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Behavior of Stainless Steel in Marine Atmosphere

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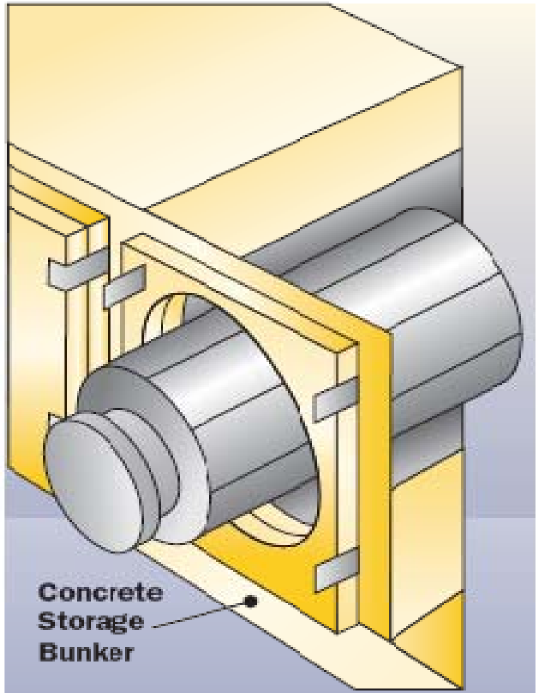
Dry Cask Storage System

NRC NUREG-1350



- Nuclear power plants have turned to dry cask storage facilities
  - Most dry storage casks are made of austenitic stainless steel (304, 304L, and 316L)
  - Most systems use a stainless steel cask inside a concrete bunker or steel in a concrete cask with passive ventilation

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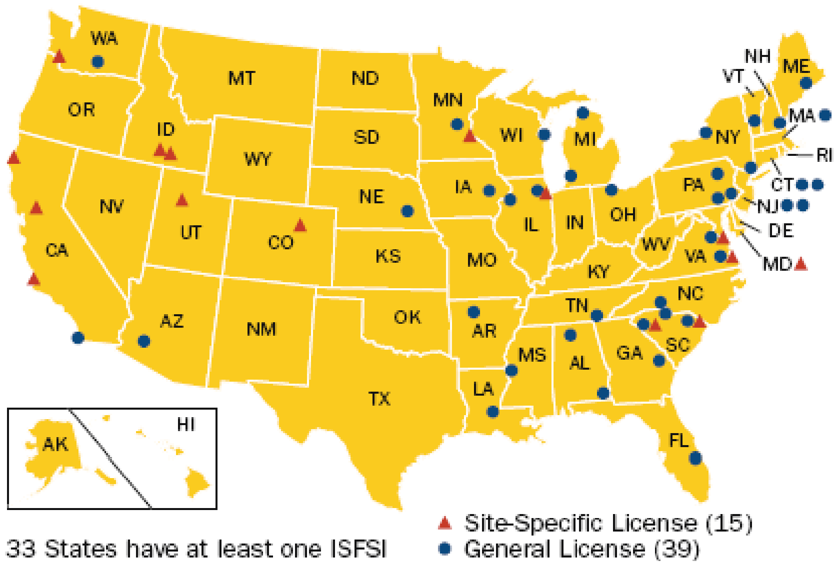
Dry Cask Storage Locations

- Currently 33 Independent Spent Fuel Storage Installation (ISFSI) sites
- Some sites are located near coastal regions
- One recent concern is whether the dry storage casks are susceptible to chloride SCC



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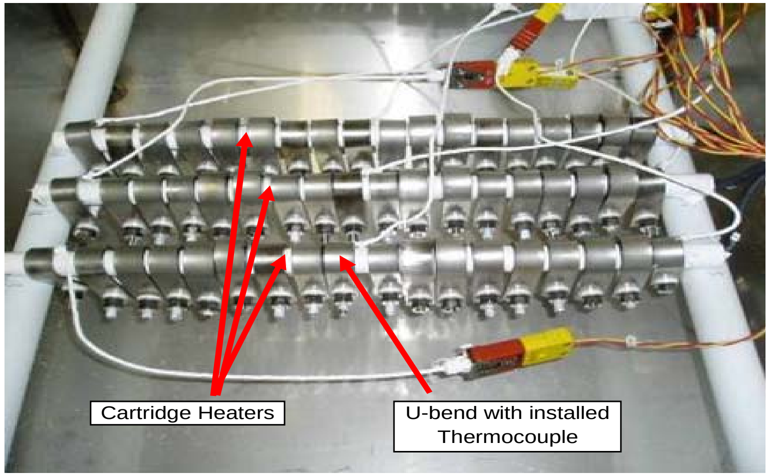
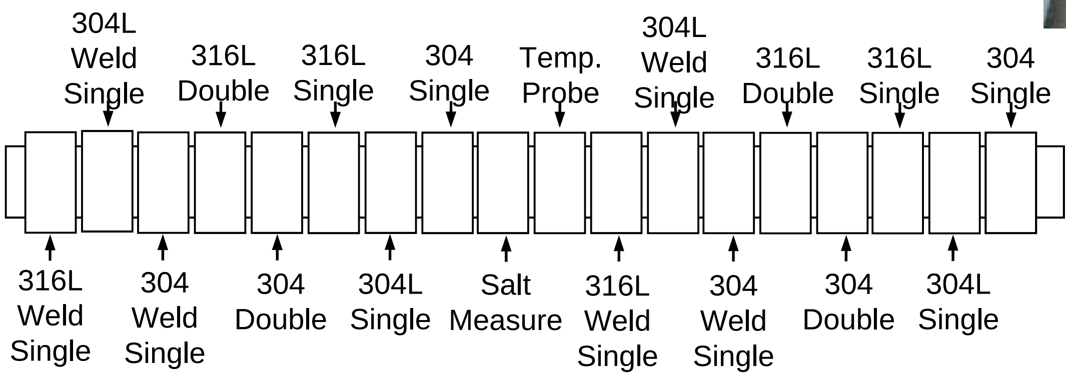
Objective

- To evaluate the susceptibility of austenitic type 304, 304L, and 316L stainless steel to chloride stress corrosion cracking (SCC) in environments typically found in dry cask storage facilities

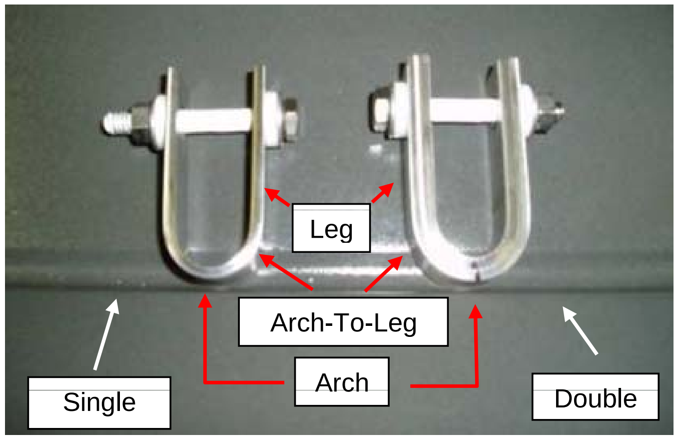
Experimental Approach - U-Bend Samples

- Single and double U-bend specimens mounted on cartridge heaters
  - 304, 304L, and 316L
- Gas tungsten arc welded U-bends
  - 304/308, 304L/308L, and 316L/316L
- Rolling direction was perpendicular to length



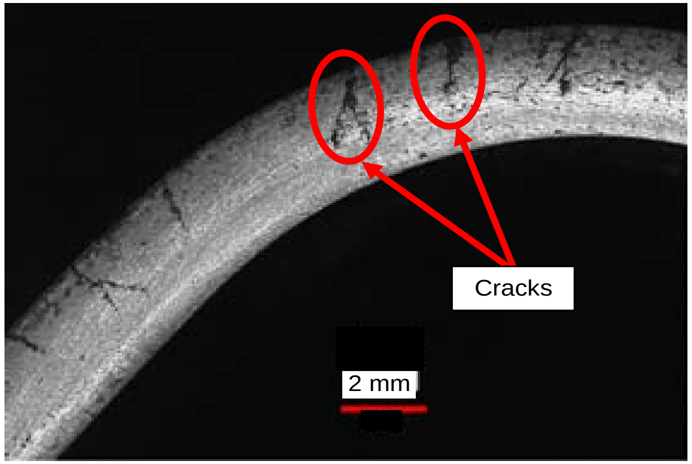


Schematic of the U-bend specimen arrangement on each cartridge heater

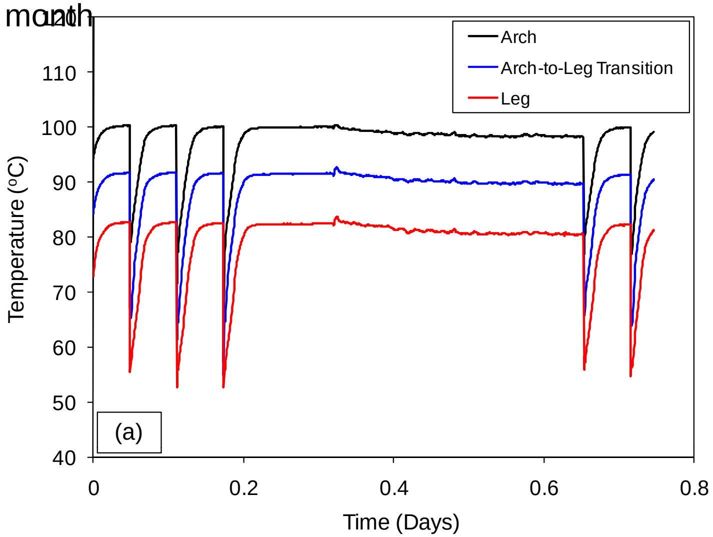


Experimental Approach 1 - Salt Spray Test

- **Experiment**
  - Salt spray test using General Motors (GM) 9540P accelerated corrosion test with ASTM simulated sea salt
  - Samples held at 25, 93, and 176 ° C [77, 200, and 350 ° F]
- **Results**
  - All 93 and 176 ° C [200 and 350 ° F] specimens cracked within 1 month
  - Cracking mostly concentrated around the specimen legs
  - Specimen temperature decreased when sprayed
  - Testing was overly aggressive



Typical SCC behavior of a 93 ° C [200 ° F] 304L stainless steel single U-bend specimen exposed for 1 month



Temperature Profile for the single U-bend specimens at 93 ° C [200 ° F]

Experimental Approach 2 - Custom Salt Fog Test

- Two Phase Process:
  - Salt Deposition: 2-week exposure, specimen temp.: 95 ° C [203 ° F]

Cycle Number	Chamber Cycle	Cycle Time, min	Cycle Description
1	Salt fog	5	Deposit salt on specimens
2	Dry	15	

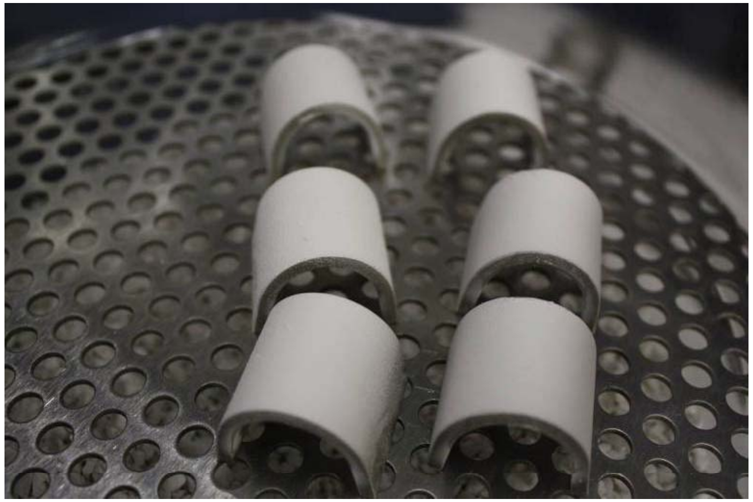
  - Wet/Dry Cycling

Cycle Number	Chamber Cycle	Cycle Time, min	Cycle Description
1	Salt fog	5	Deposit salt on the specimens
2	Ambient	60	
3	Salt fog	5	
4	Ambient	60	
5	Salt fog	5	
6	Ambient	60	
7	Salt fog	5	
8	Ambient	60	
9	Dry	100	Low relative humidity
10	Increase humidity	125	Increase relative humidity in chamber
11	High humidity	55	Highest relative humidity
12	Dry	180	Low relative humidity

  - 52-week exposure, specimen temp.: 43, 85, and 120 ° C [109, 185, 248 ° F]

Salt Deposition

- Initial deposition resulted in a salt deposit equivalent to roughly 6-18 months of natural accumulation
- Control samples showed no indication of corrosion after salt deposition
- Salt remained on the surface of the samples throughout exposure period



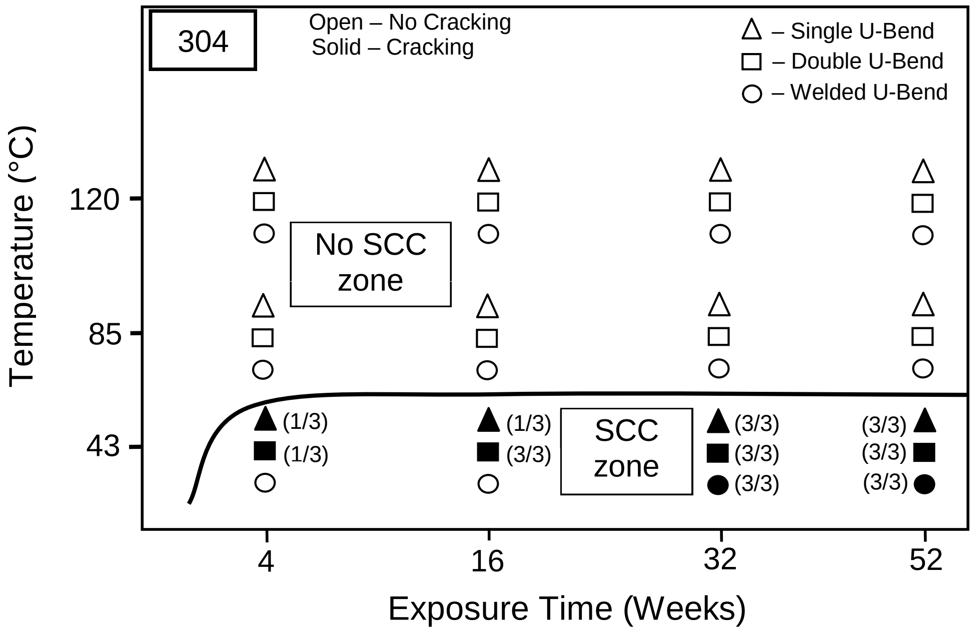
Salt deposition rates obtained from half U-bend samples

Temperature, °C [°F]	Salt Weight, mg			
	t=28 days (4 weeks)	t=112 days (16 weeks)	t=224 days (32 weeks)	t=364 days (52 weeks)
43 [109]	67.4011*	105.8200*	188.1100*	NA
85 [185]	35.9671	45.1100	87.0480	115.4595
120 [248]	45.8406	92.1700	56.5201	89.6675

The specimen area was assumed to be 0.0013 m^2 [0.014 ft^2] based on a single side 5 by 2.5 cm [2 by 1 in] specimen.
* Weight change was mainly due to corrosion product formation

Results (304 Stainless)

- Cracking was only observed in all the 43 ° C [109 ° F] samples
- Cracks had mixed transgranular/intergranular morphology
- Cracks concentrated within the arch region in all unwelded U-bends and at the heat-affected zone of the welded specimens
- Cracks initiated 4 weeks after exposure
- Cracking severity increased with exposure time



SCC susceptibility map (number in parenthesis states number of specimens cracked/total number of specimens tested)

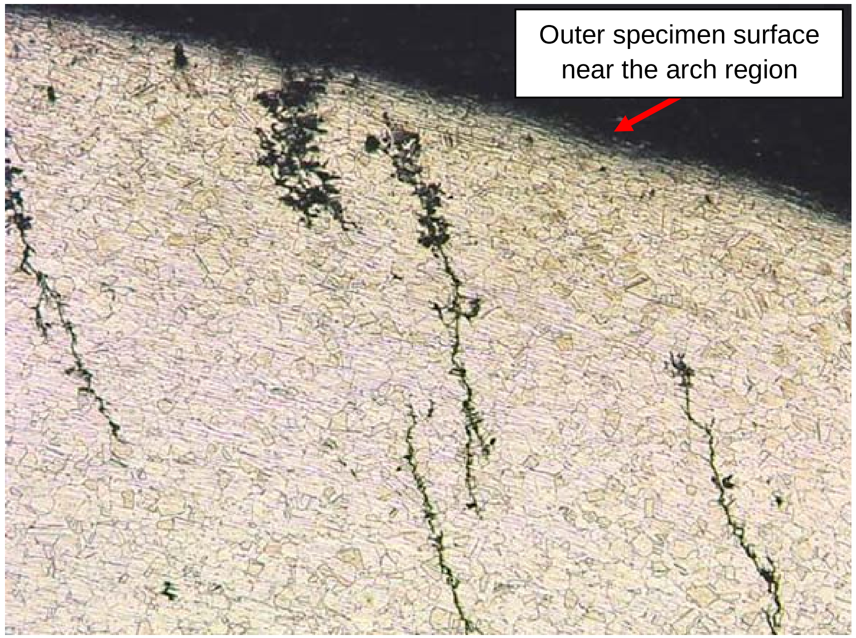
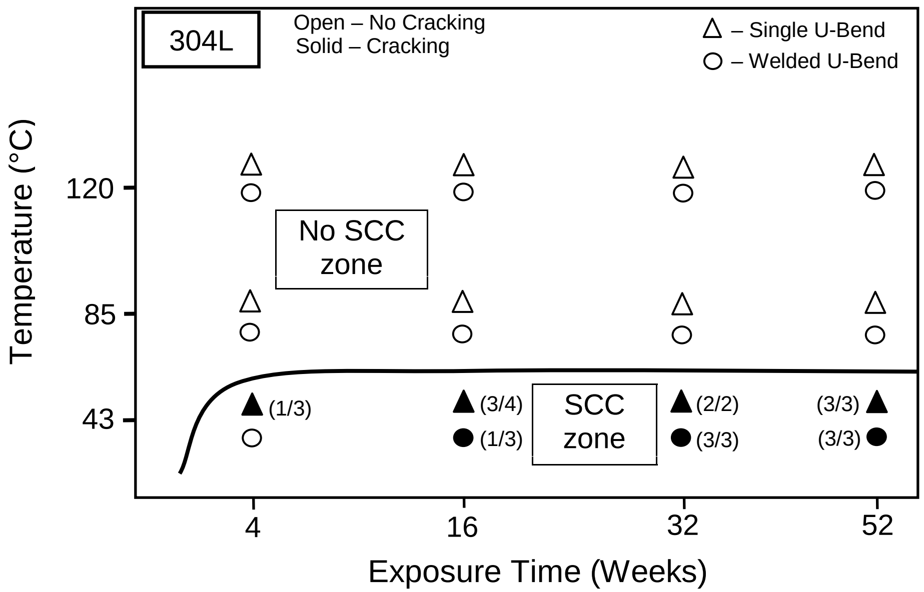


Image of a cleaned 43 ° C [109 ° F] 304 unwelded single U-bend exposed for 32 weeks

Results (304L Stainless)

- Cracking was only observed in all the 43 ° C [109 ° F] samples
- Cracks had mixed transgranular/intergranular morphology
- Cracks concentrated within the arch region in all unwelded U-bends and at the heat-affected zone of the welded specimens
- Cracks initiated 4 weeks after exposure
- Cracking severity increased with exposure time



SCC susceptibility map (number in parenthesis states number of specimens cracked/total number of specimens tested)

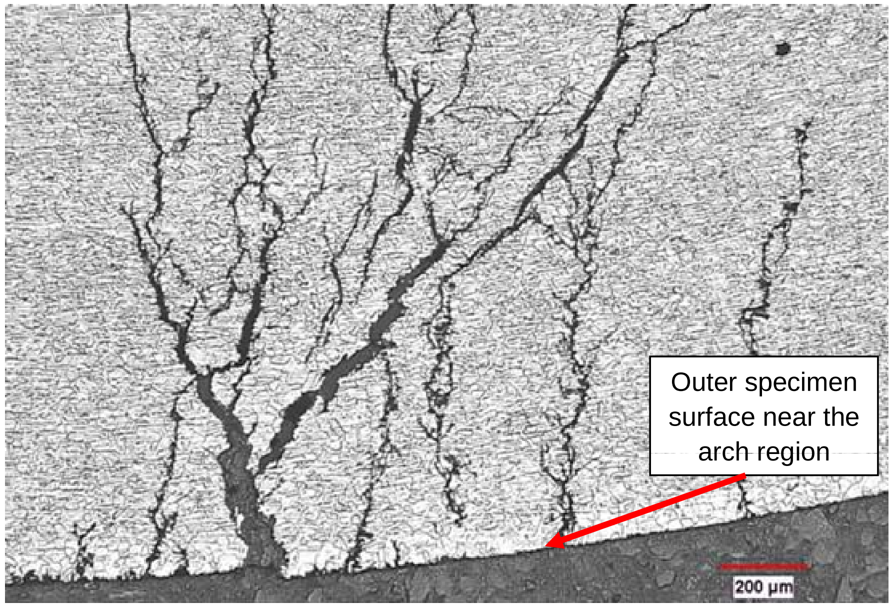
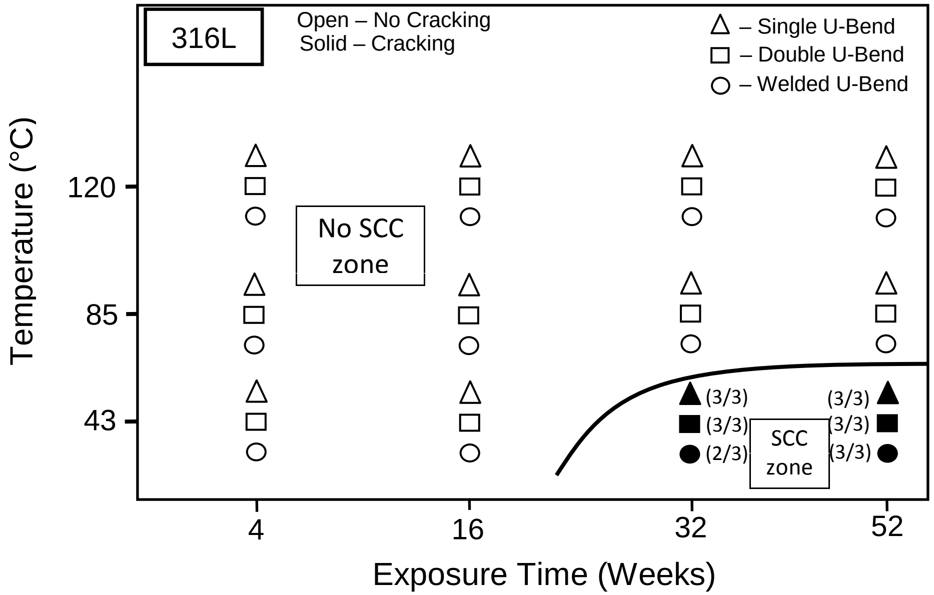


Image of a cleaned 43 ° C [109 ° F] 304L weld U-bend exposed for 32 weeks

Results (316L Stainless)

- Cracking was only observed in all the 43 ° C [109 ° F] samples
- Cracks had mixed transgranular/intergranular morphology
- Cracks concentrated within the arch region in all unwelded U-bends and at the heat-affected zone of the welded specimens
- Cracks initiated 32 weeks after exposure
- Cracking severity increased with exposure time



SCC susceptibility map (number in parenthesis states number of specimens cracked/total number of specimens tested)

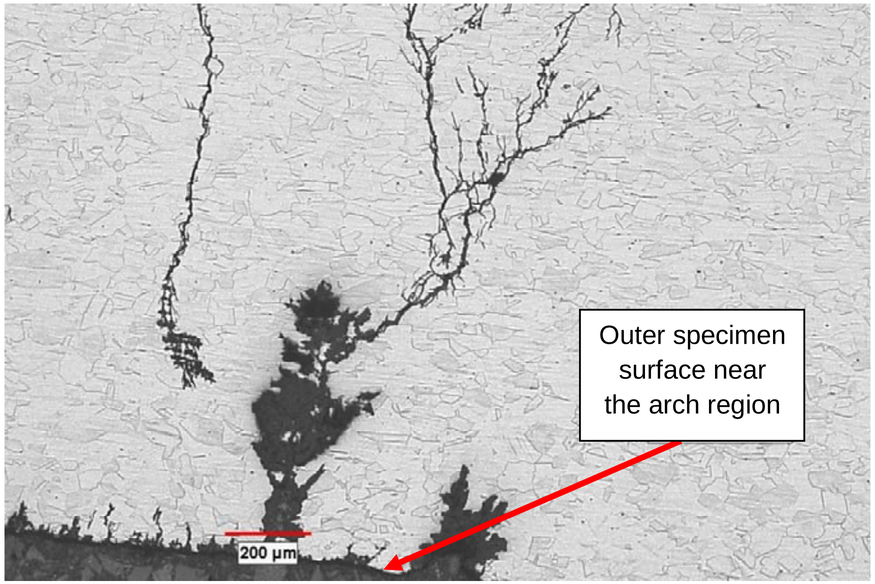
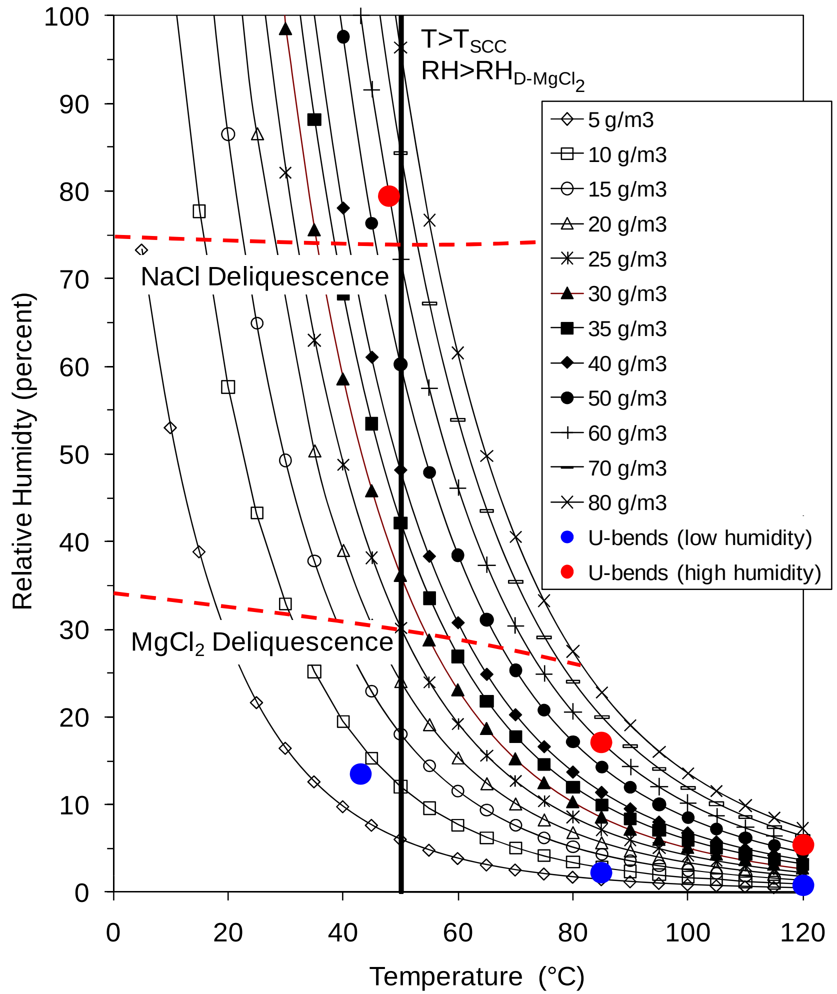


Image of a cleaned 43 ° C [109 ° F] 316L weld U-bend exposed for 32 weeks

SCC Analysis

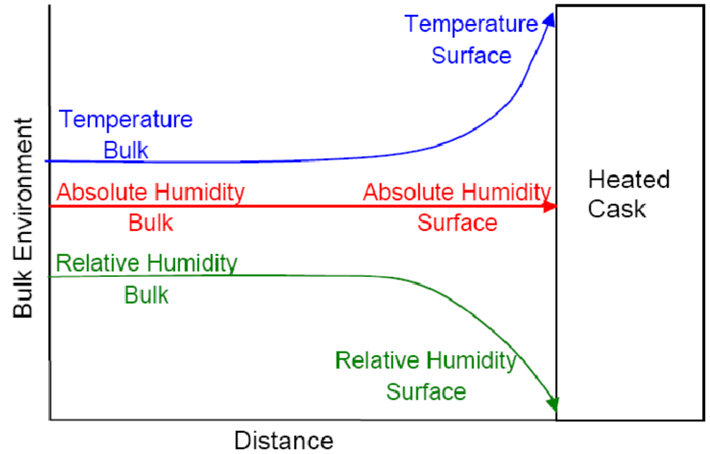
- Typically, the maximum observed absolute humidity in natural environments is less than 30 g/m^2
- Test used conservative absolute humidity of 60 g/m^2
- High absolute humidity was sufficient to exceed the relative humidity necessary for the deliquescence of salts deposited on specimens maintained at 43 ° C

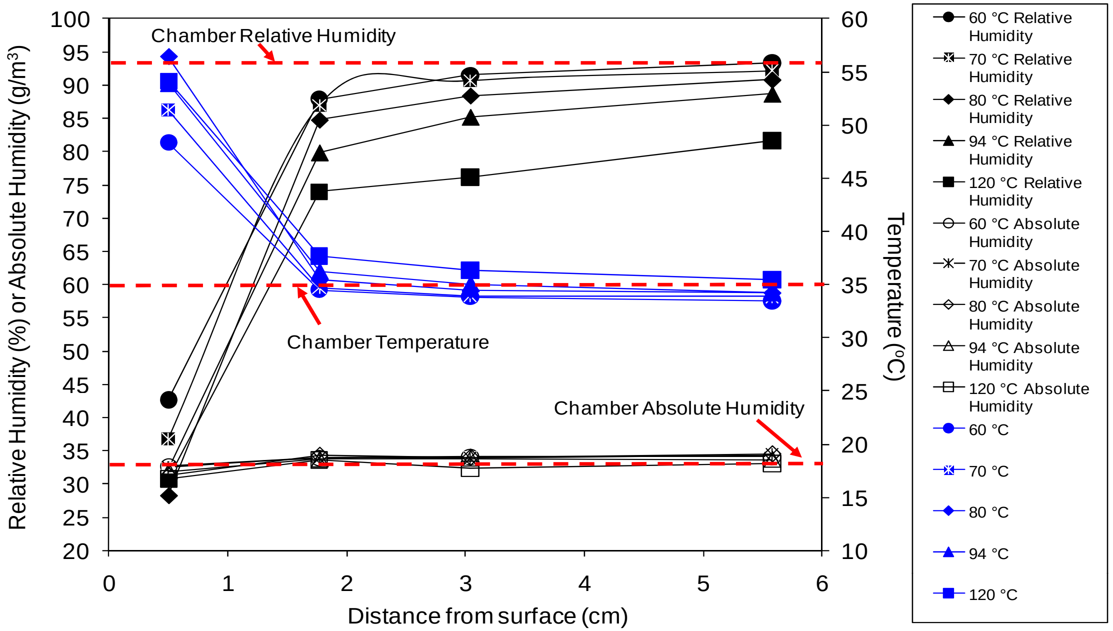


Evolution of the relative humidity versus temperature for various absolute humidity. The region between the red (maximum humidity) and blue (minimum humidity) circles indicate the expected environmental conditions near the U-bend surface in the salt fog test

SCC Analysis

- Air temperature increases near the sample surface
- Absolute humidity remains similar to bulk environment
- Relative humidity decreases near the sample surface





Temperature, absolute humidity, and relative humidity profiles versus distance from the U-bend samples heated at different temperatures

Conclusions

- Salt spray test not suitable for evaluation of SCC susceptibility
- Salt fog test showed SCC and pitting corrosion in all the 43 °C samples after 4 weeks (304 and 304L) and after 32 weeks (316L)
- None of the 85 and 120 °C [185 and 248 °F] samples showed SCC, consistent with the inability of the salt to deliquesce (low relative humidity at sample surface)
  - Chloride-induced SCC highly dependent on cask temperature and relative humidity of surrounding environment
  - Results likely conservative because of high absolute humidity used for the test but still pertinent → demonstrate that the deliquescence of dry deposited sea salt can lead to SCC of austenitic stainless steels at temperatures that are only slightly greater than ambient temperatures

Path Forward (Remaining Issues for Long-Term Storage)

- Results of this investigation indicates that SCC may be observed in dry storage systems if certain conditions are met

Unanswered questions:

- What will be the effect of relative humidity and temperature between the deliquescence and efflorescence regions on SCC?
  - Complete salt deliquescence may not be required to have SCC
  - SCC may be present above the efflorescence point

- How long will it take until enough salt is deposited, if any, on the cask for SCC to be possible?
  - Salt deposition rates inside concrete overpack are unknown
  - Is the salt able to deliquesce under the environmental conditions present?
  - Monitoring/modeling of salt deposition rate on sheltered cask (inside overpack) is needed