized corrosion and stress corrosion cracking initiation and propagation

Acknowledgements

At Sandia National Labs

- David Enos – Corrosion Chemistry
- Charles Bryan – Brine chemistry and its evolution
- Kirsten Norman, Sam Lucero – Sample preparation and analysis

EPRI

- John Kessler and Keith Waldrop – ISFSI inspections/sample collection
- Shannon Chu – CISCC Task group

Industry

- Laszlo Zsidai (Holtec) – sampling at Hope Creek and Diablo Canyon
- Bill Bracey (Areva-TN) – sampling at Calvert Cliffs

THANK YOU