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An Evaluation of Stress Corrosion Cracking (SCC) of Stainless Steel Canister in Marine Environment for Long-Term Dry Storage of Spent Nuclear Fuel

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Disclaimer

The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of any licensing action that may be under consideration at the NRC.

Introduction

- Assess the potential of the SCC susceptibility of the canister in the marine environment, given limited information and data obtained from:

  Central Research Institute of Electric Power Industry (CRIEPI) of Japan, Electric Power Research Institute (EPRI), and NRC

- Discuss key controlling issues:
  - ***temperature***
  - ***relative humidity (RH)***
  - ***amount of salt deposits***
  - ***initiation and propagation of crack***

- Summarize current understanding and uncertainties

SCC Should Not Adversely Impact Licensing Basis

- Prevent nuclear criticality (in transportation if moderator exclusion is not credited)

- Maintain confinement of radioactive material

- Maintain the retrievability of spent nuclear fuel

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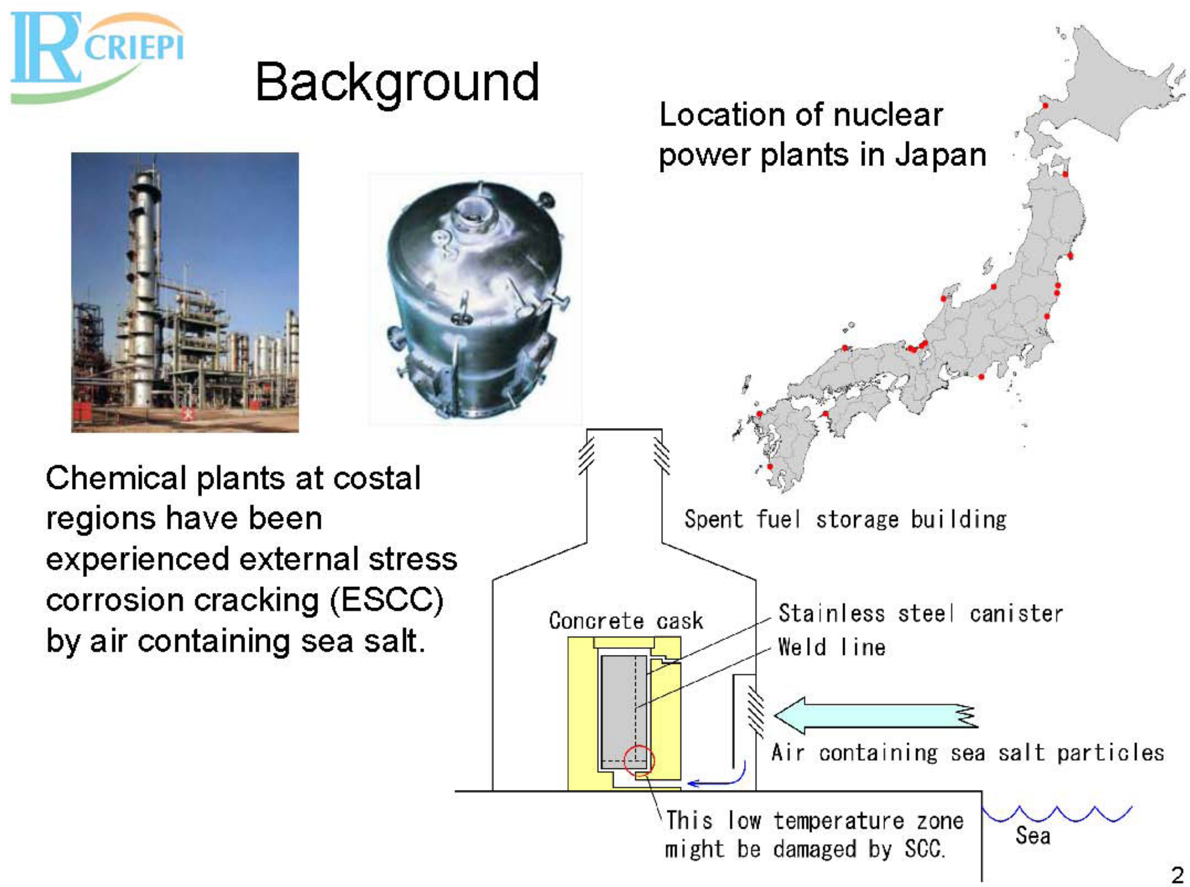
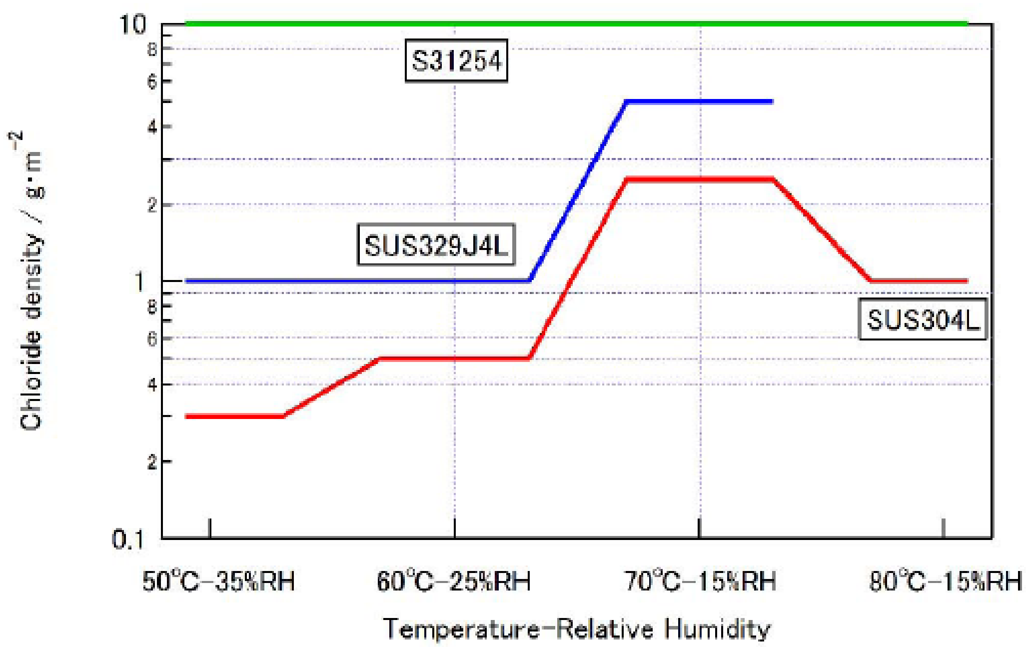
Temperature



- Air inlet area is at lower temperatures (Tani, et al., 2010).

Chloride density for Cracking



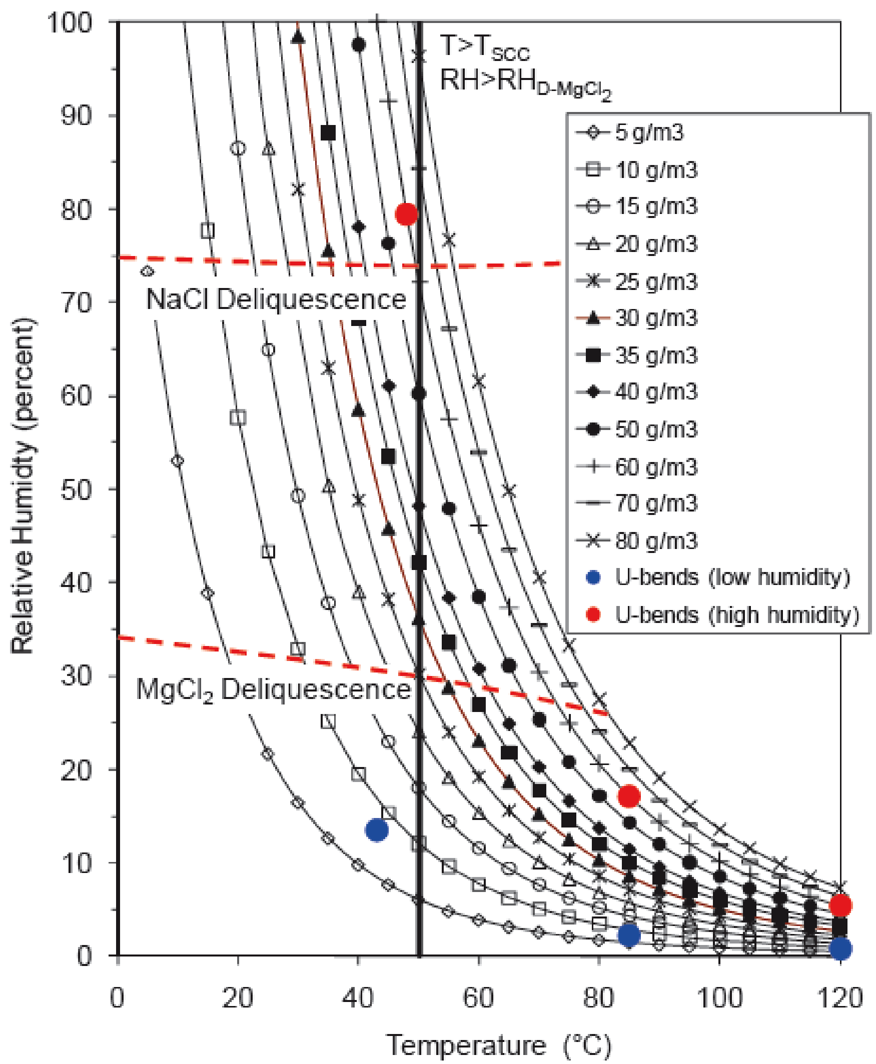
Yield stress was applied on specimens.

- Above a minimum RH of 15 % for SCC at 50, 60, 70, and 80 °C (Shirai, et al., 2011, copyright by the American Nuclear Society, ANS; Mayuzumi, et al., 2008; Kosaki, 2008)

(°F = °C×9/5 + 32)

- Insufficient information on cracking in terms of chloride density, temperature and RH

(e.g., RH 5 % at 80 °C case)



- NUREG/CR-7030 (Caseres and Mintz, 2010), three discrete temperatures, 43, 85, and 120 °C were used; SCC occurred at 43 °C only. U bend tests were done.
- Analog data under studies

Canister Surface Temperature

- T (°C) = –0.575×t + 89

  where t: time in year (Shirai, et al., 2011)

- SCC of SS304 type can occur at 80 °C and above a minimum RH = 15 % in about 40 years

(Unit: °C)

0 yr	10 yr	20 yr	30 yr	40 yr	50 yr
89	83	78	72	66	60
80	74	69	63	57	51
70	64	59	53	47	41

- Below 70 °C, RH may reach the proposed thresholds.
- Temperature varies daily and seasonally.

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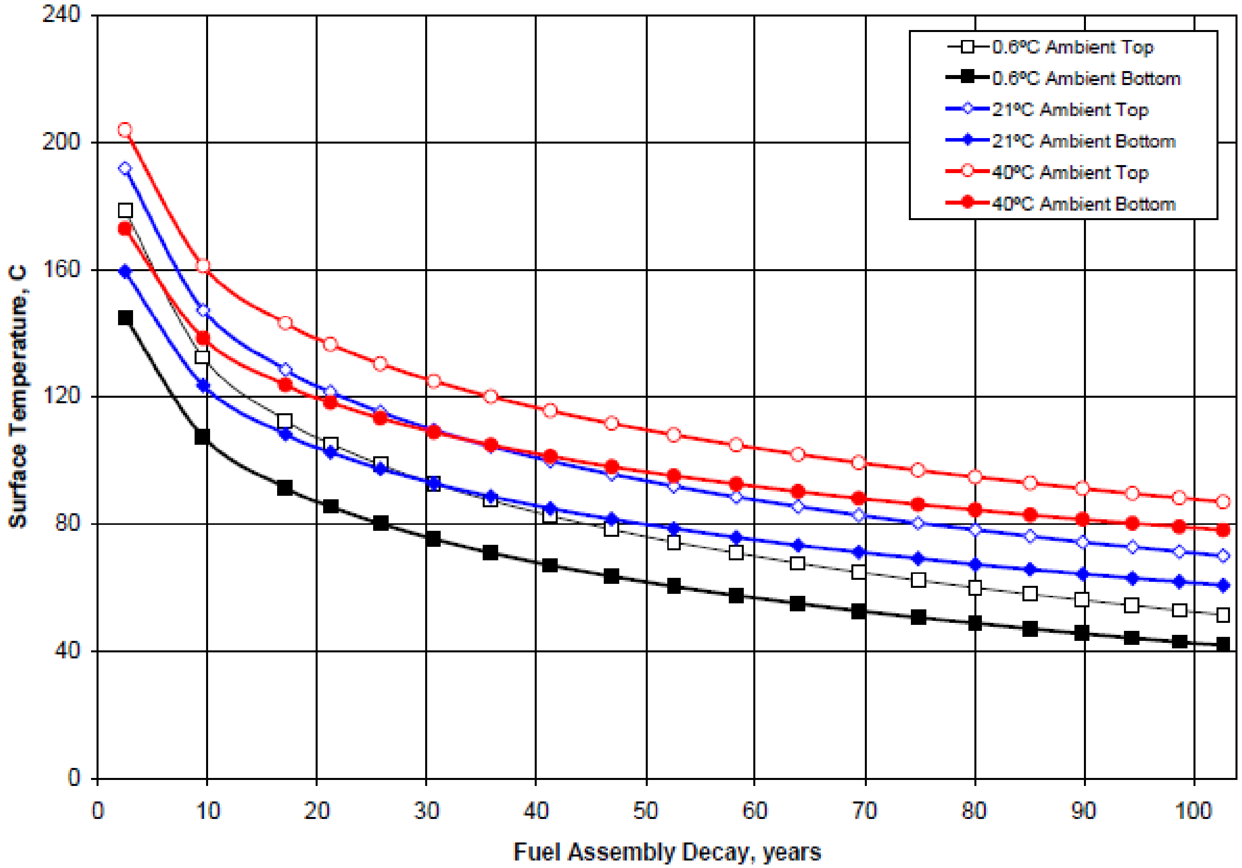
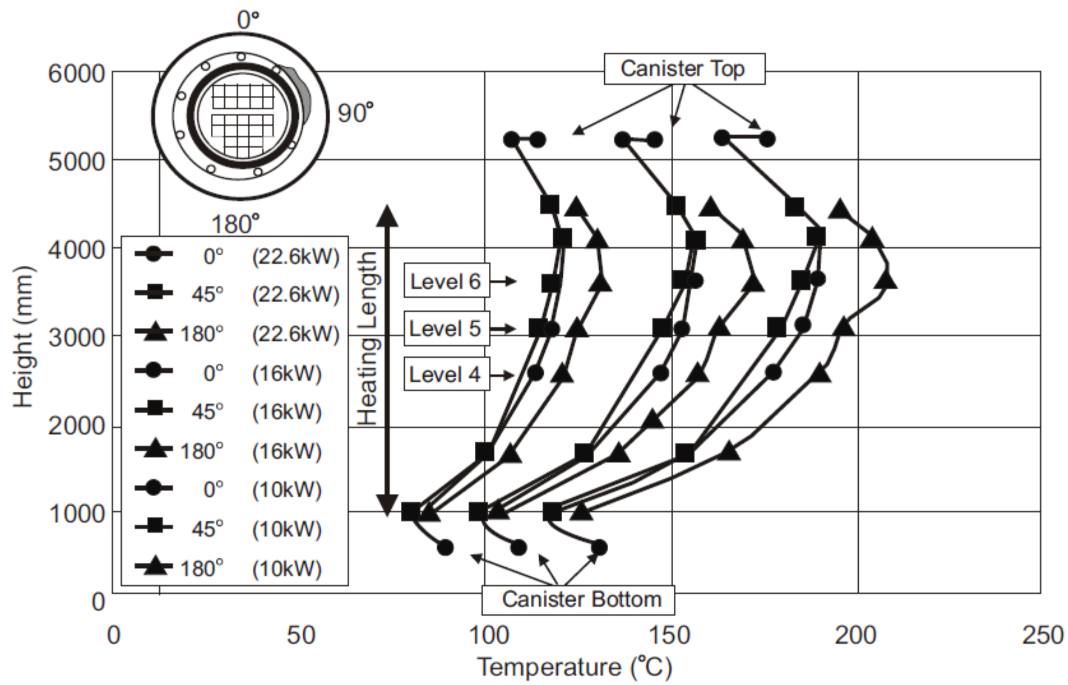
Canister Surface Temperature



- Canister surface temperature is sensitive to air temperature (EPRI, 2006)
- 1 kw per assembly for 24 assemblies, and installation time of 13.5 years

Canister Surface Temperature (continued)



The minimum temperature is 70 – 78 ºC (Takeda, et al., 2008, copy right by Elsevier; Shirai, et al., 2003)

Relative Humidity (RH)

CRIEPI

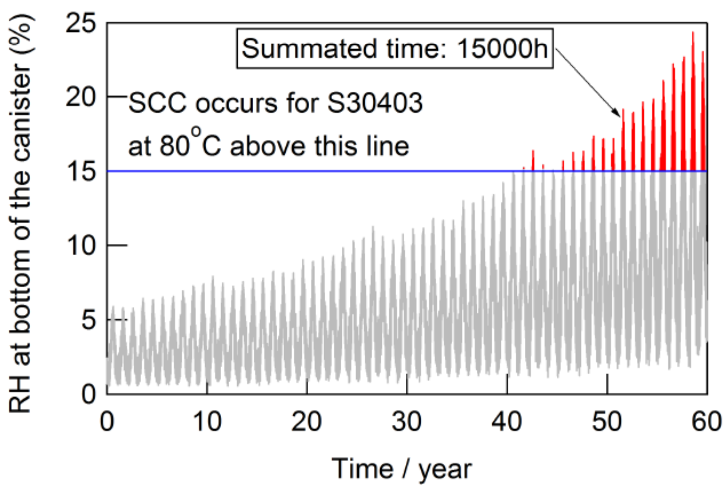
Example of crack growth evaluation

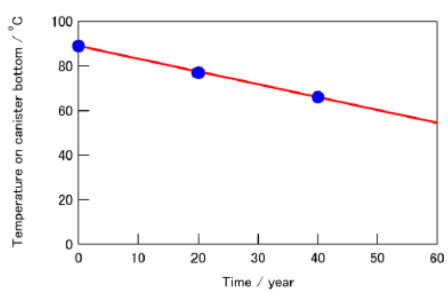
Calculated RH with data from Tsuruga weather station and data of heat decay test with model canister.

CGR: 1×10^{-11} m/s

19mm / 60years

0.5mm / 15000h





Heat decay of canister surface

(Shirai, et al., 2011, copyright by the ANS)

- At 80 °C, above a minimum15% deliquescence RH is likely due to mixed salt effects or other possibilities?

RH Calculation

Time(yr)	Canister bottom Temp(°C)	Saturated water content (g/m**3)	Env. absolute humidity(g/m**3)		Canister bottom RH(%)	
			Min	Max	Min	Max
0	89.0	404	3	23	0.7	5.7
10	83.3	325	3	23	0.9	7.1
20	77.5	265	3	23	1.1	8.7
30	71.8	213	3	23	1.4	10.8
40	66.0	167	3	23	1.8	13.8
50	60.3	131	3	23	2.3	17.6
60	54.5	102	3	23	2.9	22.5

RH60/RH0=	4.0	4.0

- Initial temperature and absolute humidity will determine RH.
- Max and Min are the Japan case.
- Absolute humidity limit: 30 g/m**3
  (RH = 7.4, 9.3, 11.3, 14.1, 18.0, 23.0, 29.3 for all time and temp)

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Average Morning and Afternoon Humidity for Kure Beach and Operating ISFSIs Located Near the Ocean

Month	Kure Beach, NC		Calvert Cliffs		Millstone		Oyster Creek		Connecticut Yankee		Maine Yankee	
	Morning	Afternoon	Morning	Afternoon	Morning	Afternoon	Morning	Afternoon	Morning	Afternoon	Morning	Afternoon
January	81	56	72	57	69	58	78	59	69	58	76	61
February	79	53	72	54	69	56	78	56	69	56	76	58
March	82	52	72	51	70	55	78	54	70	55	75	58
April	81	48	72	49	68	52	77	51	68	52	73	55
May	84	55	77	52	75	59	79	56	75	59	75	58
June	85	59	77	51	78	61	81	56	78	61	78	60
July	87	63	80	53	78	61	83	57	78	61	80	59
August	90	64	84	55	79	61	87	58	79	61	83	59
September	90	62	85	55	81	61	88	58	81	61	86	60
October	88	56	84	54	79	59	88	56	79	59	84	59
November	85	53	78	55	77	60	84	57	77	60	82	62
December	82	56	74	58	74	61	79	59	74	61	79	61
Average	85	56	77	54	75	59	82	56	75	59	79	59

(EPRI, 2006); less variation compared the Japan case

Relative Humidity on Canister Surface

- Diffusion and Convection of Moisture on the Canister Surface
  - Concentration diffusion
  - Thermal diffusion
  - Baro diffusion
  - Convection

- If the concentration diffusion is higher than the thermal diffusion and the baro diffusion, moisture pressure could be higher than the saturation value; or vice versa; and a boundary layer may form.

- Mixed salt effect on deliquescence relative humidity

Amount of Salt Deposits

Amount of Salt Deposition

$$Q = \{5.07 - 0.022\,(T - 30)\}\,(1.55\,t \times C/10000)^{1/2}$$

Q: amount of salt deposition (mg/m^2 as Cl^-)
T: temperature of canister surface (°C)
t: time (hour)
C: airborne salt concentration ($\mu g/m^3$ as Cl^-)

$T = -0.575\,t + 89$, t: time (year)

(Shirai, et al., 2011)

Amount of Salt Deposition: Calculated Values based on Shirai, et al. (2011)

Time (year)	Temperature (°C)	Amount of salt deposit (mg/m^2)
0.114 (10^3 hours)	89	7
	30	9
	0	10
50	60	162
100	32	262

- Some on the metal cask surface and others on the near by places
- No substantial variation for all temperatures
- Model estimates ~ x20 times increase in 50 years (not observed)
- Low Rate, mg/(m^2 day) : 0.17 (0.114 year), 0.01 (50 years)

Amount of Salt Deposition: Measured (after Wataru, et al., 2006)

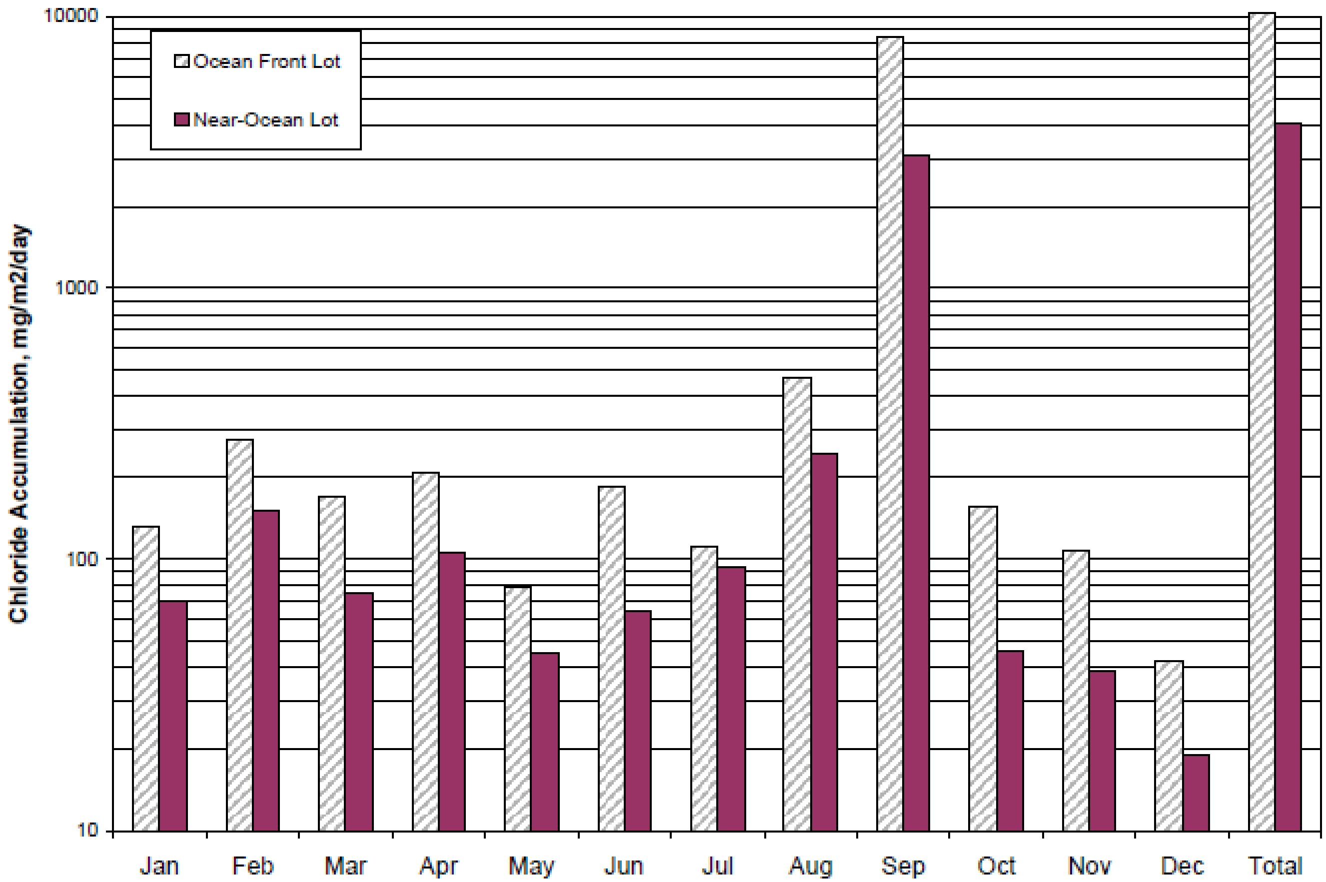
Deposits at different positions

Site	mg/m^2	Exposure time*[1]
Tokai No. 2	5, 3, 3, 3, 2, 5, 6, 3	3 years 4 months
	742, 19	3 years 8 months
Fukushima Daiichi	184, 48, 145, 7, 75, 122, 207, 77	3 months
	263, 221	20 years 5 months*[2]

*[1] Period between the last time of cleaning and the date of measurement

*[2] Possibility of maintenance and cleaning during this period

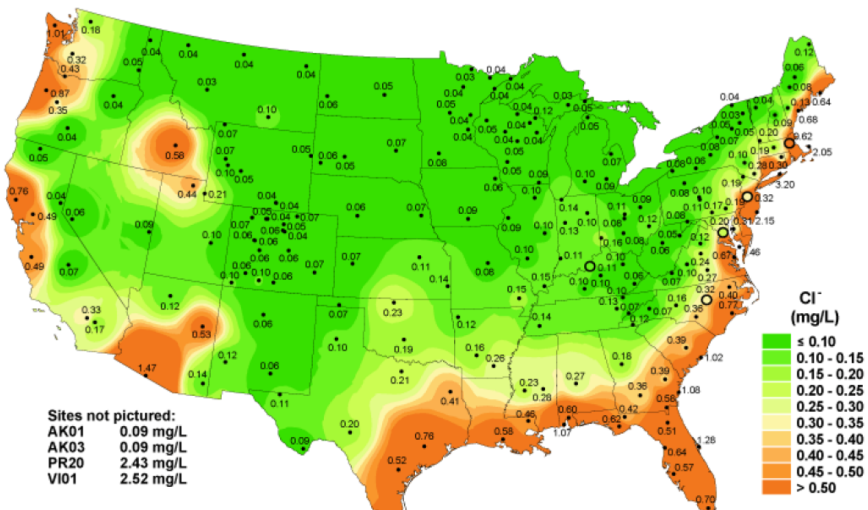
- Large difference between two sites, max > x100; and also depends on air flow pattern
- not much difference between (3 months) and (25 years and 5 months)
- 100 $mg/(m^2$ 3 month$)$ = 1.1 $mg/(m^2$ day$)$



2004 Monthly Chloride Accumulation at Kure Beach, NC ($mg/m^2/day$)

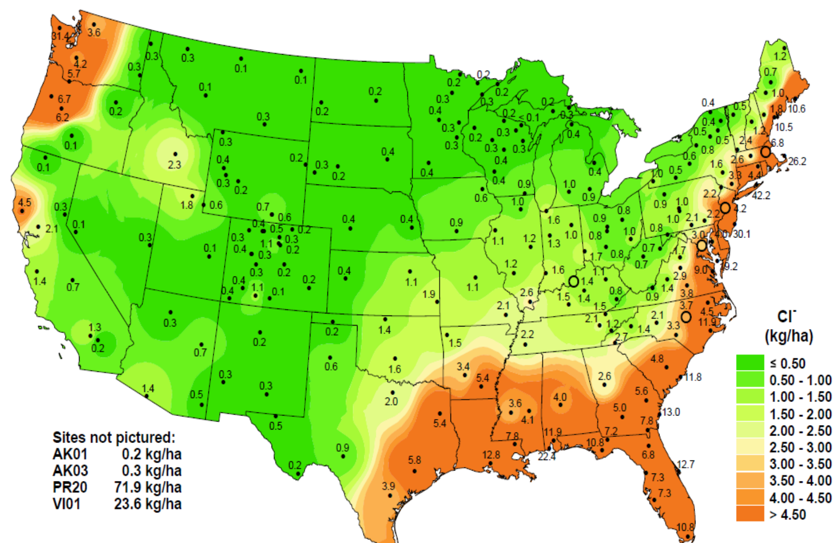
(EPRI, 2006). Kure Beach seems to be an upper bound case

Chlorides from Precipitation



National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

Chloride ion wet deposition, 2009



National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

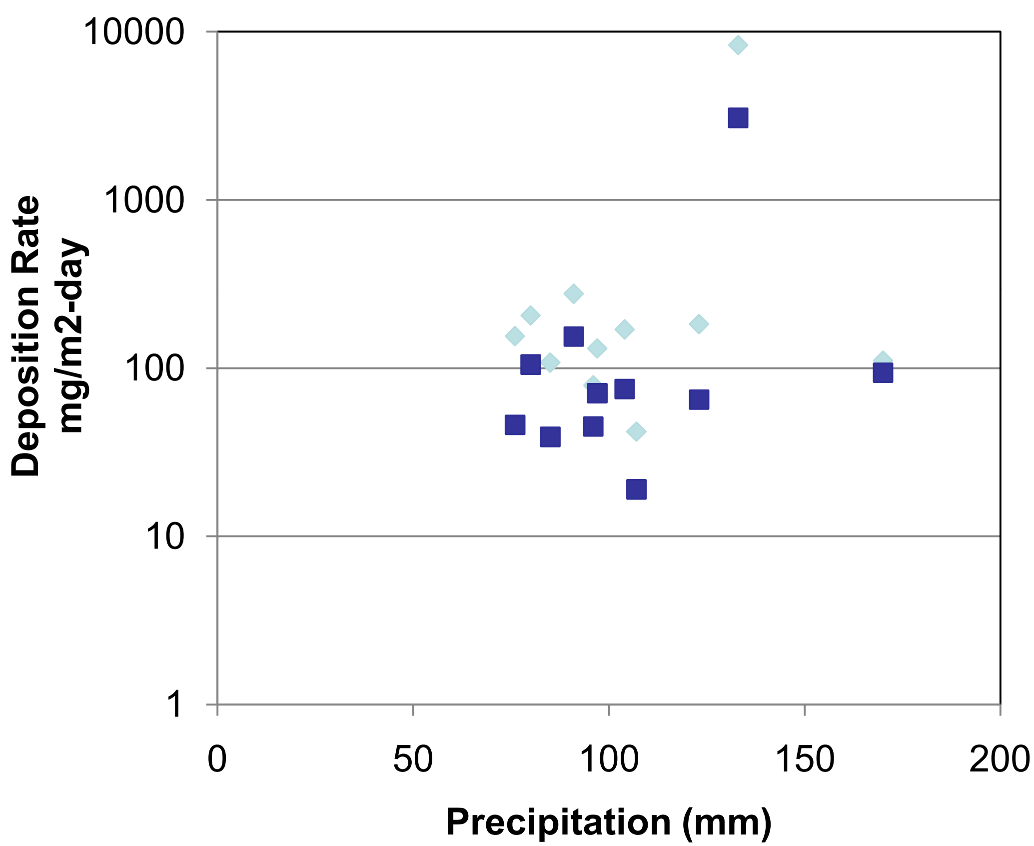
- Aqueous concentration shows relative severity.
  (1 mg/L = 1000 mg/m^3)

- It can go up to higher values at different sites.

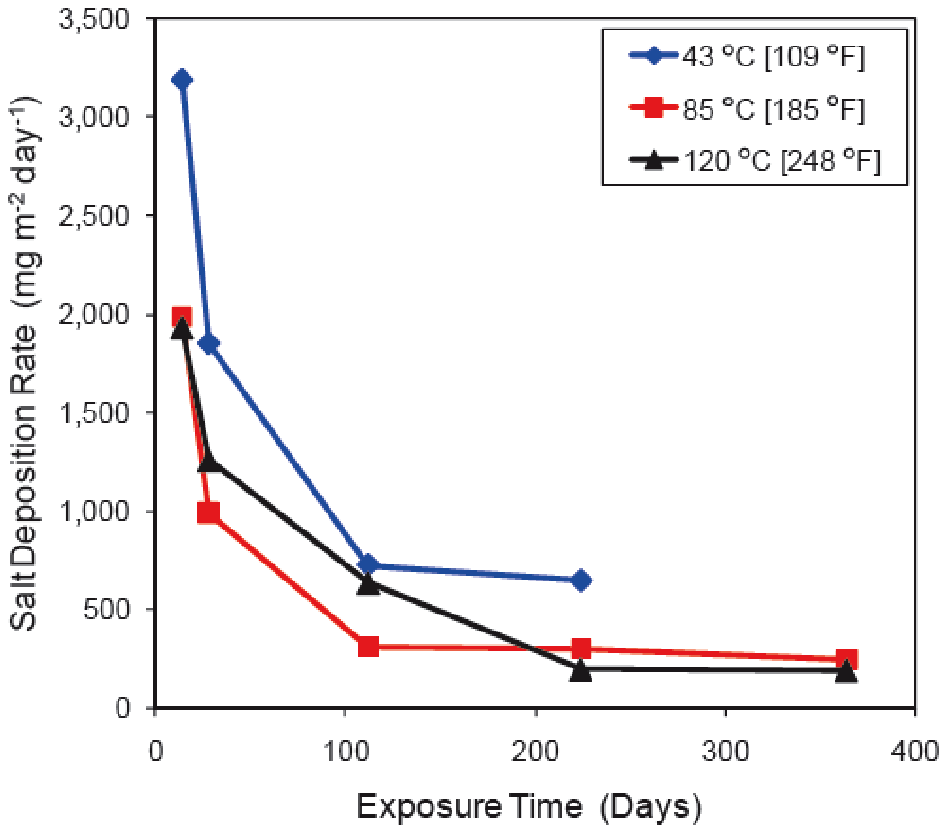
  (1 kg/ha = 0.1 g/m^2)

http://nadp.sws.uiuc.edu/maps/Default.aspx

Deposition Rate Vs. Precipitation



- Dark: near-ocean lot; Light: ocean-front lot at Kure Beach (replot from EPRI, 2006); weak correlation without outlier
- Fog water has higher chloride concentration than rain water; The salt deposition from precipitation could be an indirect measure of that from salt air droplets by wind.
- Failure and inadequate drying of overpack will allow aqueous conditions.
- Model for evaporative chemical evolution of moisture impinging on the canister surface: suggests SCC could occur.



Salt Deposition Rates as a Function of Time for the Half U-Bend Samples Exposed to the Salt Fog. Due to the Condensation Issue Inside the Chamber, the Salt Deposition Rates for the 120 °C [248 °F] Samples are Inaccurate Between 100 and 365 Days of Exposure

(Caeseres and Mintz, 2010)

- NUREG/CR-7030
  - ✓ Inaccuracy is minor
  - ✓ Initial rates are very high in a short time – consistency with other field observations

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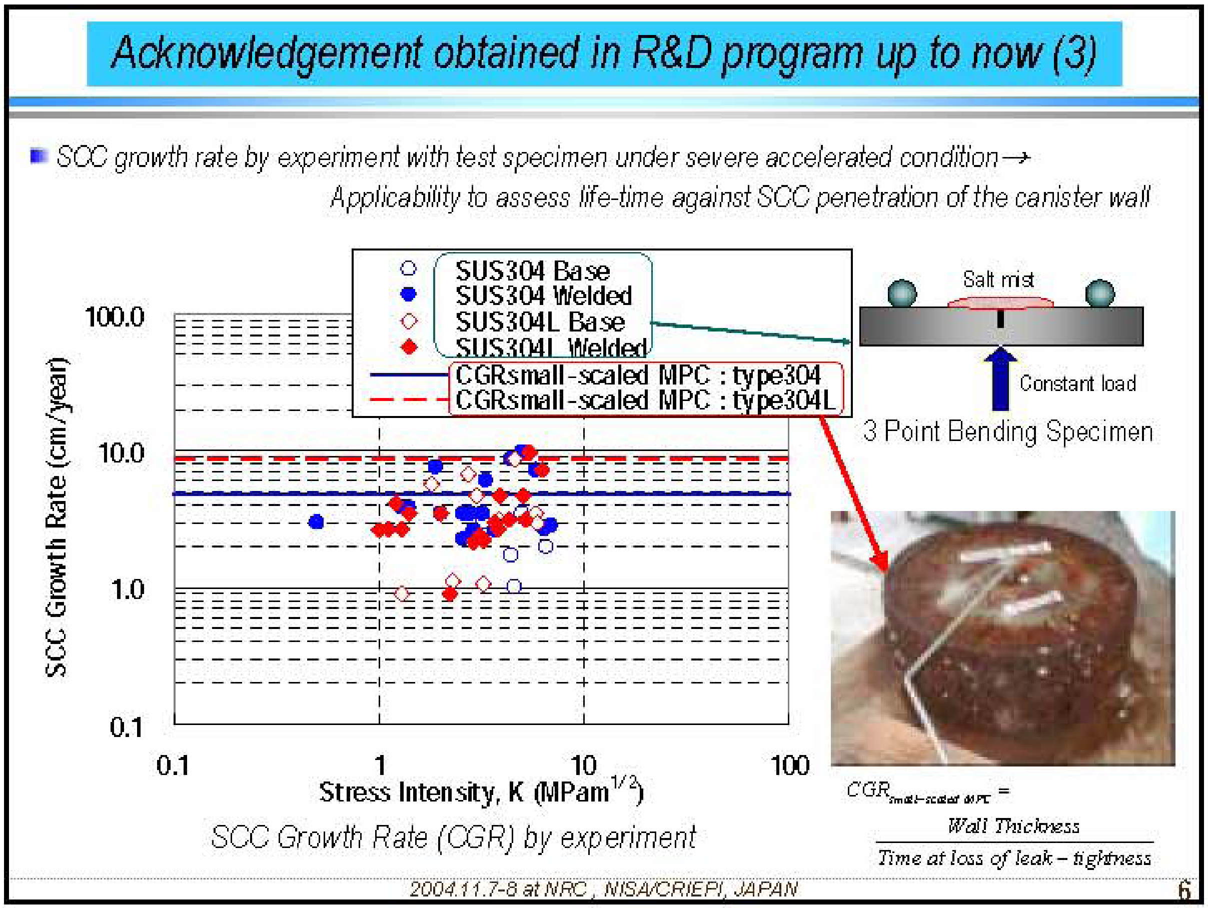
Initiation and Propagation of Crack

Crack Growth Rate: salt deposit (EPRI, 2005, quotation of CRIEPI program)



- 3 point bend test:

  $3\times(10^{-10}$ to$10^{-9})$ m/s

- K independent crack growth rate

- $MgCl_2$ containing salt, 35% RH, and 80 °C

Threshold K Values with Pits

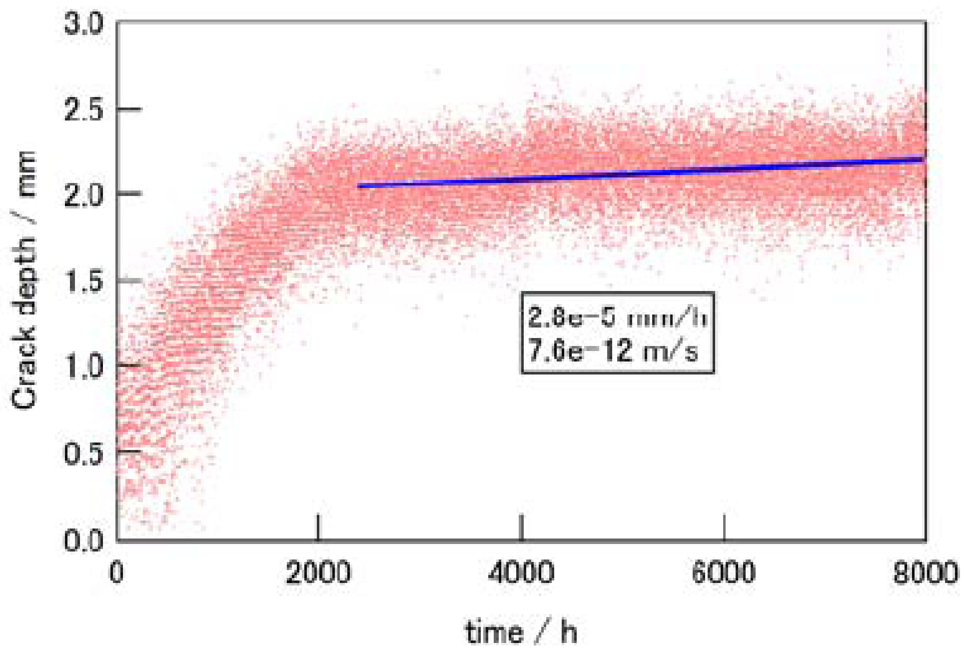
- Pit sizes from Kure beach test facilities at room temperature (EPRI, 2005): 10 – 100 μm
- Weld stress (CRIEPI Case, US may have higher values):
  50 – 150 MPa (Tani, et al., 2010); weld flaws are bigger.

Using $K = \pi^{1/2}$ stress x (crack size)$^{1/2}$

- Mean (100 MPa, 50 μm), K = 1.3 MPa $m^{1/2}$
- Max (150 MPa, 100 μm), K = 2.7 MPa $m^{1/2}$
- Min (50 MPa, 10 μm), K = 0.3 MPa $m^{1/2}$

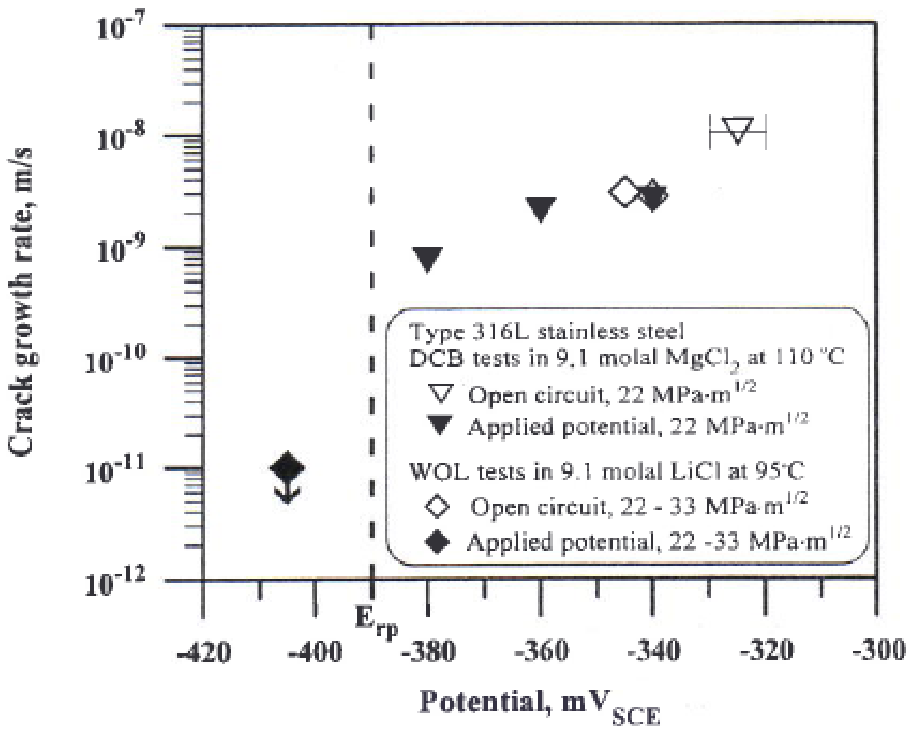
Threshold K values (Tani, et al., 2010) from 3 point bend tests:
0.5 – 7.0 MPa $m^{1/2}$

Crack Growth Rate: salt deposit (Shirai, et al., 2011, copy right by the ANS)



- 4 point bend test
- two crack growth rates
  - initial: 4.4×10^{-10} m/s
  - steady state: 7.6×10^{-12} m/s
- Rates are lower in an order of magnitude than 3 point test
- 80 °C, 35% RH, 270 MPa, 10 g/m^2 salt deposit

Crack Growth Rate: Cl^- Solution

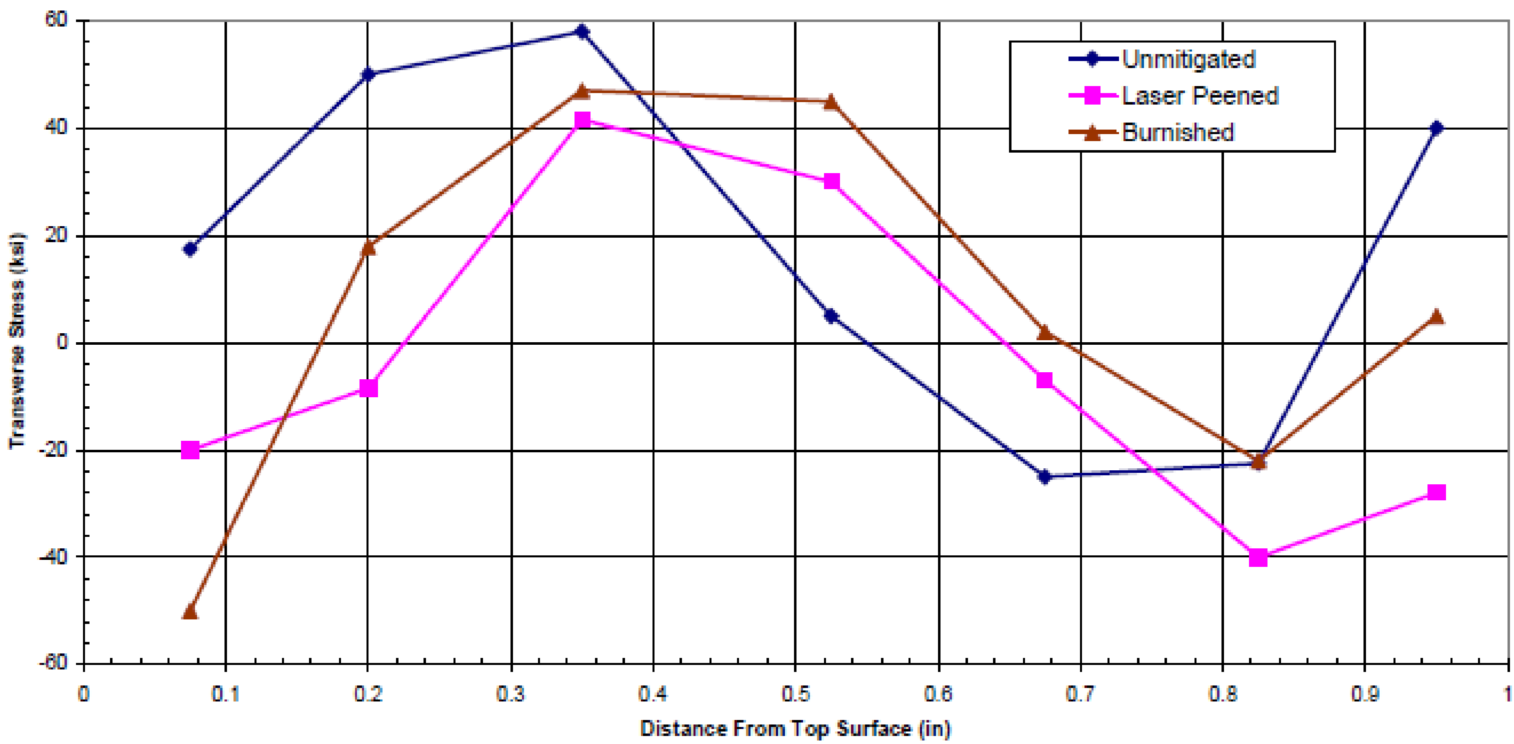


(Pan, et al., 2000, reprinted, with permission, from ASTM STP 1401, copy right ASTM International)

- 10^{-9} - 10^{-8} m/s in 3 % and 0.03 % NaCl at 80 °C
- 10^{-7} - 10^{-6} m/s in 44.7 % $MgCl_2$ at 154 °C (316)

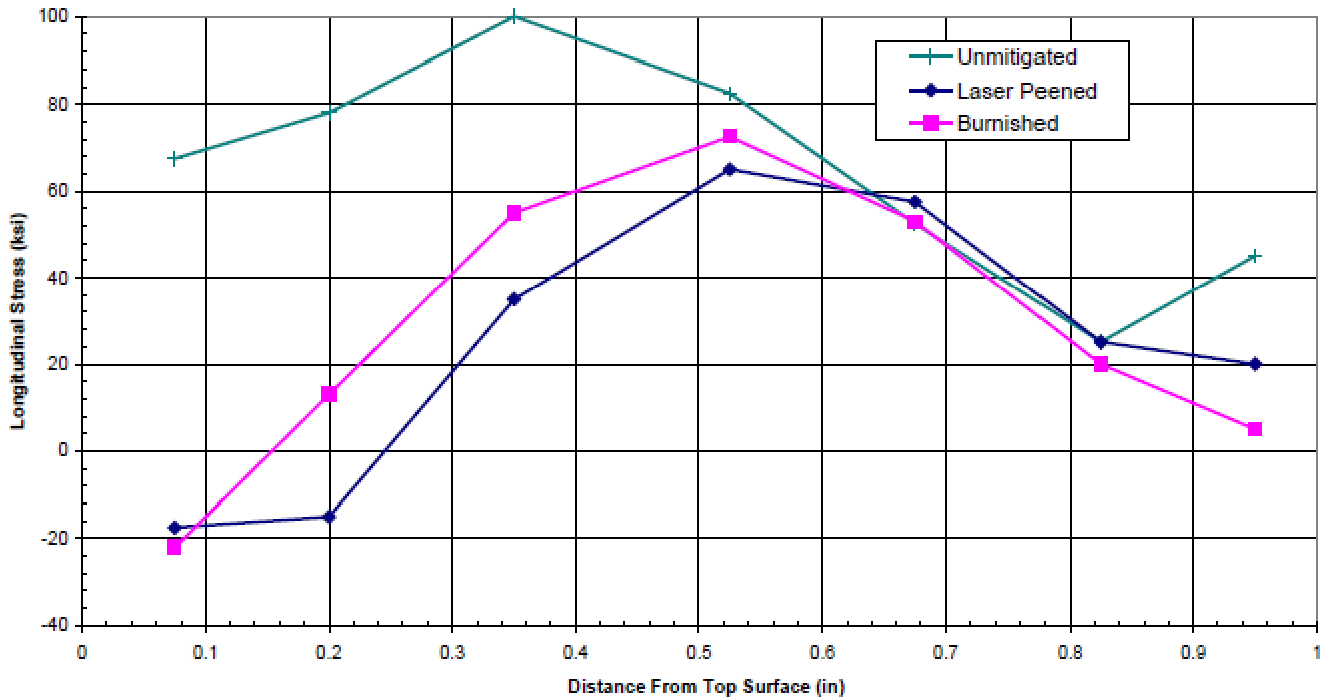
304 and 316 stainless steel (Newman, 1995, Courtesy of NACE)

Weld Stress (EPRI, 2005)



Data for Alloy 22; 100 ksi is 690 MPa: CRIEPI data for stainless steel are available.

Weld Stress (EPRI, 2005, continued)



Data for Alloy 22; 100 ksi is 690 MPa: CRIEPI data for stainless steel are available.

Potential Crack Growth Schematic (for non-stress relieved stainless steel)

- Longitudinal tensile stress may cause continuous crack propagation (longitudinal crack)

- Transverse stress may become compressive, and crack may stop to propagate (radial crack)

- **U Bend Tests – Slide 8**

Summary: Current qualitative understanding and involved uncertainties

- Temperature and RH will not be homogeneous on the canister surface because the SNF configuration and air flow between the canister and the concrete overpack are not uniform.
- Temperature on the canister surface could significantly vary, depending on the SNF heat loading and temporal weather variations.
- RH on the canister surface could significantly vary, depending on the canister surface temperature and absolute humidity of the atmosphere at different sites.

Summary: Current qualitative understanding and involved uncertainties (continued)

- The deposition rate and amount of salts on the canister surface could be insensitive to the canister temperature and time in a steady state. They vary at different sites having various precipitation and salt concentration in air. RH (depending on temperature) affects more deliquescence.
- The salt deposition from precipitation could be an indirect measure of salt air droplets and deposition by wind. The deposition will also depend on air flow pattern.
- The amount of salt deposits and different SCC test methods affect SCC susceptibility.
- Axial cracks seem to propagate more readily than radial cracks due to potential compressive stress in the radial direction.

Summary: Current qualitative understanding and involved uncertainties (continued)

- SCC may be of concern sooner in 304 stainless steel canister with low thermal loading and/or in cooler air.
- The uncertainties associated with selected important issues described here (T, RH, salt deposits, and cracking) are large, depending on sites, SNF conditions, and test methods.
- Proper inspection for bench marking, laboratory tests, field tests, and model studies should be pursued.

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