EVALUATION OF AUSTENITIC STAINLESS STEEL DRY STORAGE CASK STRESS CORROSION CRACKING SUSCEPTIBILITY

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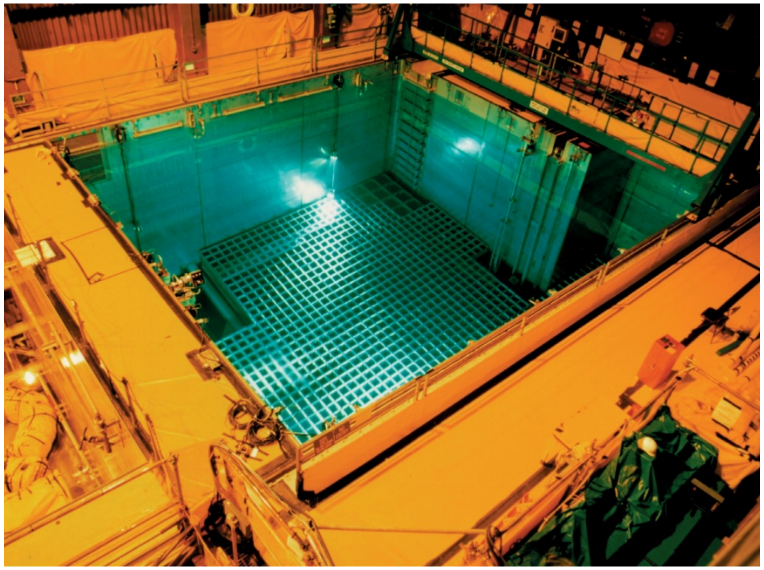
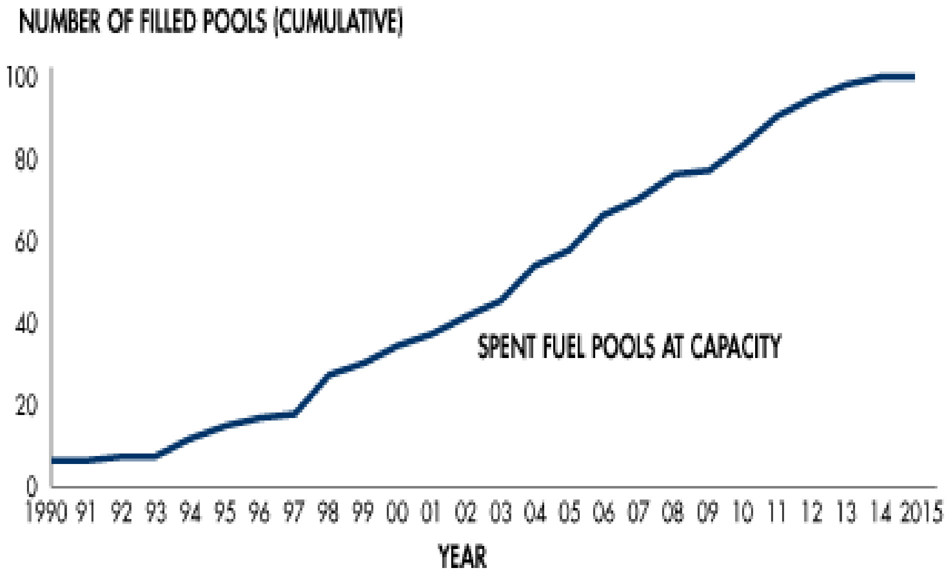
Background





Commercial nuclear power reactors refuel every 18 to 24 months

- Spent nuclear fuel is placed in spent fuel pools
- Pools at many commercial nuclear power plants (NPP) are reaching capacity

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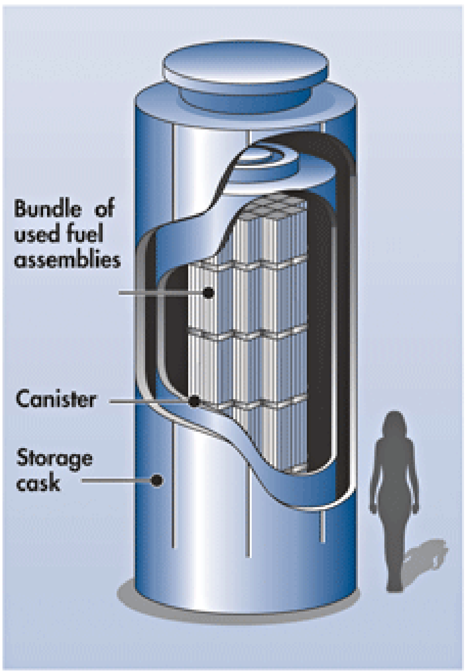
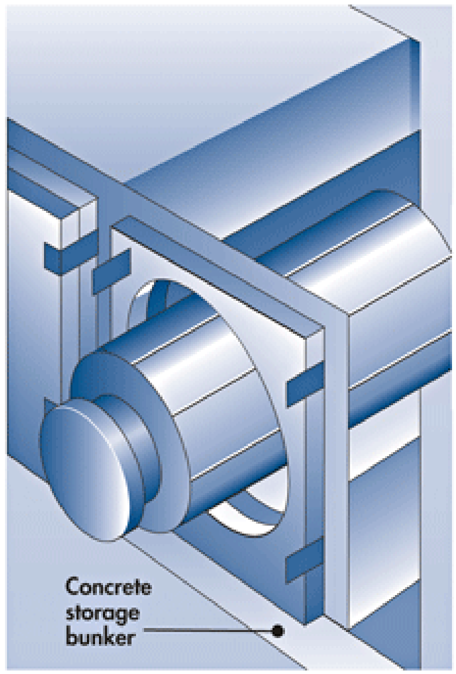
Dry Storage System Designs





Austenitic stainless steel dry storage canister

- Typically 304/304L/316/316L stainless steel (SS) construction
- Some systems use a SS cask inside a concrete bunker or a combination steel/concrete cask with passive ventilation
- Currently 44 Independent Spent Fuel Storage Installation (ISFSI) sites
- 73 ISFSI sites anticipated by 2020
- ISFSI are licensed for 20 years
- License renewals required for older ISFSI sites

Dry Storage Systems Examples

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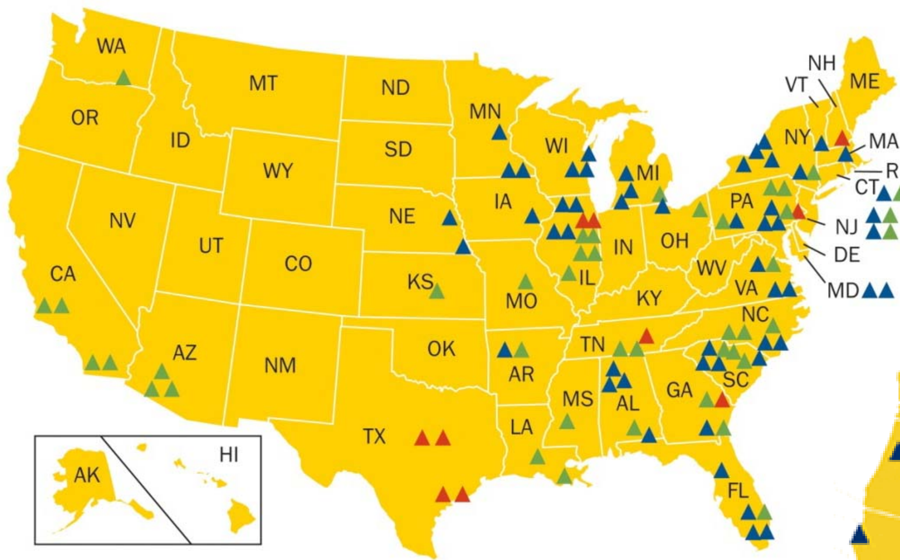
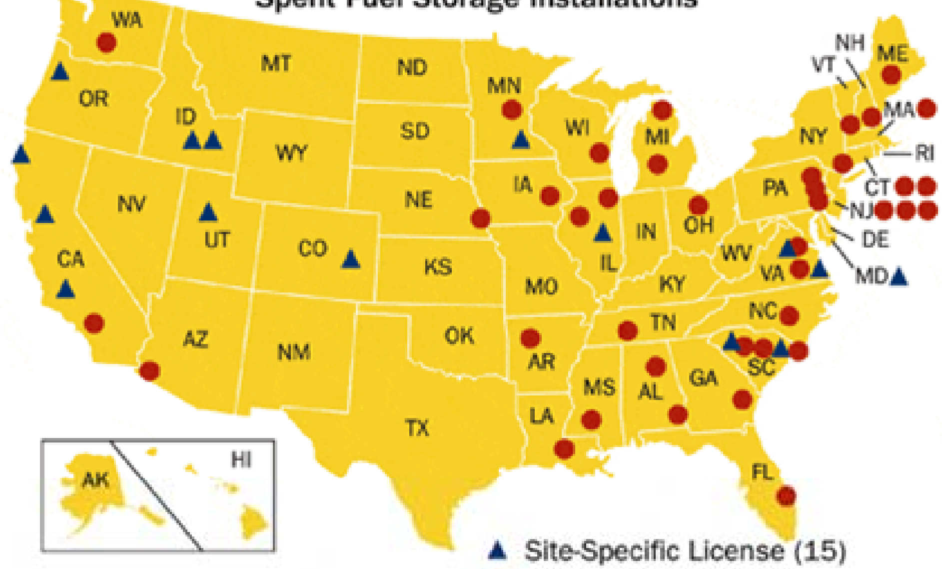
NPP and ISFSI Locations

U.S. Commercial Nuclear Power Reactors—Years of Operation



Years of Commercial Operation	Number of Reactors
△ 0-9	0
▲ 10-19	10
▲ 20-29	42
▲ 30-39	52

Licensed/Operating Independent Spent Fuel Storage Installations



Issues and Objectives

Issues

- Extended operation of existing ISFSIs must be evaluated
- Additional ISFSIs will be necessary
- Long term exposure to marine atmospheres possible

Objectives

- Evaluate the susceptibility of austenitic type 304, 304L, and 316L stainless steels to chloride SCC in marine environments
- Determine inspection needs for existing and future SS storage casks

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Chloride SCC

- Environmental chloride concentration
  - High chloride concentration leads to high probability of SCC development
  - Coastal storage facilities may have a higher probability of developing SCC as a result of deposition of chloride containing aerosols
- Composition
  - Low susceptibility to sensitization of low carbon steel grades may reduce intergranular SCC susceptibility
  - Addition of molybdenum is suggested to enhance passivity and decrease SCC susceptibility
- Temperature
  - Low temperatures reduce probability for SCC initiation (below 50 °C [122 °F], the possibility of chloride SCC initiation is significantly reduced)

Alloy Compositions Tested

Material (Heat)	Fe	Cr	Ni	Mo	Mn	C	S	P	N	Si	Cu
304 (2N379)	Bal	18.19	8.07	N/A	1.21	0.039	0.002	0.026	0.042	0.55	N/A
304L (7470395)	Bal	18.14	8.07	0.18	1.29	0.025	0.001	0.025	0.032	0.34	0.27
316L (7470663)	Bal	16.43	10.13	2.06	1.35	0.019	0.0006	0.027	0.022	0.51	0.32
ER308 (E72000)	Bal	19.92	9.61	0.10	1.55	0.051	0.002	0.023	0.019	0.36	0.14
ER308L (D88069A)	Bal	20.12	9.79	0.05	1.75	0.009	0.010	0.014	0.043	0.47	0.05
ER316L (S66892)	Bal	18.10	11.05	2.22	1.63	0.023	0.016	0.026	0.04	0.41	0.39

Specimen Configurations

- Single U-bend: 304, 304L, 316L
- Double U-bend: 304, 316L
- Gas tungsten arc welded U-bend: 304/308, 304L308L, 316L/316L

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Initial Tests

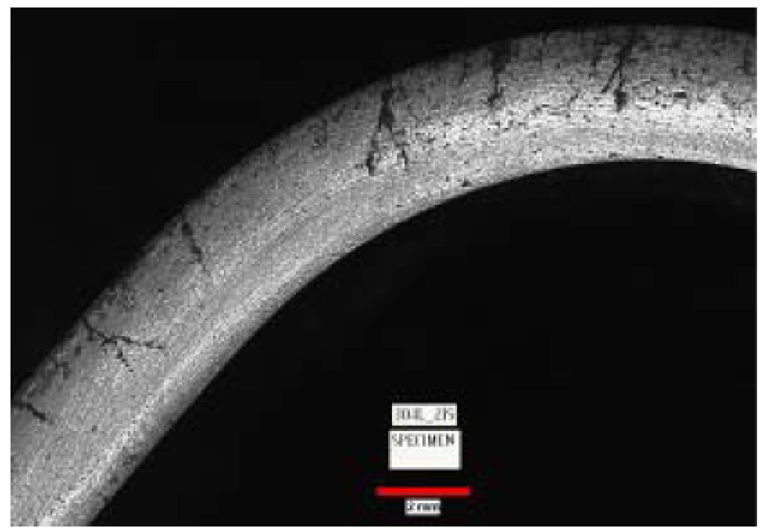
Approach

- Type 304, 304L and 316L U-bends
- Specimens placed on cartridge heaters and heated to 25, 93, and 176 °C [77, 200, and 350 °F]
- General Motors (GM) 9540P accelerated corrosion test using ASTM simulated sea salt

Results

- All specimens cracked within 2 months
- Specimen temperature was not maintained

Salt spray resulted in an overly conservative test



SCC of 304L SS exposed for 1 month at 93 °C

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Modified Test Development

- Test Requirements
  - Need realistic accelerated test
  - High salt deposition rate is desirable
    - Can be related to actual exposure
    - Means to obtain accelerated test
  - Wet/dry cycles desirable
  - Must avoid seawater spray
- Materials
  - Type 304, 304L, and 316L base metals
  - Type 304/308, 304L/308L, 316L/316L welded specimens

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Modified Test Method

Cycle	Chamber Cycle	Time, minutes	Chamber Temp °C [°F]
1	Salt fog/deposition	5	30 [86]
2	Ambient	60	30 [86]
3	Salt fog/deposition	5	30 [86]
4	Ambient	60	30 [86]
5	Salt fog/deposition	5	30 [86]
6	Ambient	60	30 [86]
7	Salt fog/deposition	5	30 [86]
8	Ambient	60	30 [86]
9	Dry Period	100	30 [86]
10	Increasing Humidity	125	30 [86]
11	High Humidity Period	55	46 [115]
12	Extended Dry Period	180	40 [104]

- 52 week exposure at 40, 85, and 120°C [104, 185, and 248°F]
- Modified GM 9540P with 4 salt fog periods, a high humidity period and an extended dry period every 12 hours

Salt Deposition

Specimen Exposure Temperature °C [°F]	Weight change, mg/m^2		
	2 weeks salt deposition (95°C)	Salt deposition + 4 weeks exposure	Salt deposition + 16 weeks exposure
40 [104]	18,677	51,847*	81,400*
95 [185]	23,405	27,667	34,700
130 [248]	18,290	35,262	70,900

- Specimens maintained at 95°C [203°F] during 2 week accelerated salt deposition period using 5 min fog periods every 20 min
- 2-week deposition resulted in a salt deposit equivalent to approximately 6-18 months of natural accumulation
- Control tests showed no indication of corrosion after salt deposition
- No removal of salt deposit during testing

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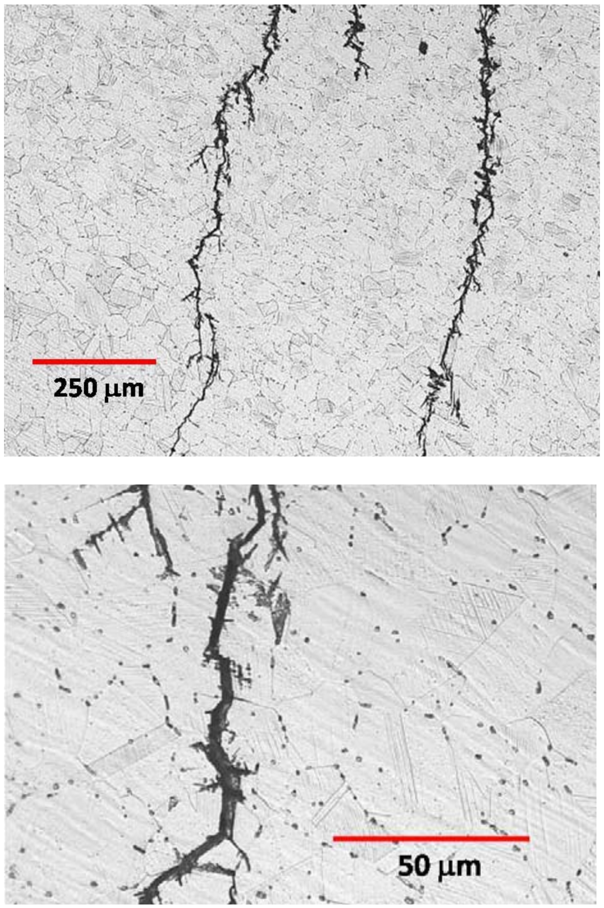
Test Results

Alloy	Base metal or welded	Specimen Configuration	SCC Observed vs. Exposure Time		
			4 weeks	16 weeks	32 weeks
304	Base metal	Single U-bend	Yes	Yes	Yes
304/308	Welded	Single U-bend	No	Yes	Yes
304	Base metal	Double U-bend	Yes	Yes	Yes
304L	Base metal	Single U-bend	No	Yes	Yes
304L/308L	Welded	Single U-bend	No	Yes	Yes
316L	Base metal	Single U-bend	No	No	Yes
316L/316L	Welded	Single U-bend	No	No	Yes
316L	Base metal	Double U-bend	No	No	Yes

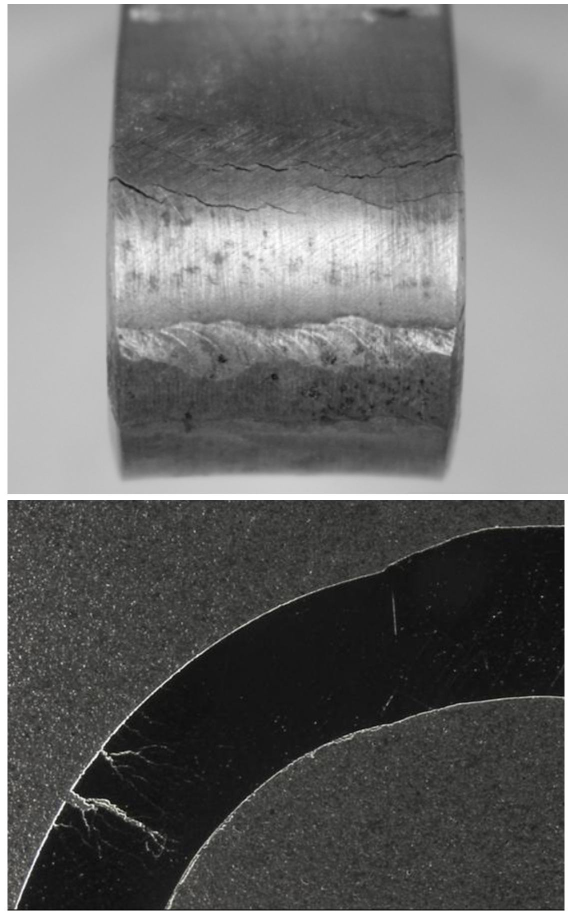
- Results for specimens tested at 40°C [104°F]
- Pitting observed on 40°C [104°F] specimens after 32 weeks
- No SCC on specimens tested at 85 and 120°C [185 and 248°F]

Specimen Examination

304, 40^{o}C, 16 wks

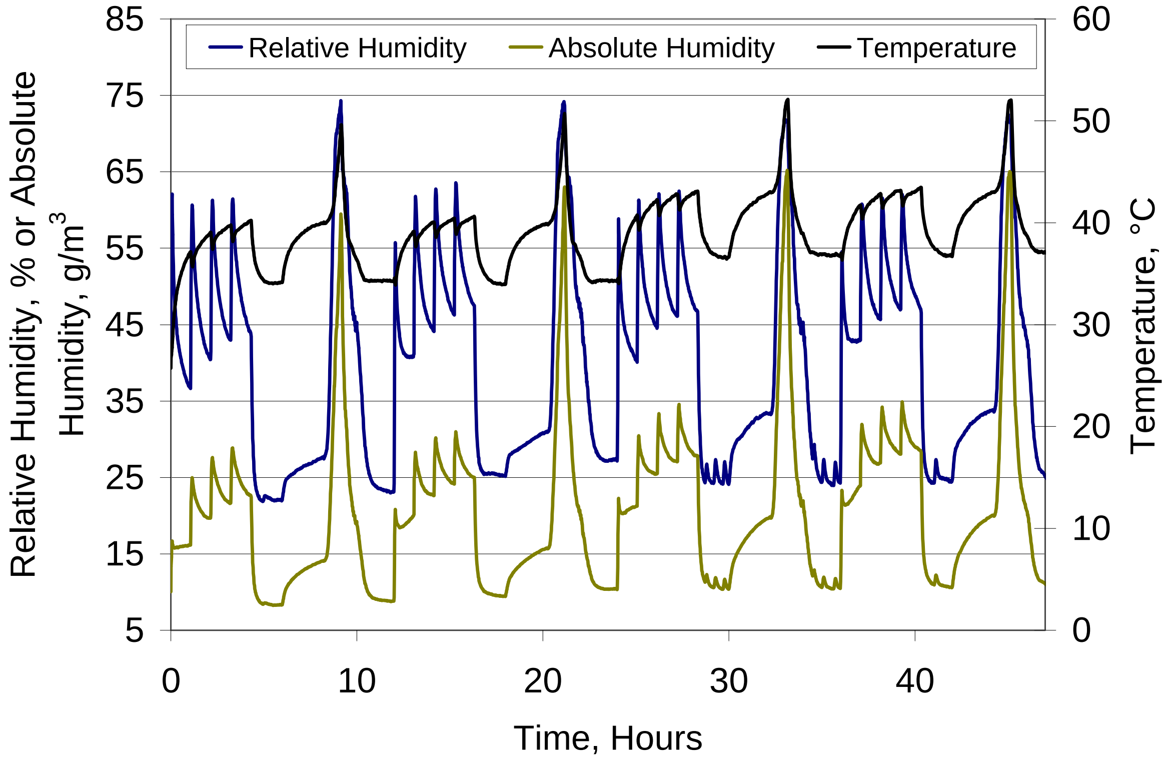


304L/308L, 40^{o}C, 32 wks



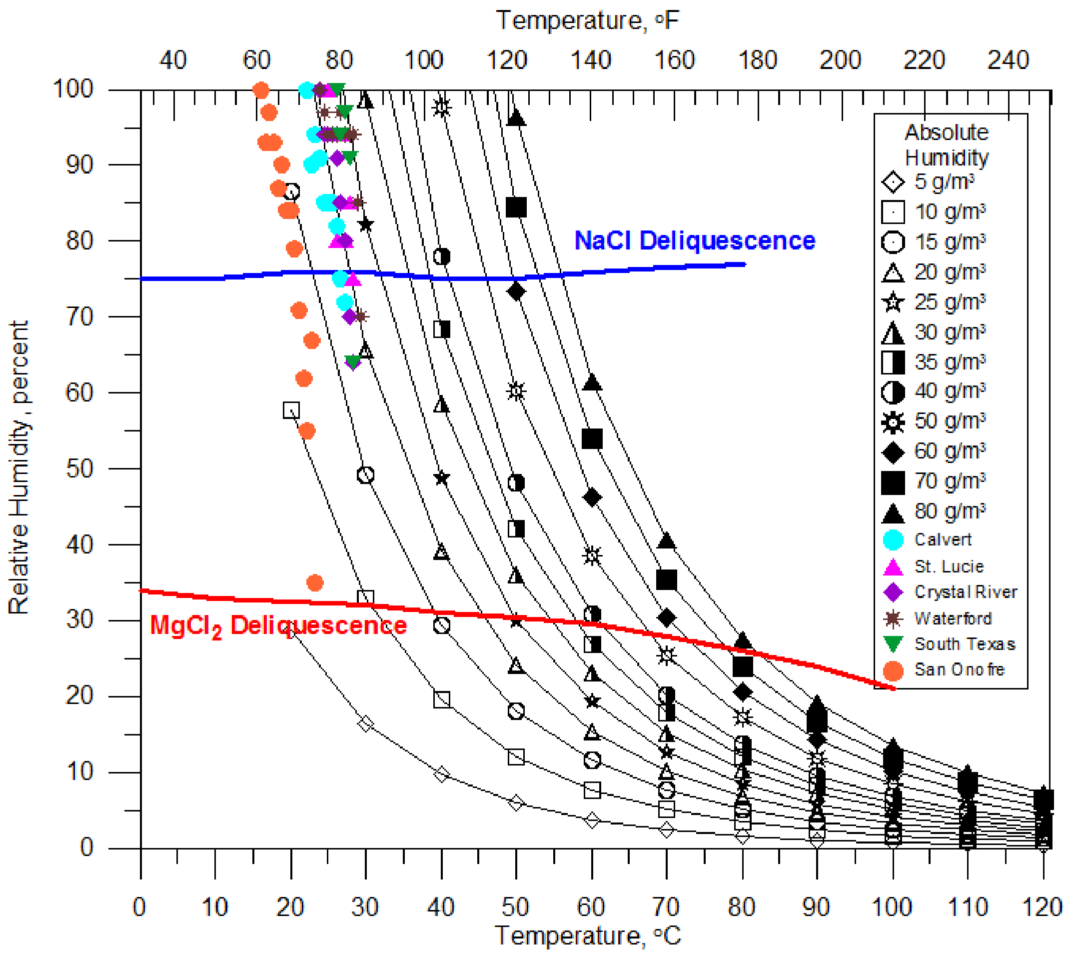
316L, 40^{o}C, 32 wks

Test Conditions



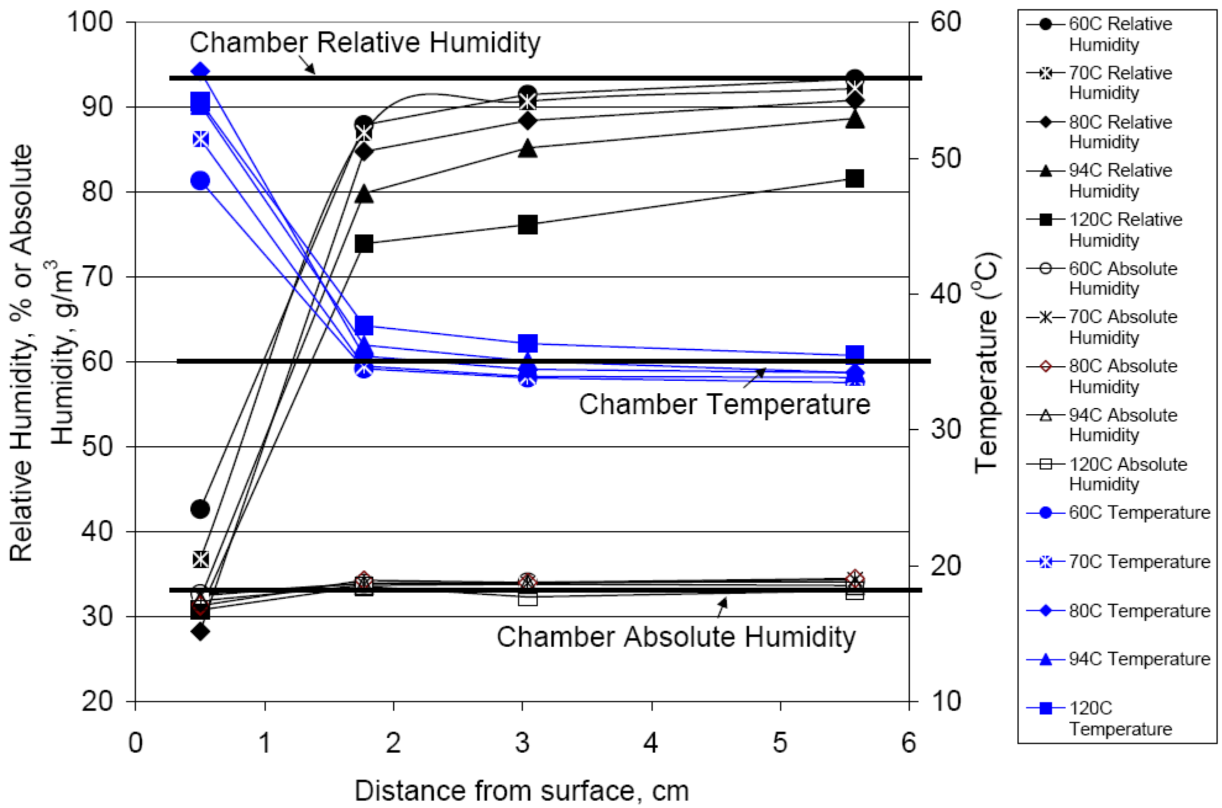
Thermal load in chamber required high absolute humidity to achieve representative relative humidity

Marine Climate and Test Conditions



- RH as a function of temperature and absolute humidity
- Atmospheric data shows dew points below 30ºC [85ºF]
- Maximum absolute humidity typically less than 30 g/m²
- Possible to have temperature > 50ºC [122ºF] and RH sufficient for deliquescence of $MgCl_2$
- Test conditions used a conservative absolute humidity value of 60 g/m²

Temperature and Relative Humidity Profiles



- Relative humidity lower near sample surface
- Temperature increased near the samples
- Little variation in absolute humidity

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Interpretation of Results

- No corrosion after 2-week salt deposition
  - Accelerated salt deposition achieved
  - Method not overly conservative
- SCC occurred on specimens tested at 40^{o}C [104^{o}F]
  - High RH led to partial deliquescence of deposited salts
  - Partial deliquescence sufficient to initiate SCC
- SCC of 316L observed after 32 weeks of testing
  - Marginal increased resistance of 316L compared to 304 and 304L
- No SCC on specimens tested at 85 and 120^{o}C [185 and 248^{o}F]
  - No deliquescence at high temperature and lower RH
  - Limited susceptibility of ISFSI casks to chloride SCC in marine atmospheres

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Conclusions

- A method for conducting accelerated testing in marine atmospheres was developed
- Deliquescence of deposited sea salts can promote SCC in austenitic stainless steels
- Higher temperatures, which generally promote SCC, are beneficial because salt deliquescence is prevented
- SCC susceptibility of ISFSI storage canisters is limited to a narrow range of environmental conditions

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