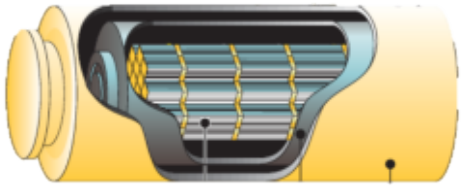
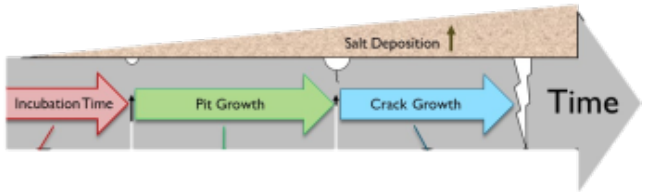
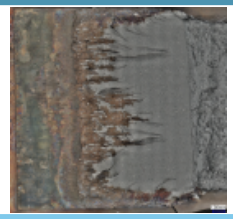
SAND2022-2195C

Sandia National Laboratories

Stress Corrosion Cracking of Austenitic Stainless Steels in Concentrated Chloride Environments







PRESENTED BY

Ryan M. Katona

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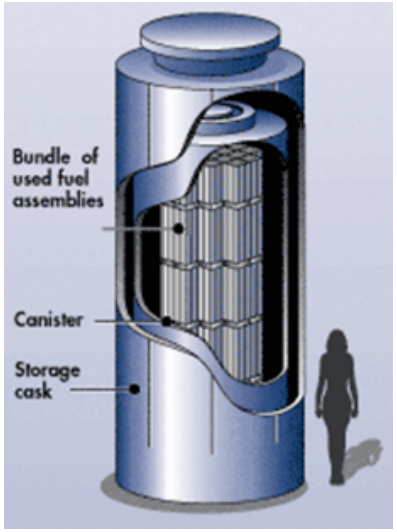
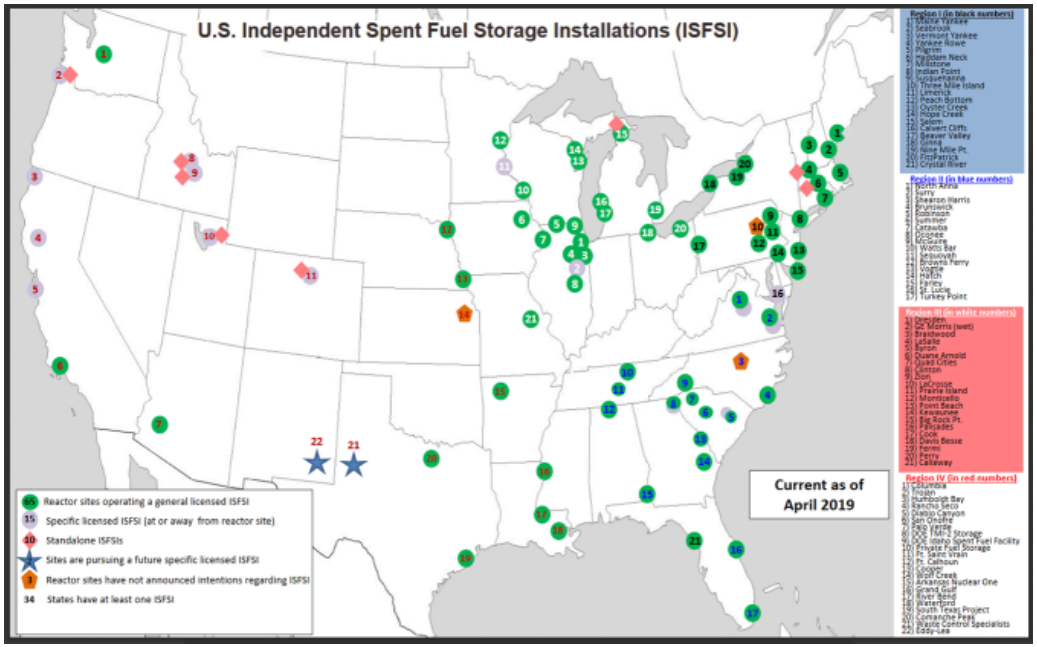
U.S. DEPARTMENT OF ENERGY NNSA

Spent Nuclear Fuel Storage

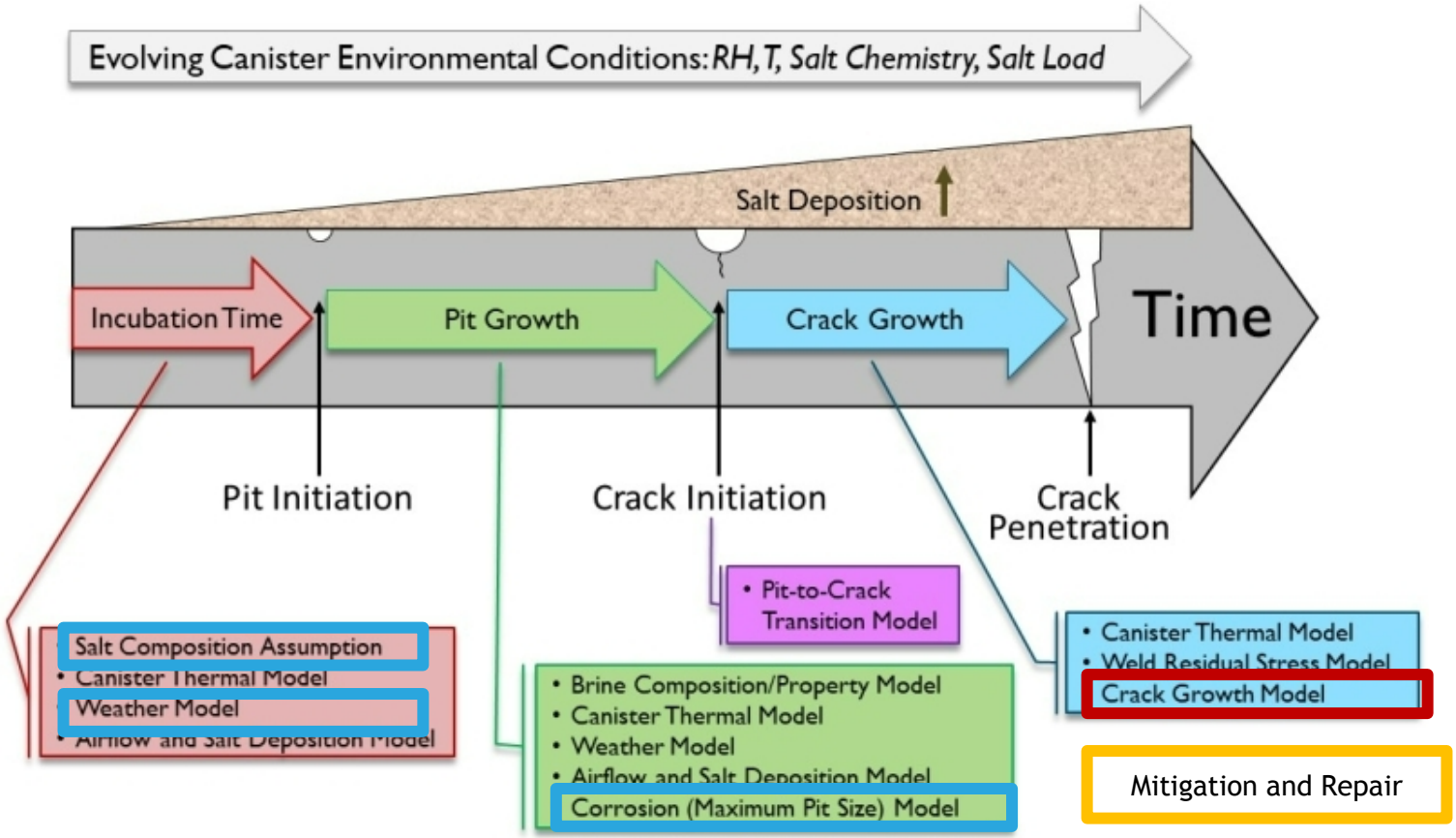
- US has over 86,000 metric tons of Spent Nuclear Fuel (SNF)
  - > 3600 stainless steel (SS) canisters
  - > 70 storage sites
- Interim storage sites being utilized longer than initially intended
- US has no permanent disposal site selected for SNF



SNF Canister inside concrete overpack

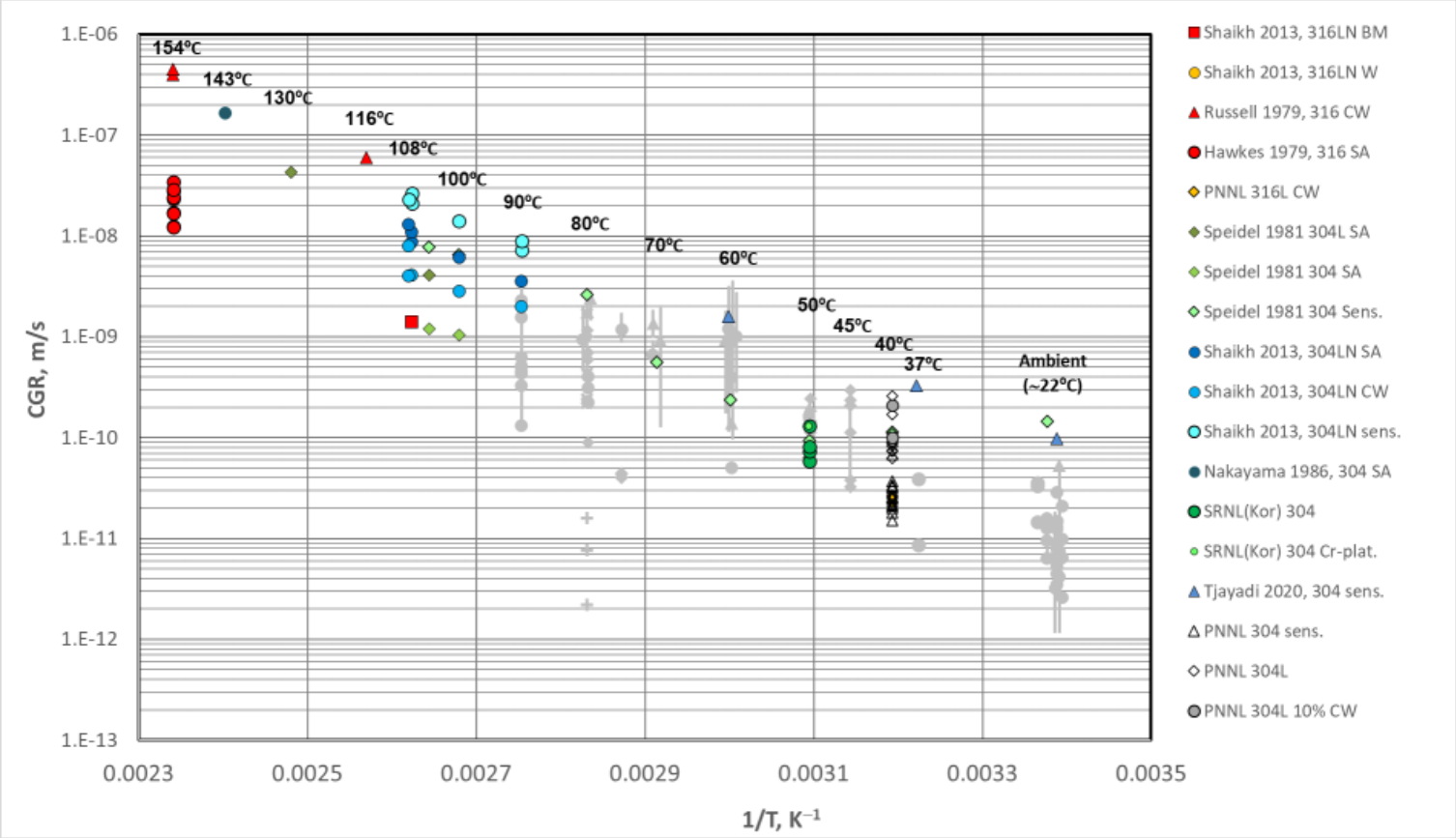


Integrated Mechanistic/Probabilistic Model for Canister SCC



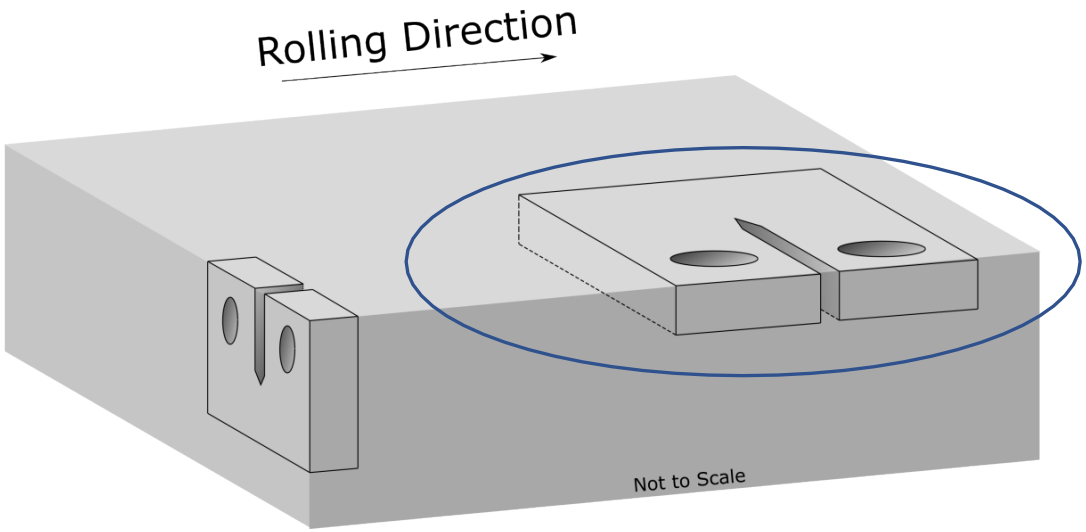
- Check out:
  - **Dr. Erin Karasz** (*Accelerated Corrosion Testing Of Cold Spray Coatings On 304L In Chloride Environments*)
  - **Dr. Ryan Katona** (*Environmental Influences on Maximum Pit Sizes for Austenitic Stainless Steels Utilized in Spent Nuclear Fuel Storage*)
  - **Timothy Montoya** (*Poster Session - Long term, simulated marine diurnal exposure of Austenitic Stainless Steel at elevated temperatures*) and **Armando Shehi** (*The Effect Of Sulfate-To-Chloride And Nitrate-To-Chloride Ion Ratio On The Kinetic Parameters For Pit Stability*)

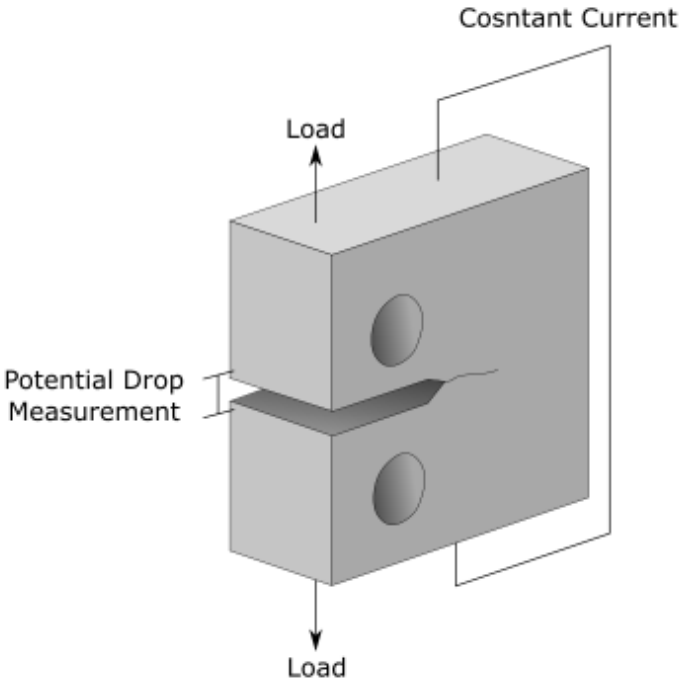
Arrhenius Temperature Dependence of Crack Growth

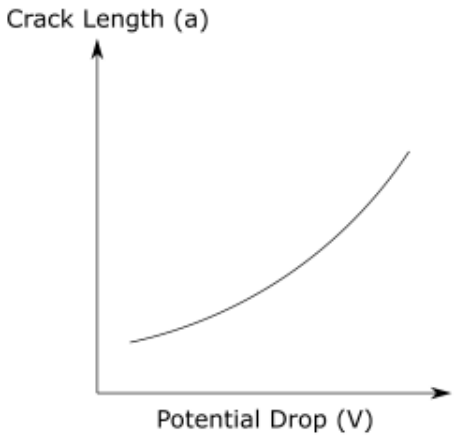


- Various collection methods, environments, lot of material, sensitization state, etc.
- ***What are the governing factors and will certain factors cause accelerated growth?***

Sample Orientation and *In-Situ* Testing Methodology

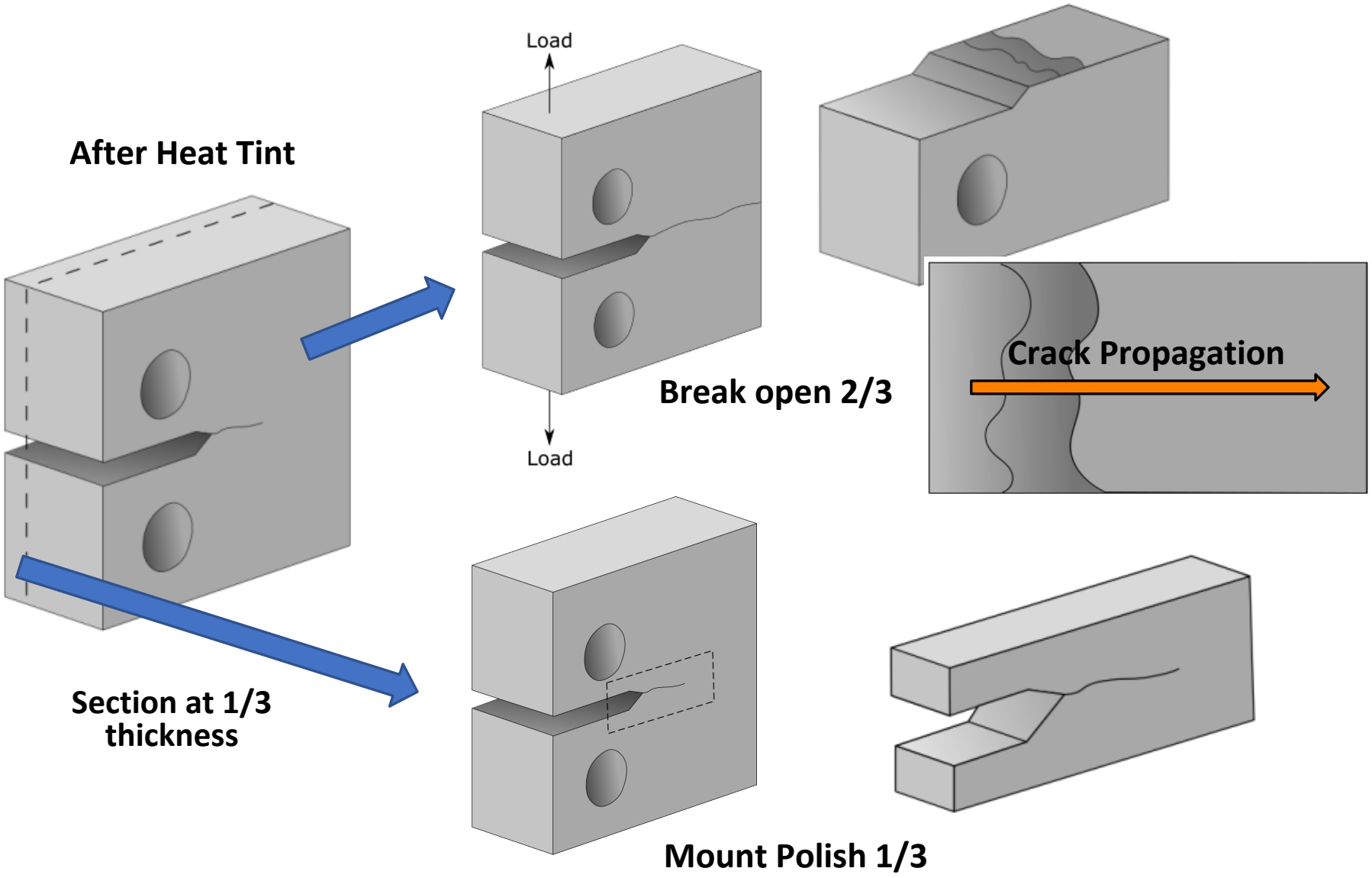




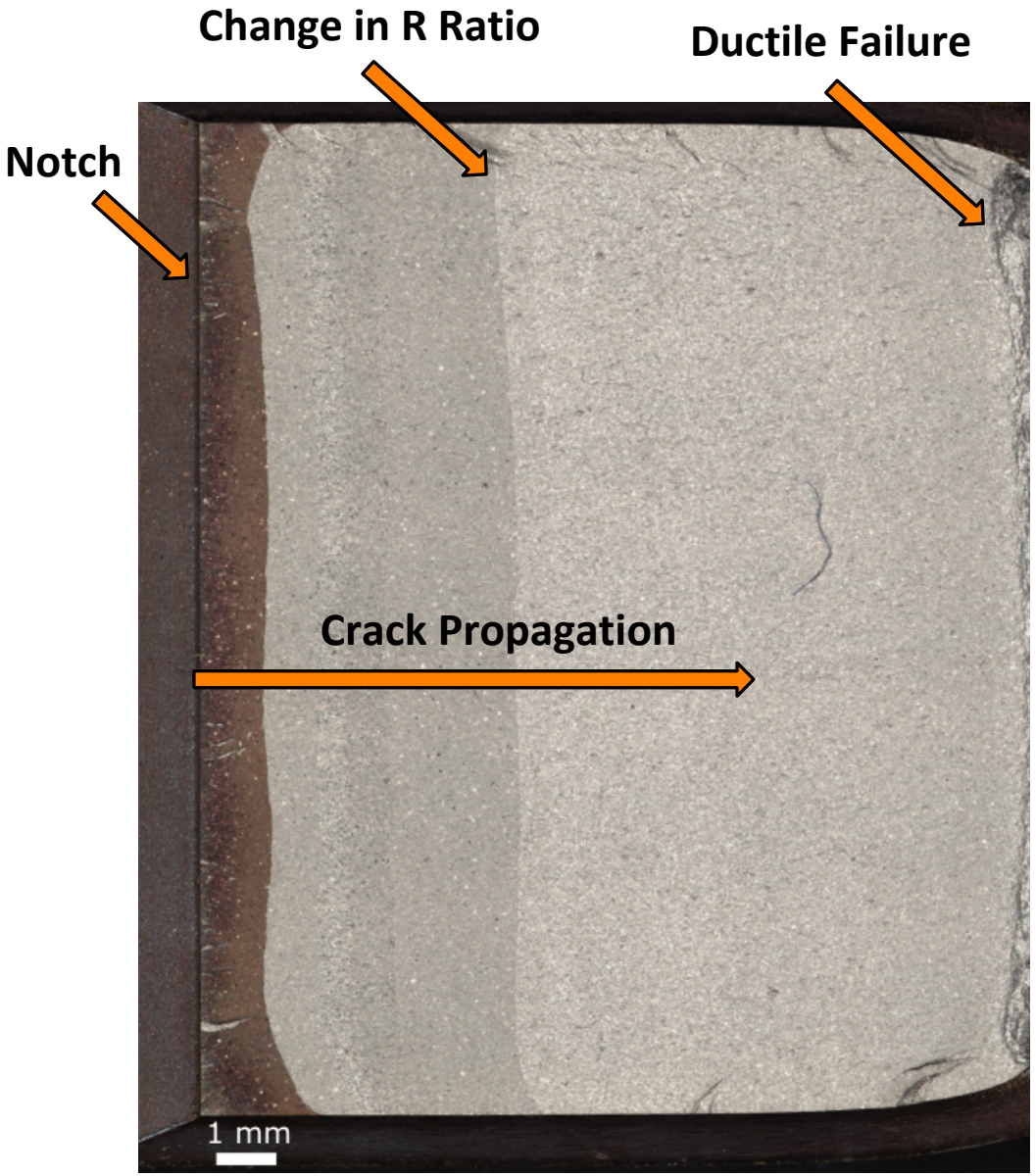


- Majority of samples presented will be in the L-T orientation
- Annealed ASTM SS304L (information in supplemental)
- Utilizing Direct Current Potential Drop (DCPD)

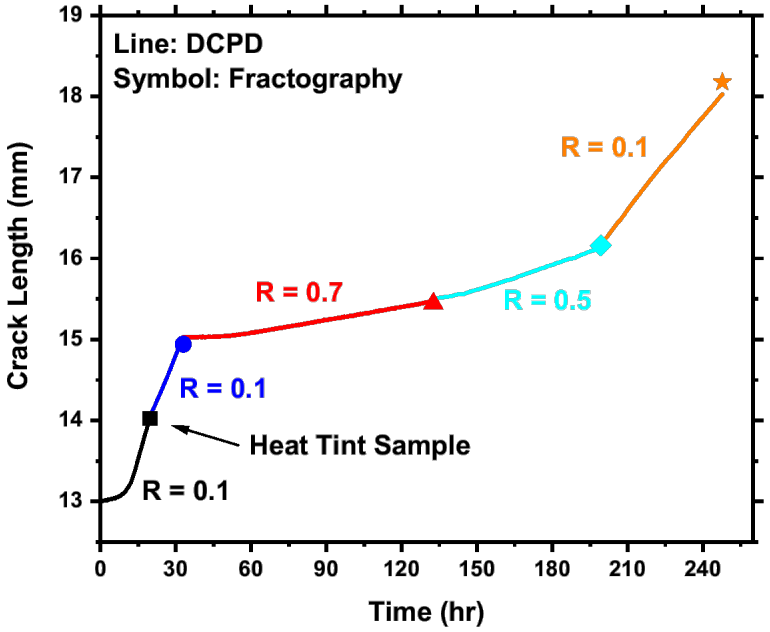
Methods for Post Test Sample Analysis



Calibration of DCPD Set-up

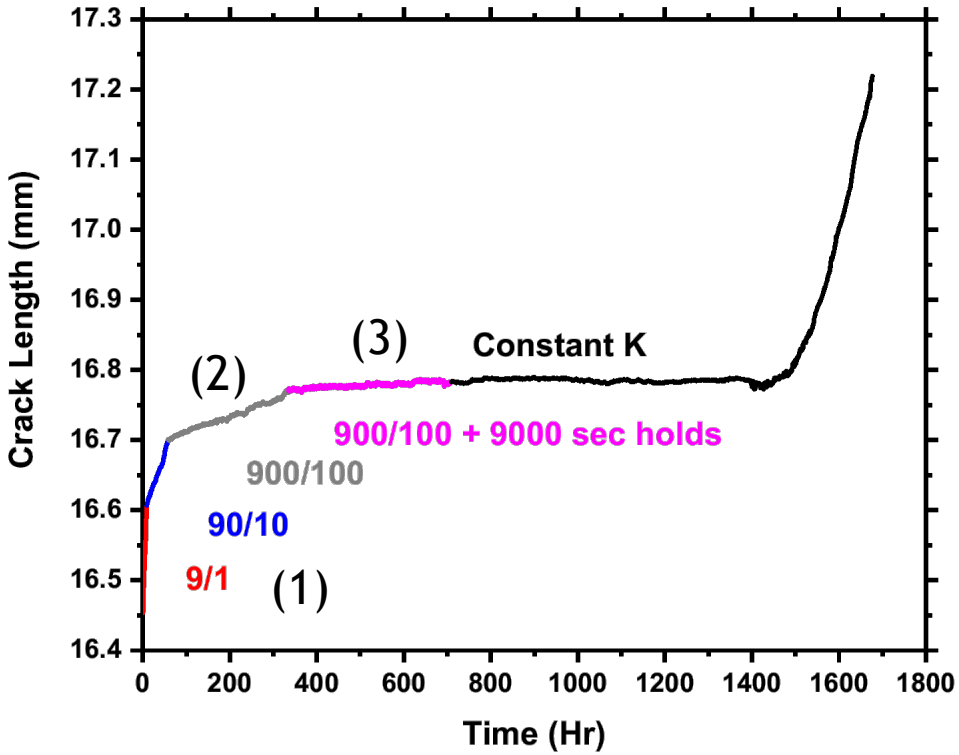


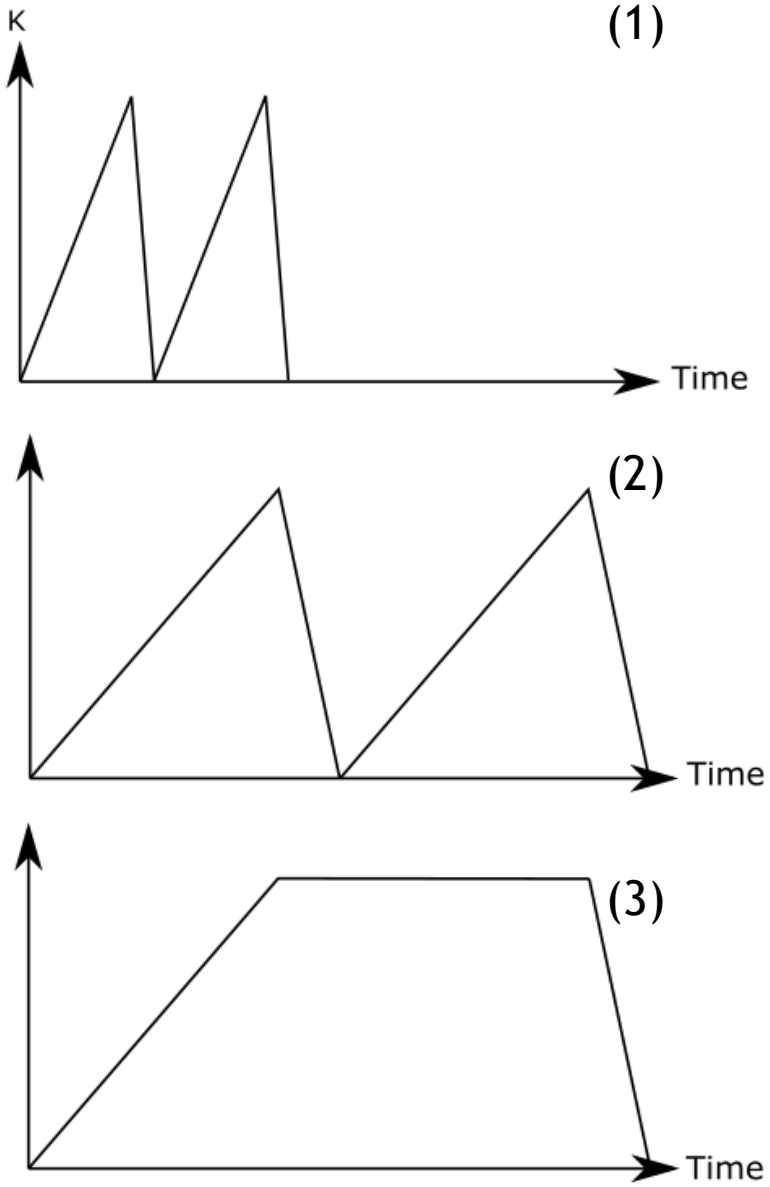
Calibration of DCPD Set-up



- Performed on two different load frames
- Confidence DCPD system is set-up correctly

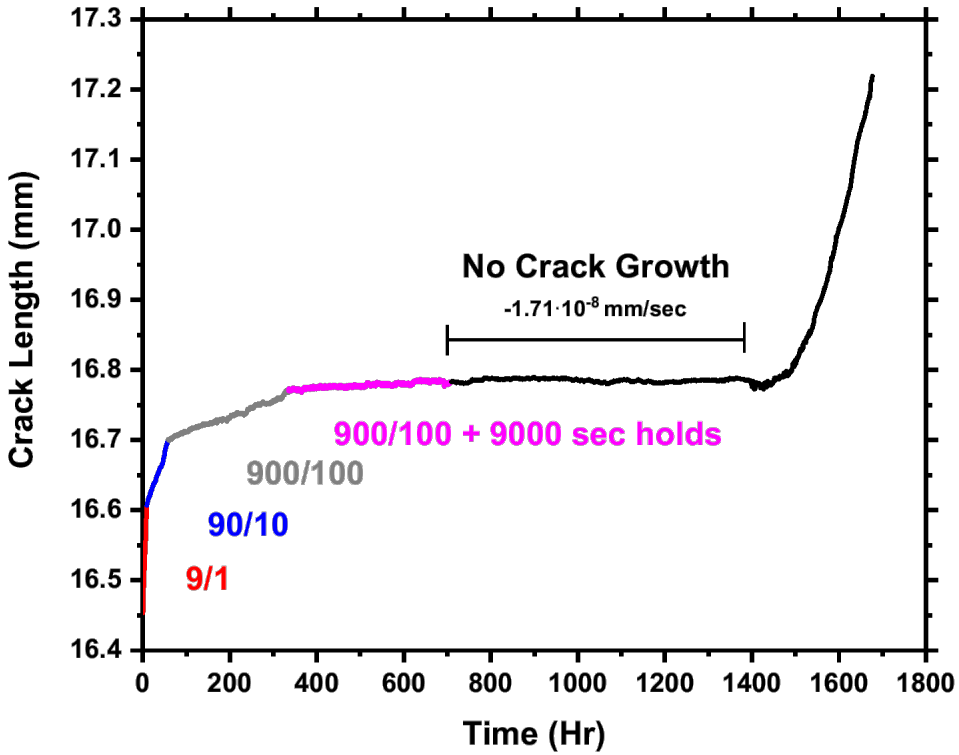
SS304L Exhibits Delayed Crack Growth Under Constant K in $MgCl_2$ at 55 ˚C





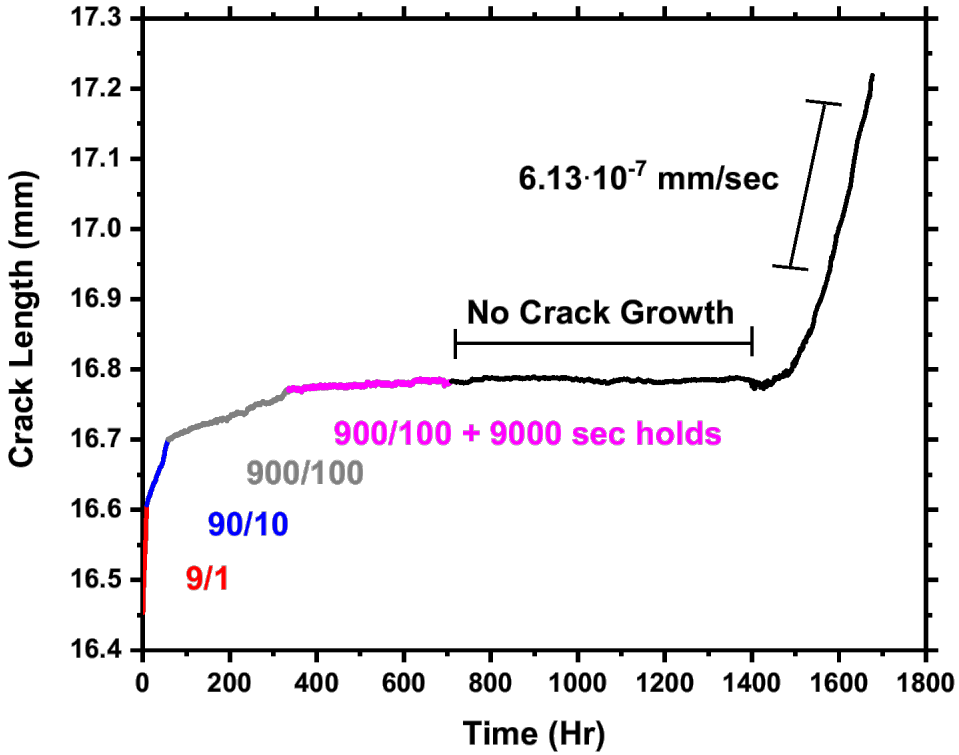
- Decreasing frequency under K control to constant K state
  - 'True' crack plane for constant K SCC
- $K_{max} = 20\ MPa\sqrt{m}$

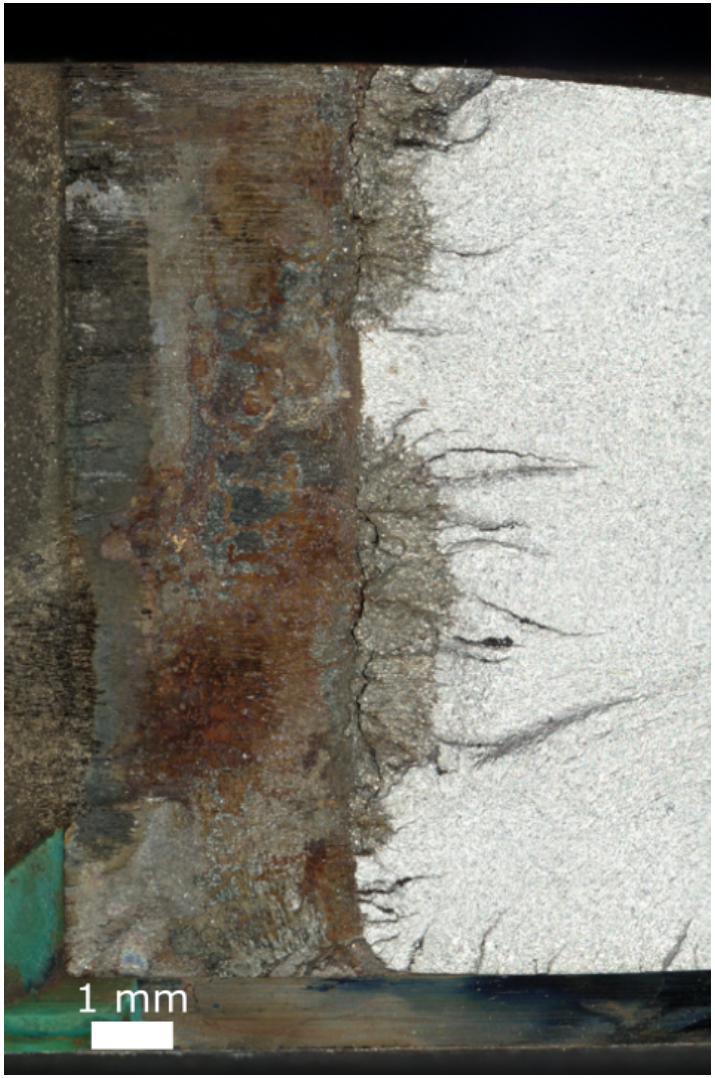
SS304L Exhibits Delayed Crack Growth Under Constant K in $MgCl_2$ at 55 ˚C



- No growth for ~ 700 hours

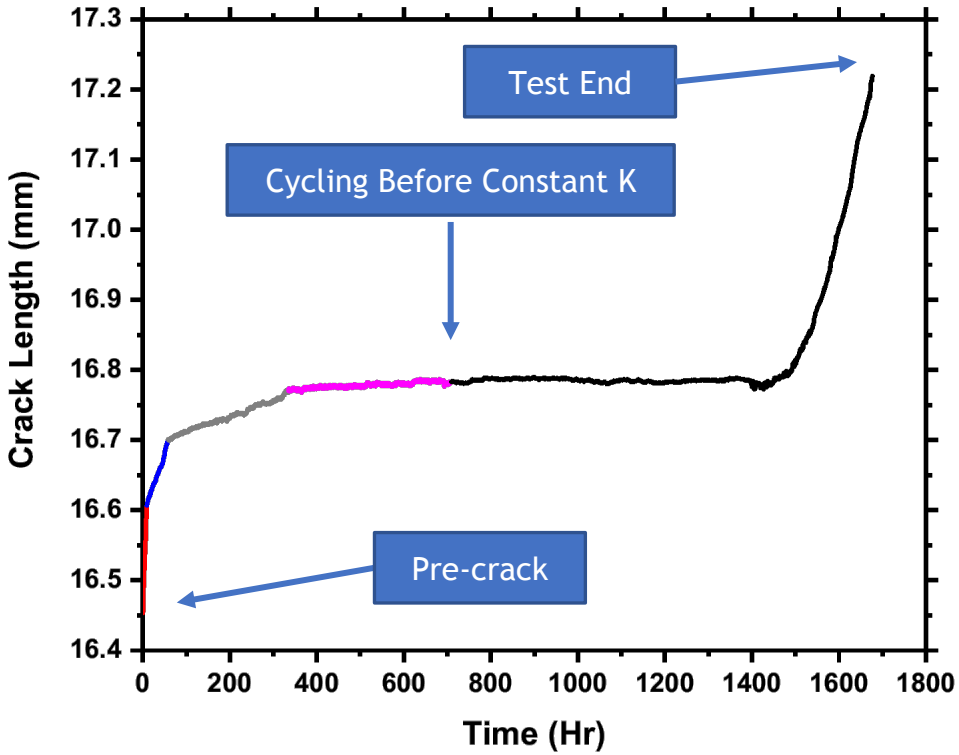
SS304L Exhibits Irregular Crack Front in Saturated $MgCl_2$ at 55 ˚C

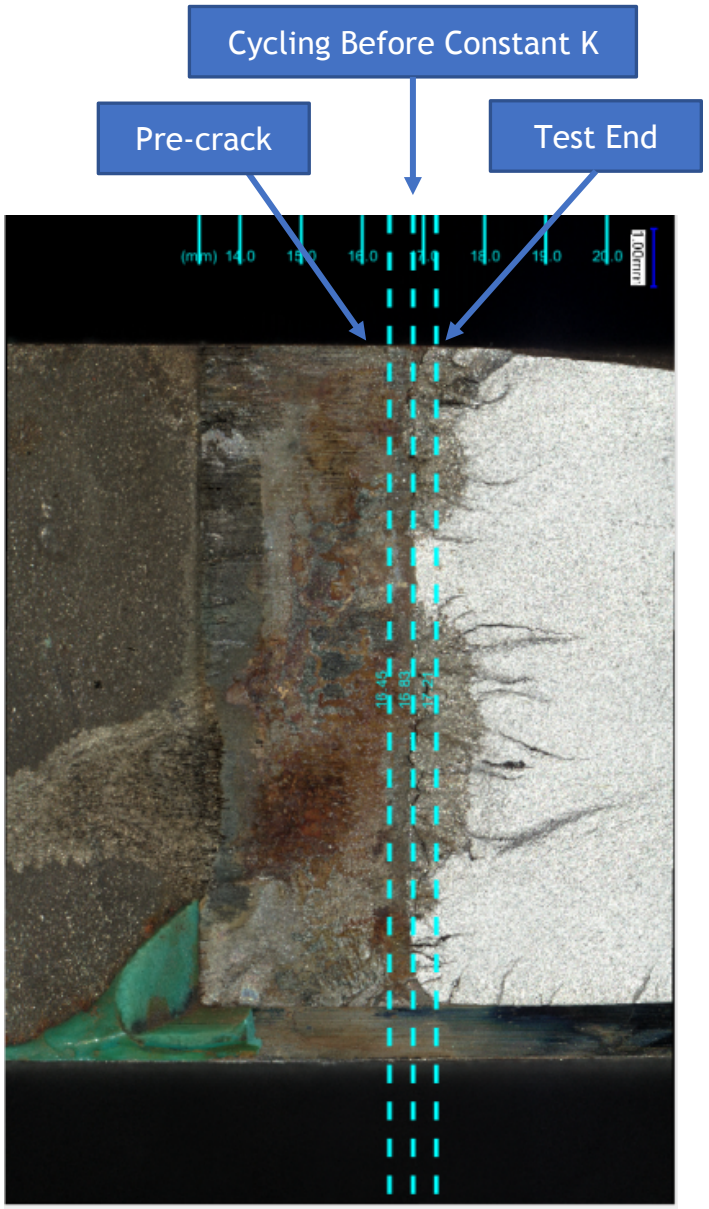




- After roughly 1500 hours of total test time, cracking ensues
- Sample was cut at 1/3 of thickness

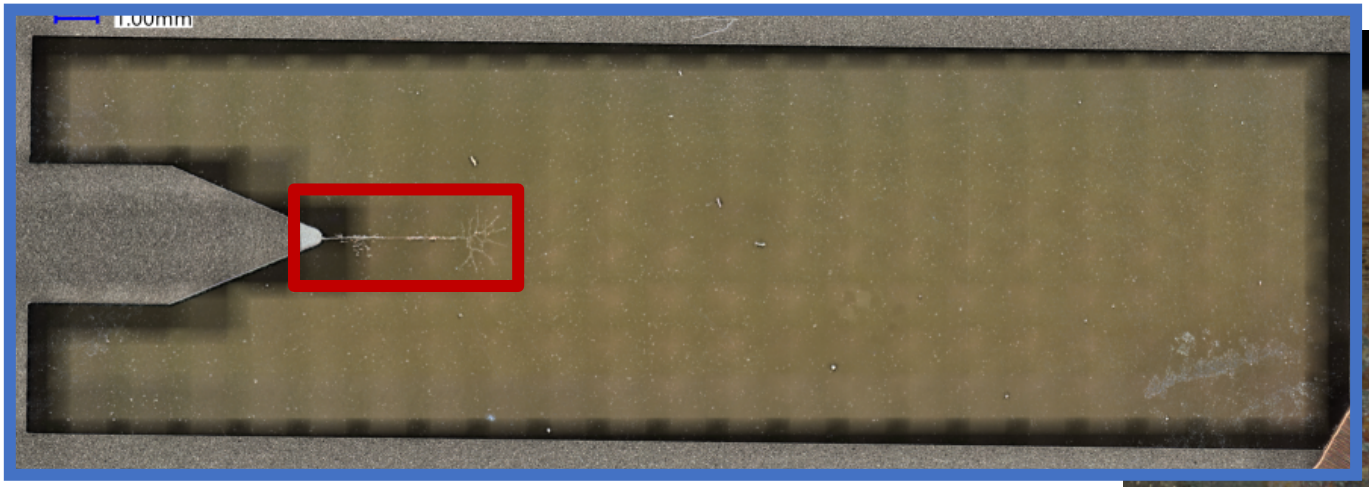
SS304L Exhibits Irregular Crack Front in Saturated $MgCl_2$ at 55 ˚C

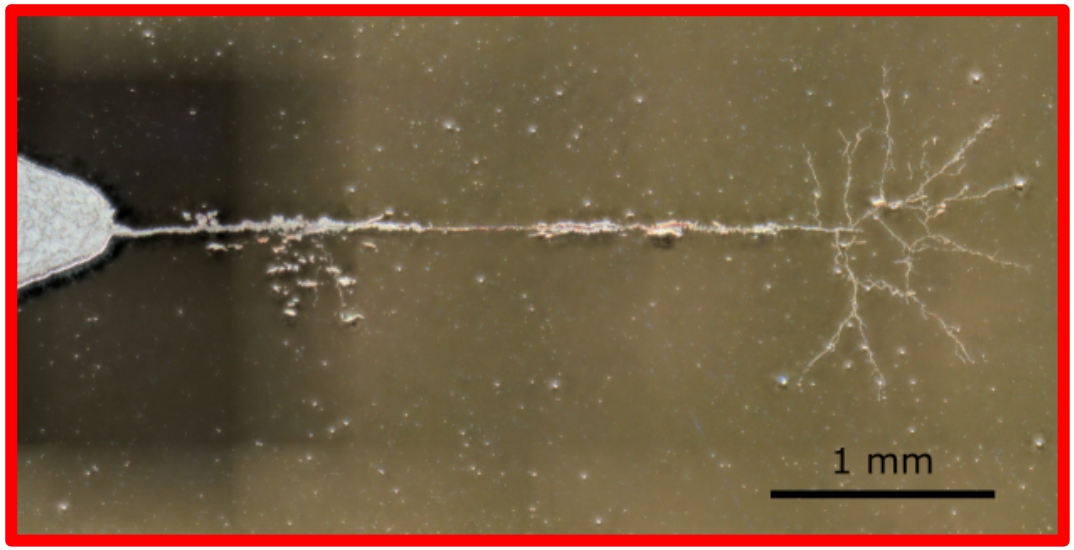


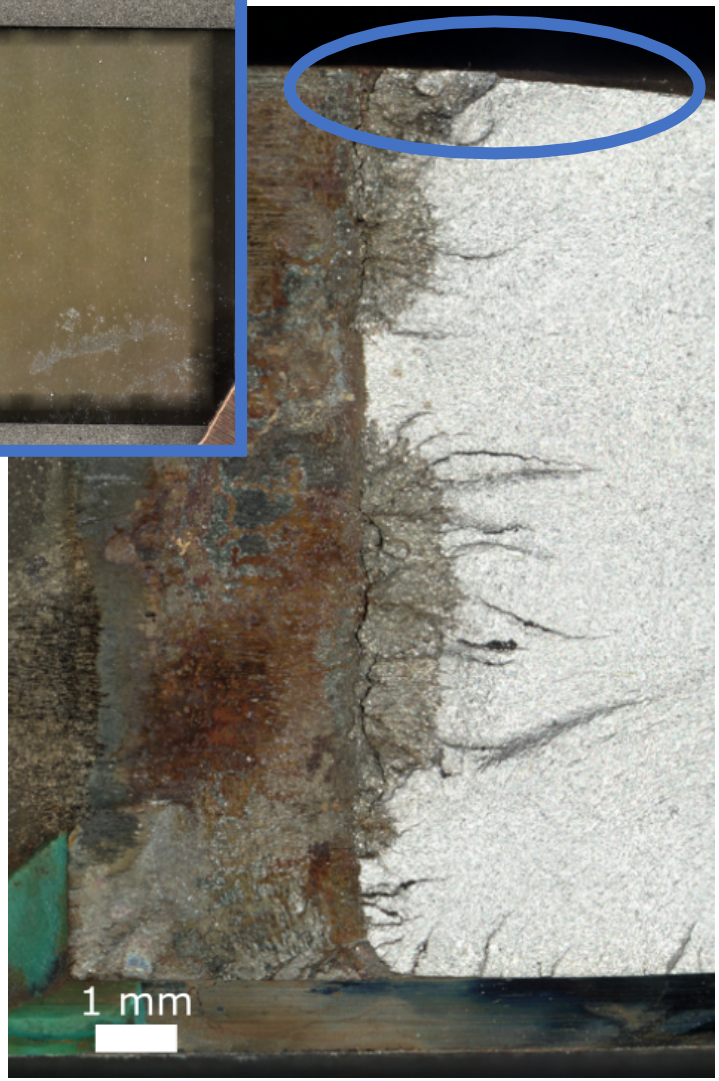


- Overlay of DCPD on fractography potentially suggests cracking halted at the uniform ‘ledge’

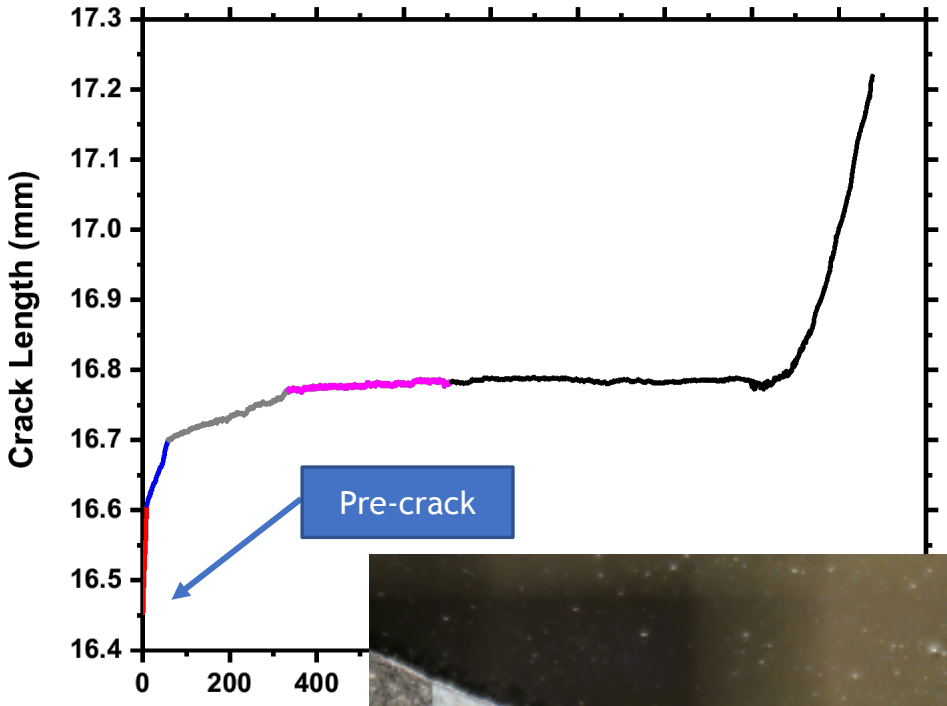
SS304L Exhibits Crack Branching in Saturated $MgCl_2$ at 55 ˚C

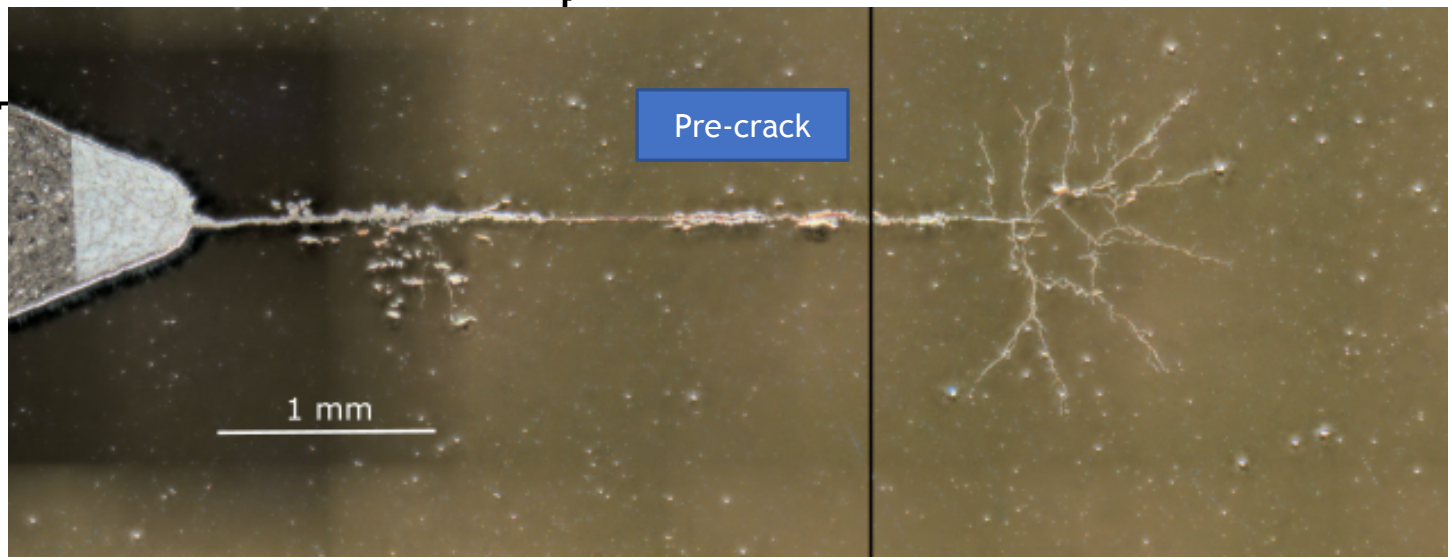






SS304L Exhibits Crack Branching in Saturated $MgCl_2$ at 55 ˚C





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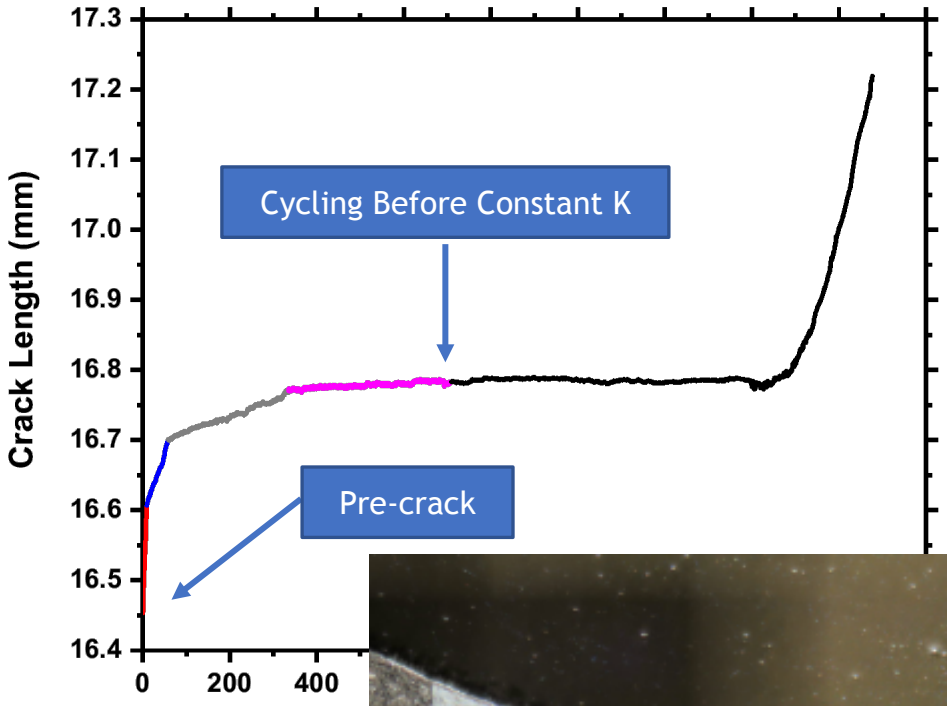

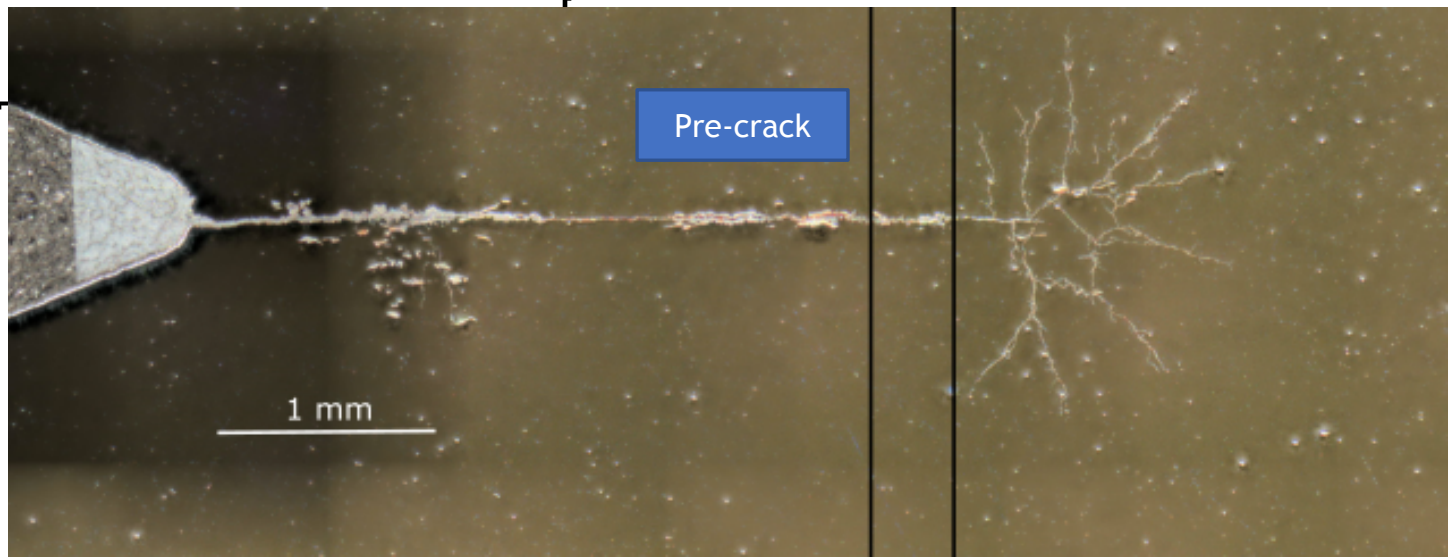

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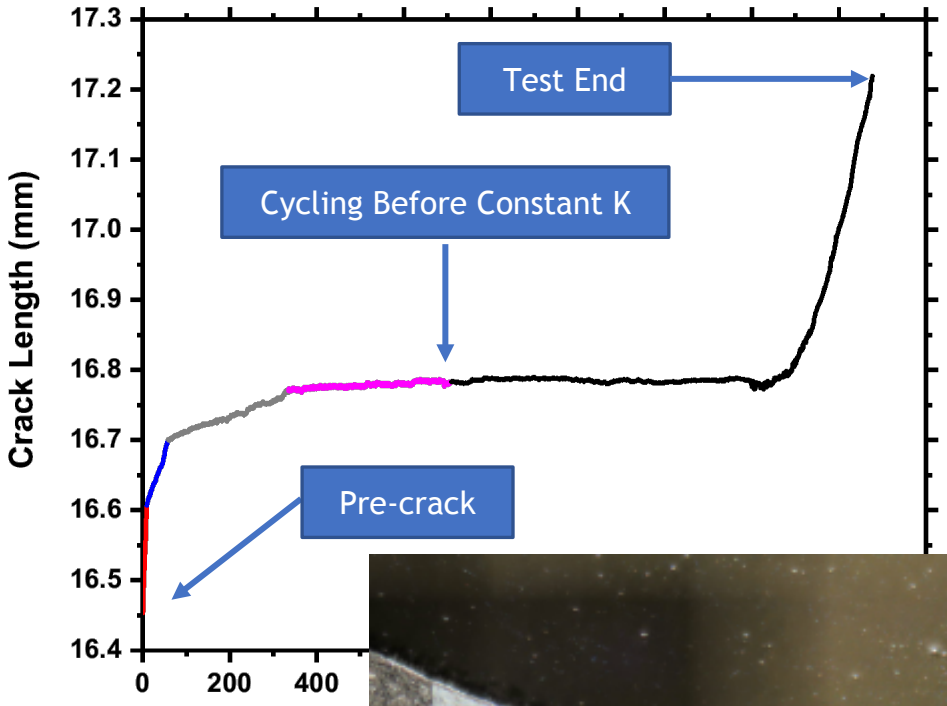

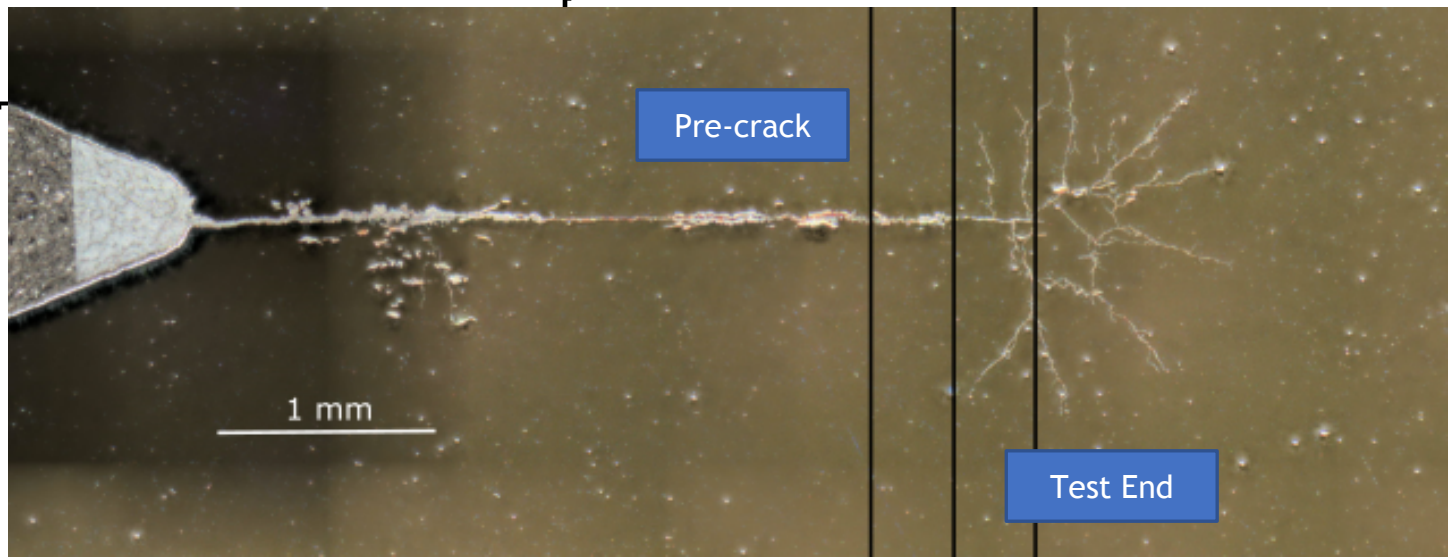

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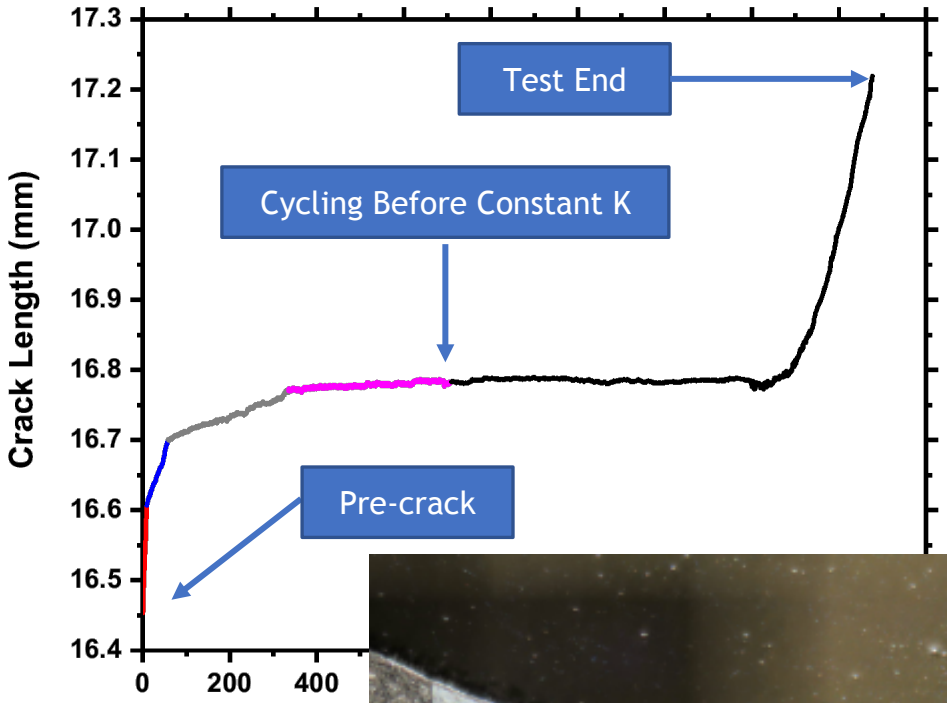
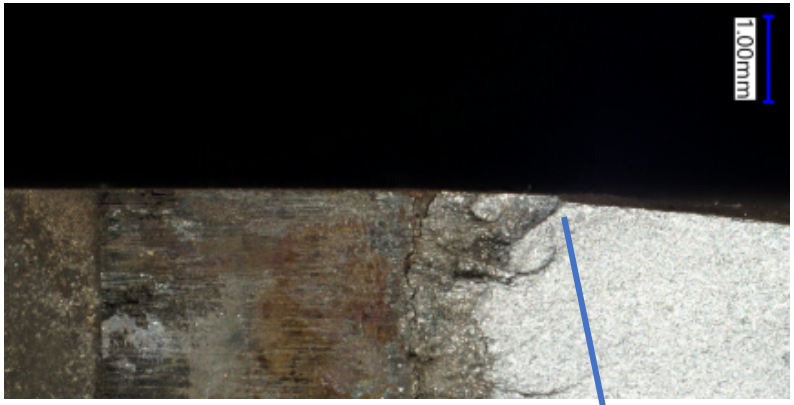
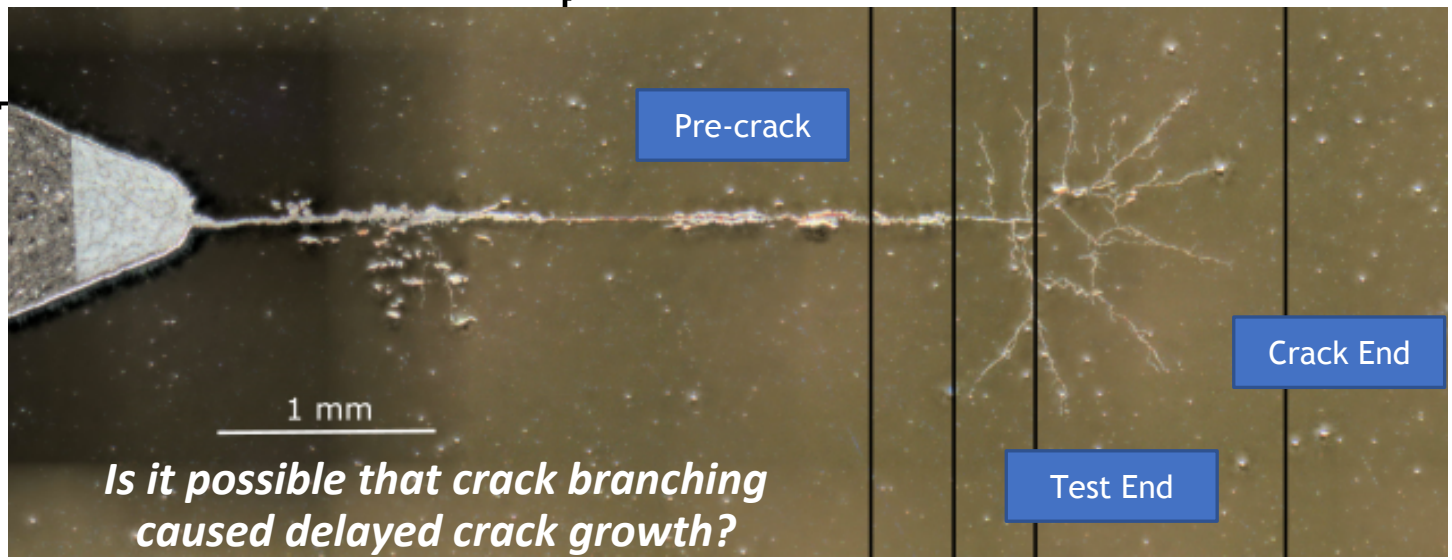


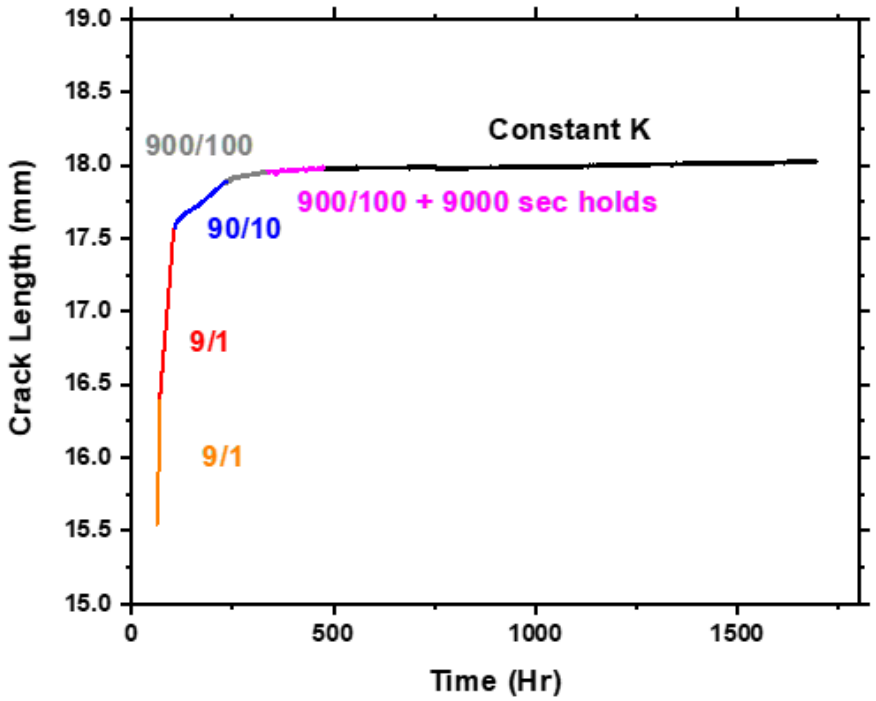


Cycling Before Constant K

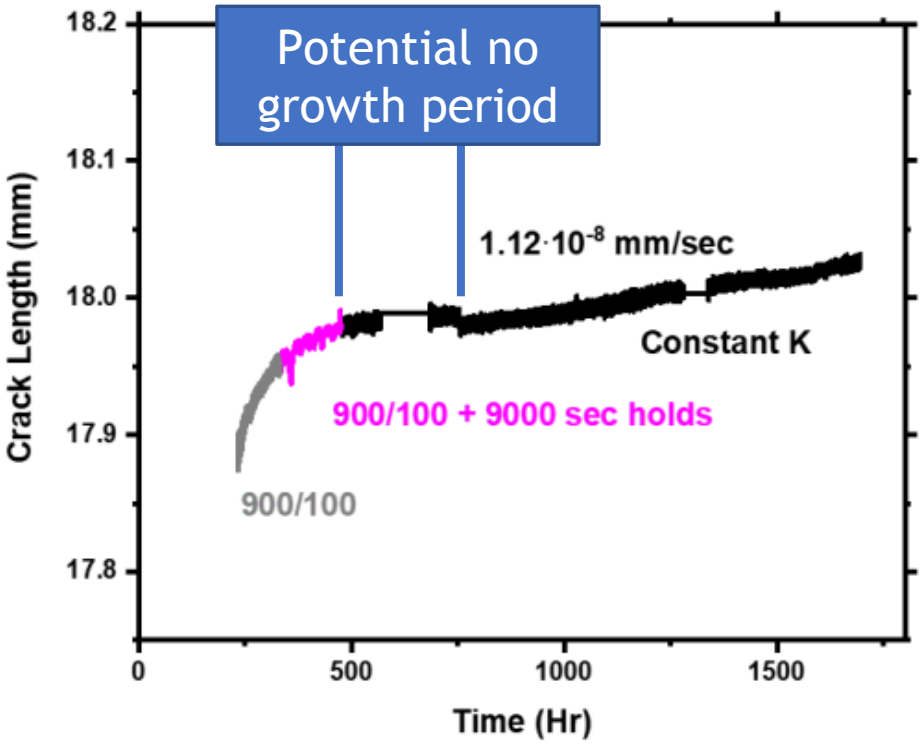


Is it possible that crack branching caused delayed crack growth?

Low Crack Growth Rate for in Saturated $MgCl_2$ at 25 ˚C

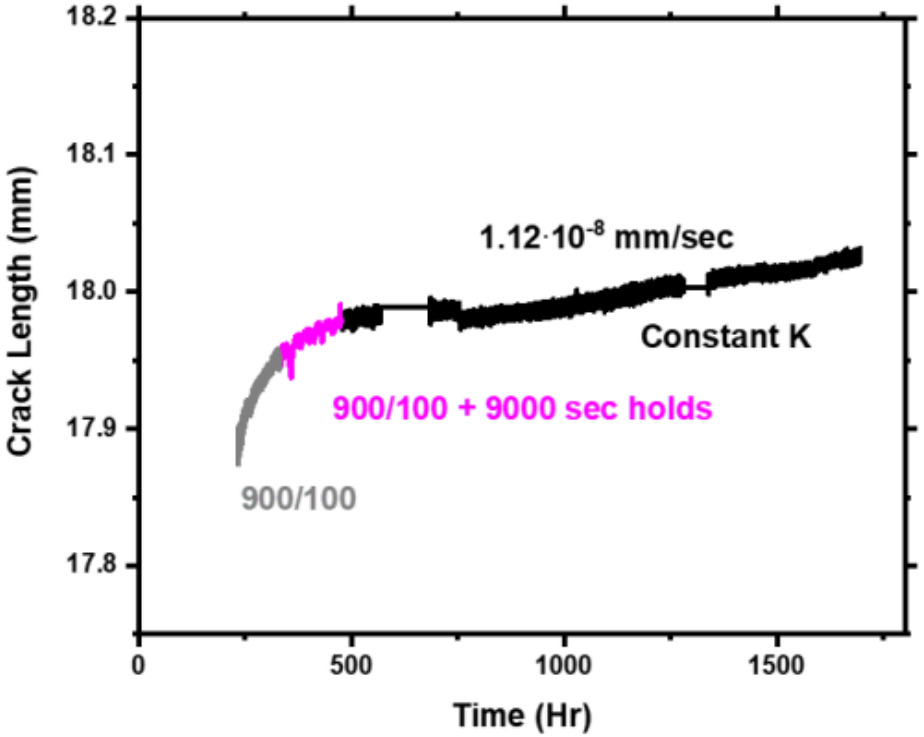


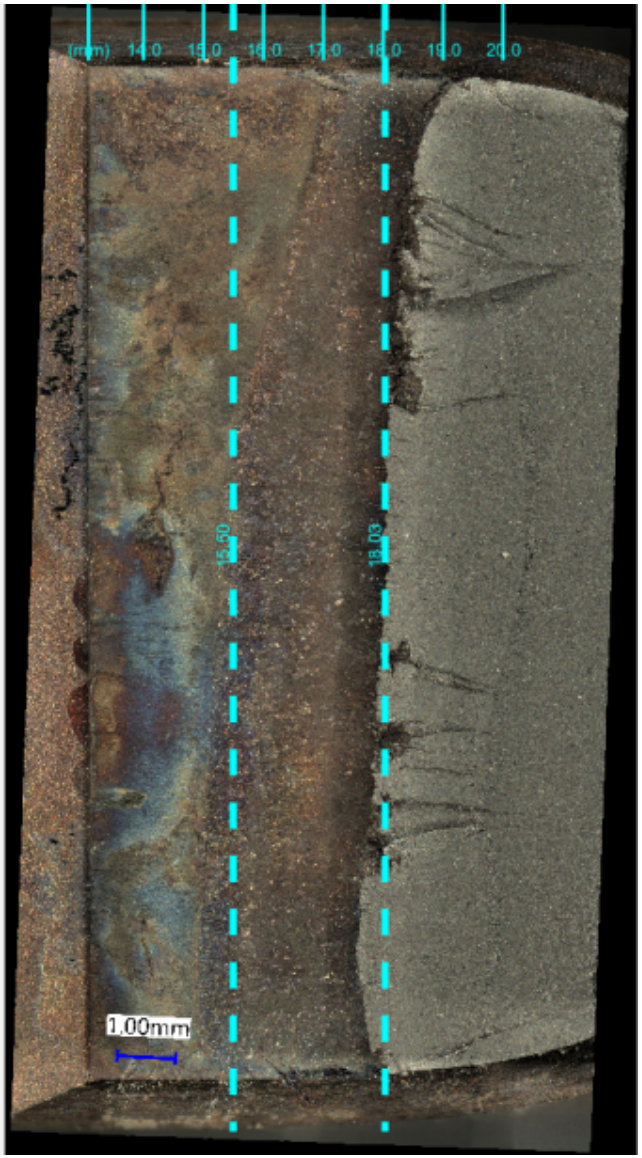
Low Crack Growth Rate for in Saturated $MgCl_2$ at 25 ˚C Experienced Localized Cracking



- Similar delay in indicated crack growth to 55 ˚C
- Sample was not sliced but fractured open
- Similar crack morphology to 55 ˚C however are thinner regions

SS304L Exhibits Irregular Crack Front in Saturated $MgCl_2$ at 25 ˚C





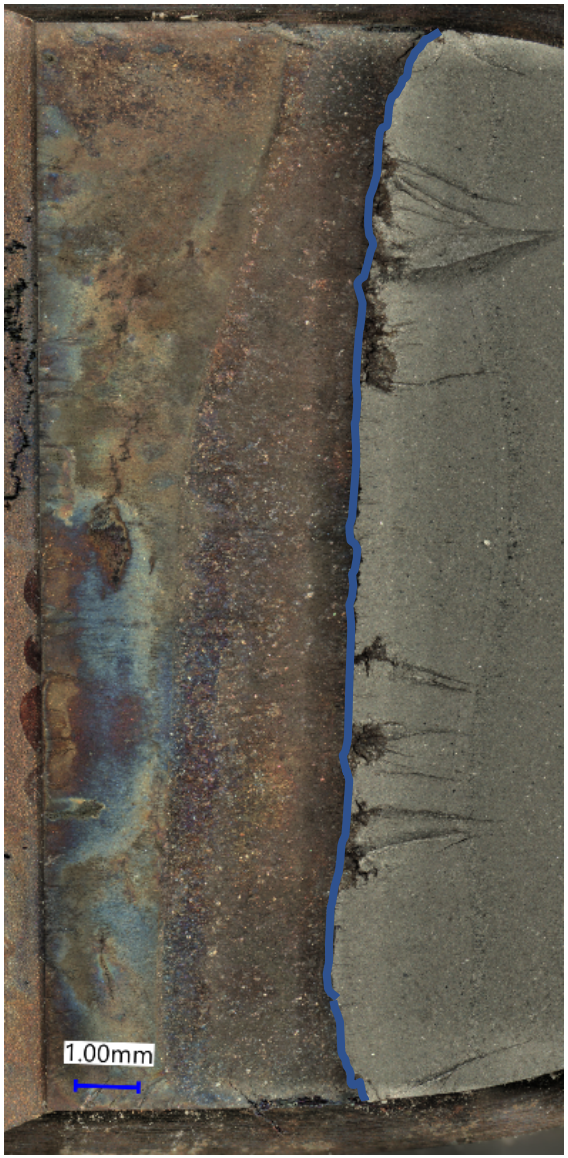
- Slightly curved crack front makes overlay of DCPD difficult

SS304L Exhibits Irregular Crack Front in Saturated $MgCl_2$ at 25 ˚C

- Measured 100 points of extension from the drawn blue line and averaged
  - Integration of crack extension by hand

Method	Δa
DCPD	53.8 mm
Fractography	60.1 mm

- Compared to total crack extension during constant K portion
- Possible that growth in ‘protrusions’ ahead of blue line occurred during the constant K portion



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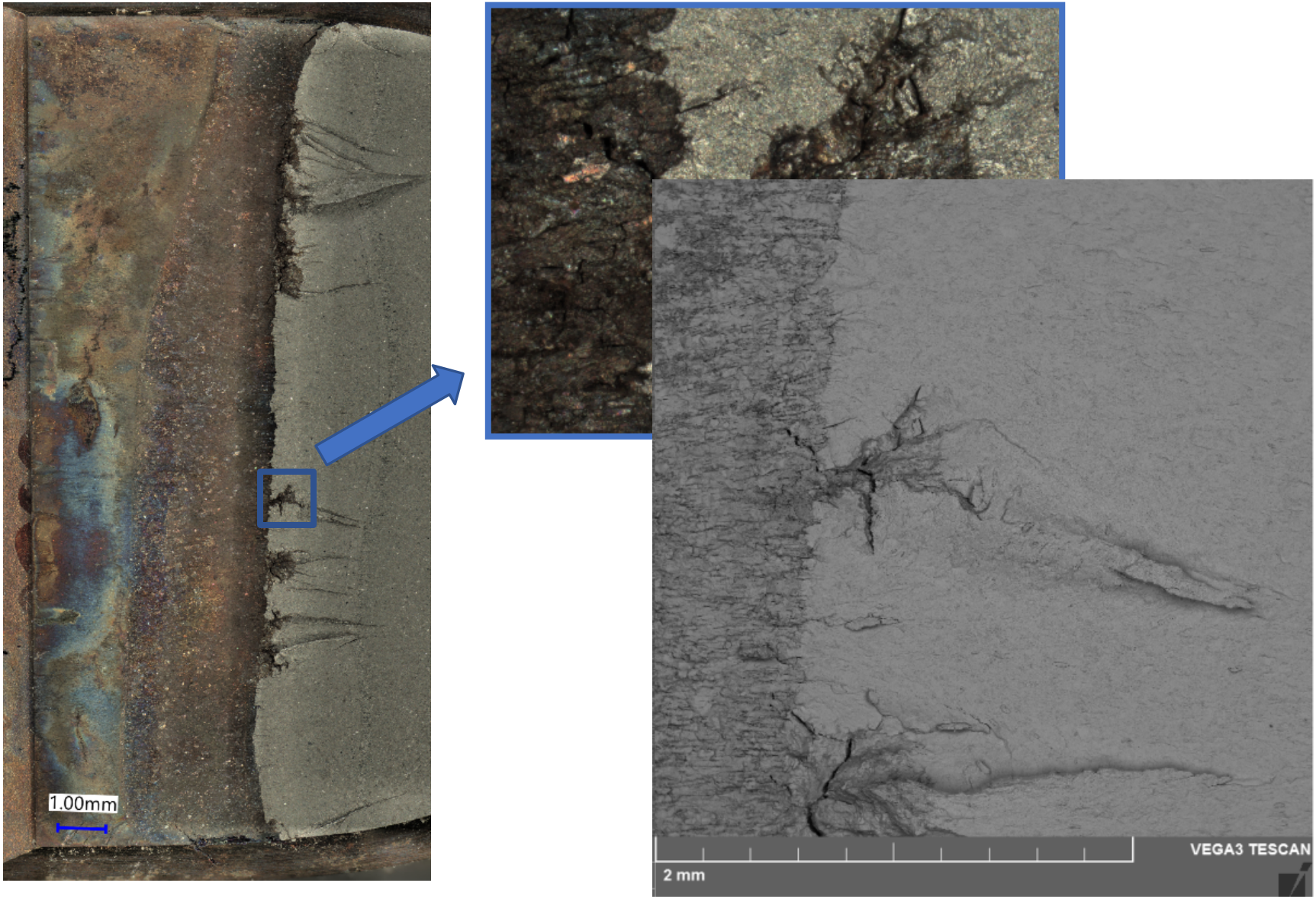

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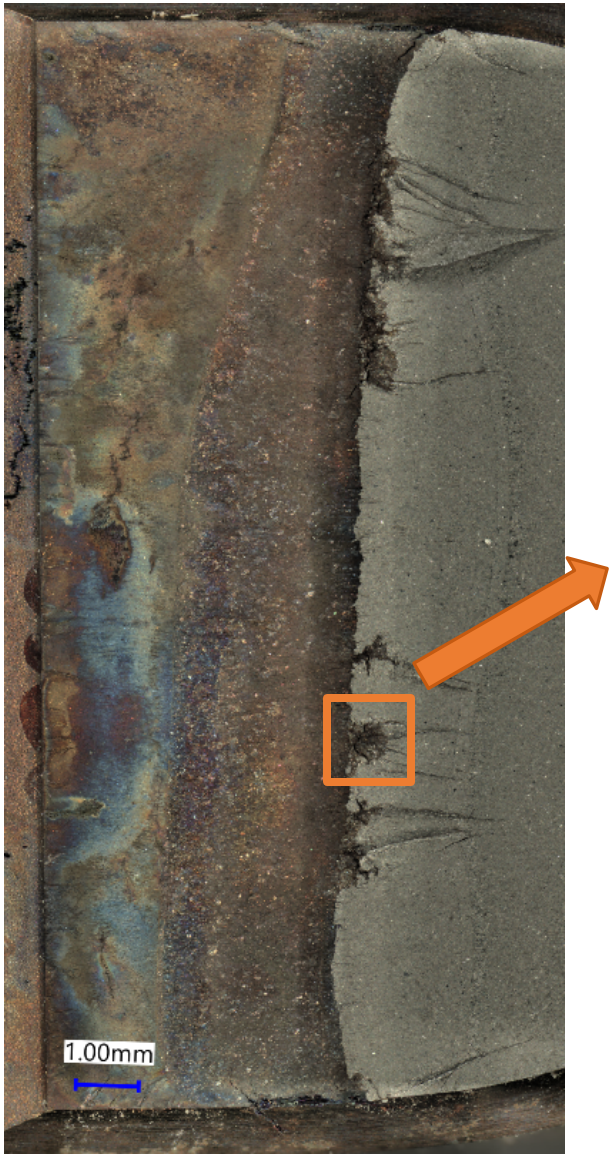
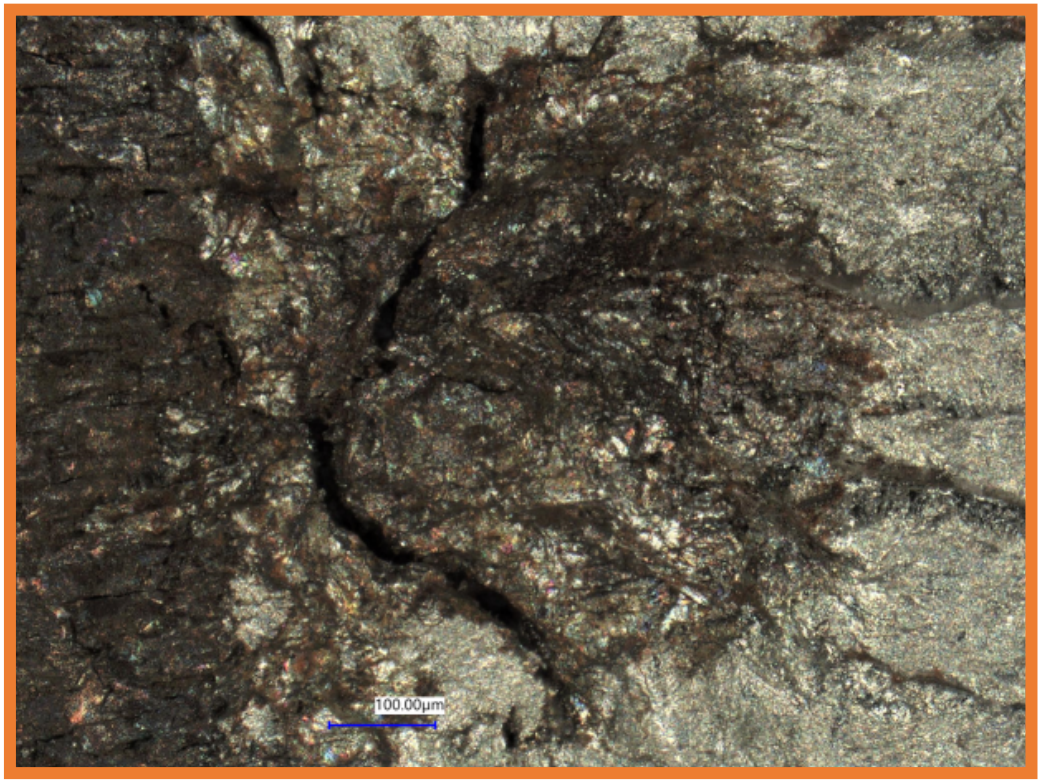
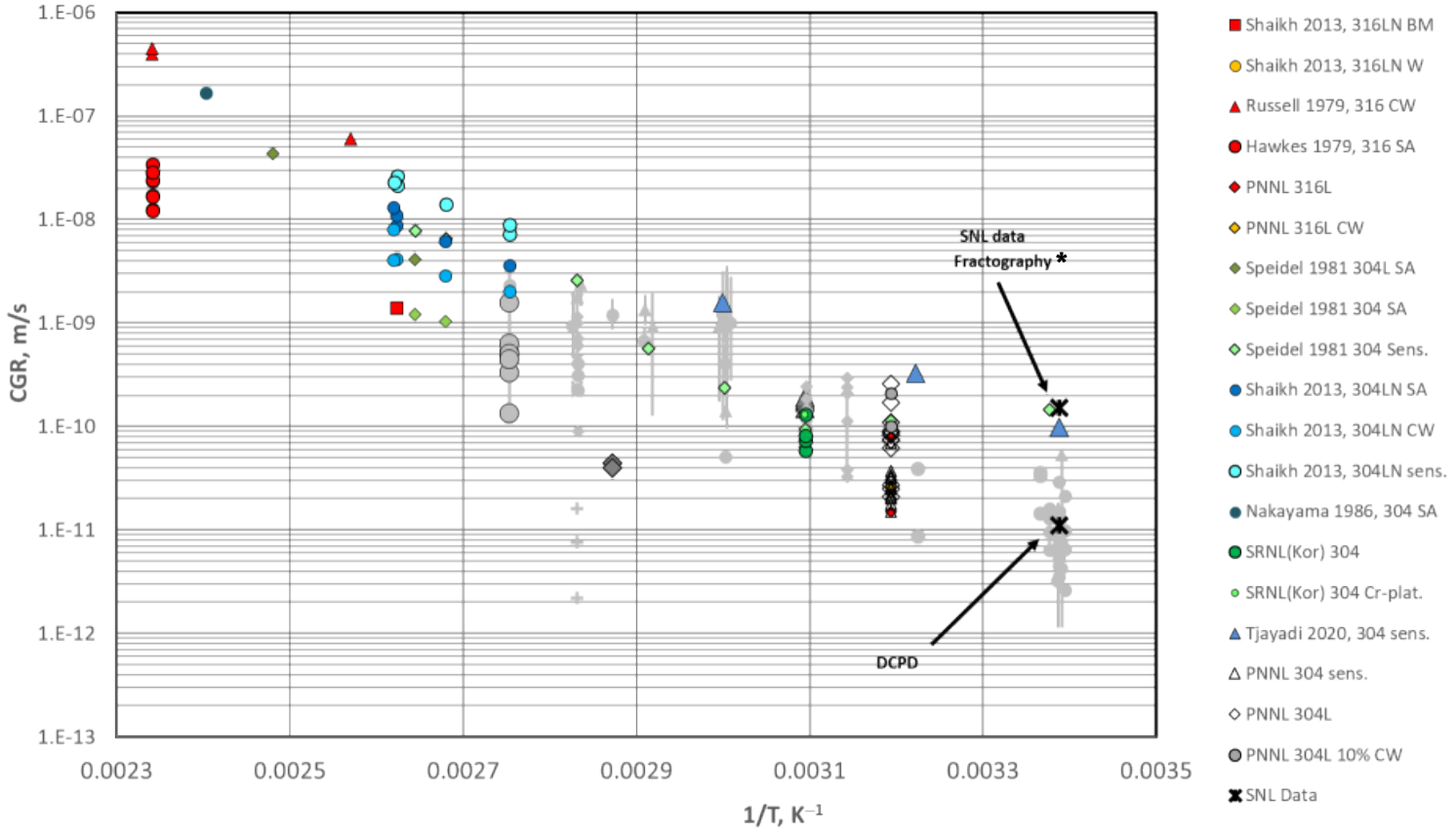




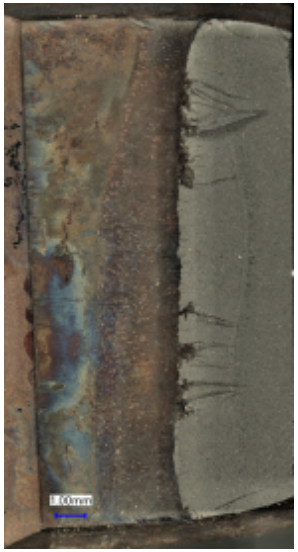
- Significant corrosion products on the surface
- Enhanced cleaning needed, however, crack wake corrosion could be eliminating features of interest
  - Looking for intergranular/transgranular fracture

Crack Growth of Furthest 'Protrusion' Potentially Order of Magnitude Higher Than DCPD



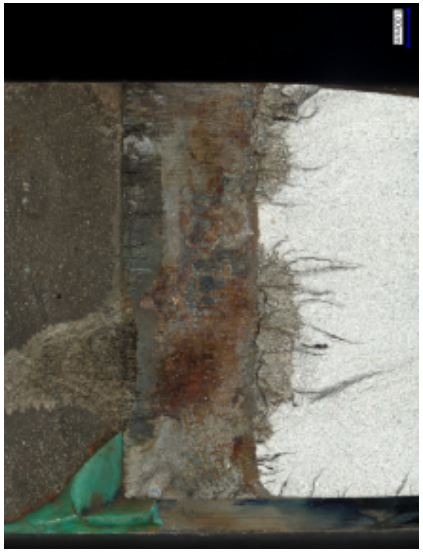
- Considering protrusion occurs during constant K portion of the test, an increased crack growth rate is calculated
  - *measured from deepest point of protrusion

Overview of $MgCl_2$ Samples



Lot 1 – RT

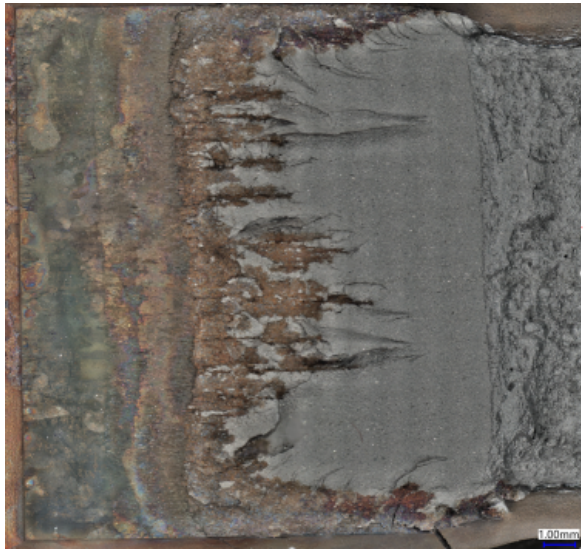
(1218 hours)



Lot 1 - 55 ˚C

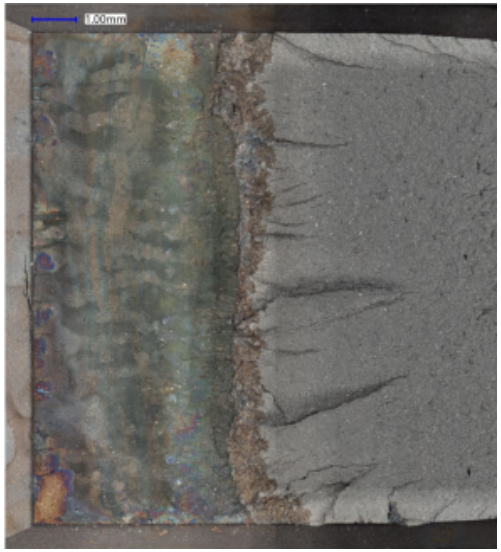
(709 Hours)

(450 hours of growth)



Lot 3 - 55 ˚ C

(650 Hours)



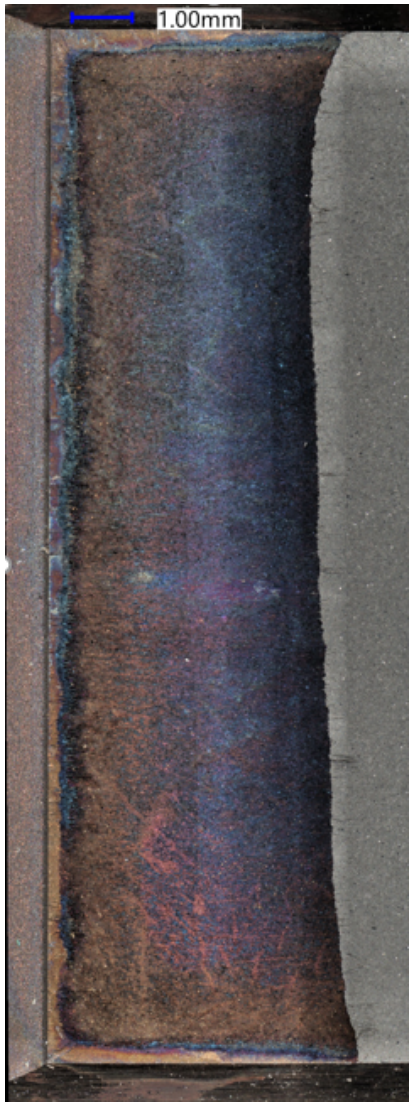
Lot 3 - 55 ˚ C (T-S)

(800 Hours)

(Time under Constant K)

- Crack morphologies show influence from temperature, lot, and direction

Overview of Saturated NaCl Samples



No indicated crack growth

Lot 1 – RT

Roughly 50 µm of crack extension during constant K

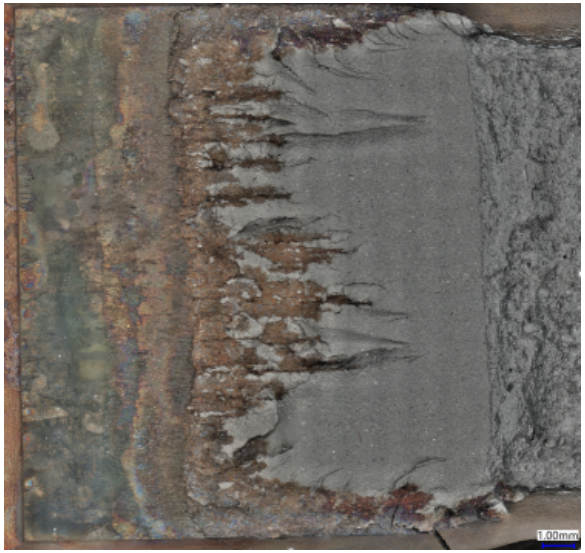
Crack growth rate of $2.1 \cdot 10^{-8}$ mm/sec

Lot 3 – 60 ˚C

What Causes Different Morphology Between Solution?

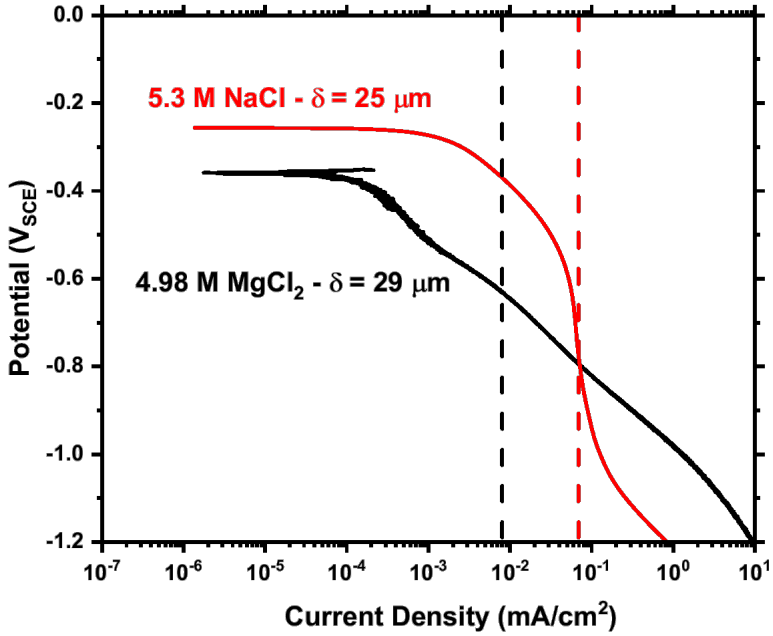
NaCl

Lot 3 – 60 ˚C

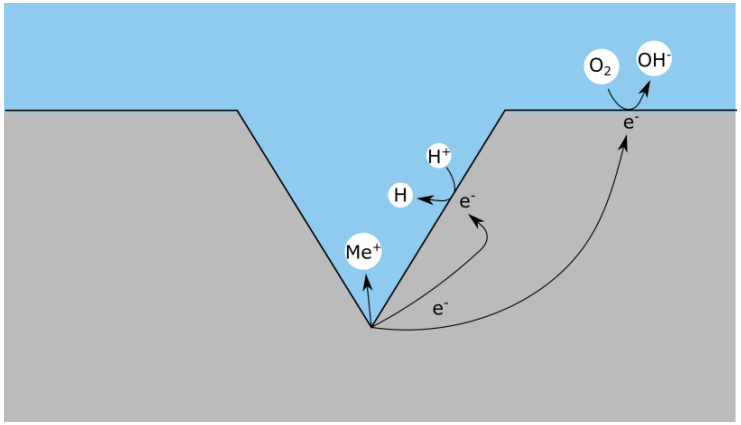


$MgCl_2$

Lot 3 - 55 ˚ C

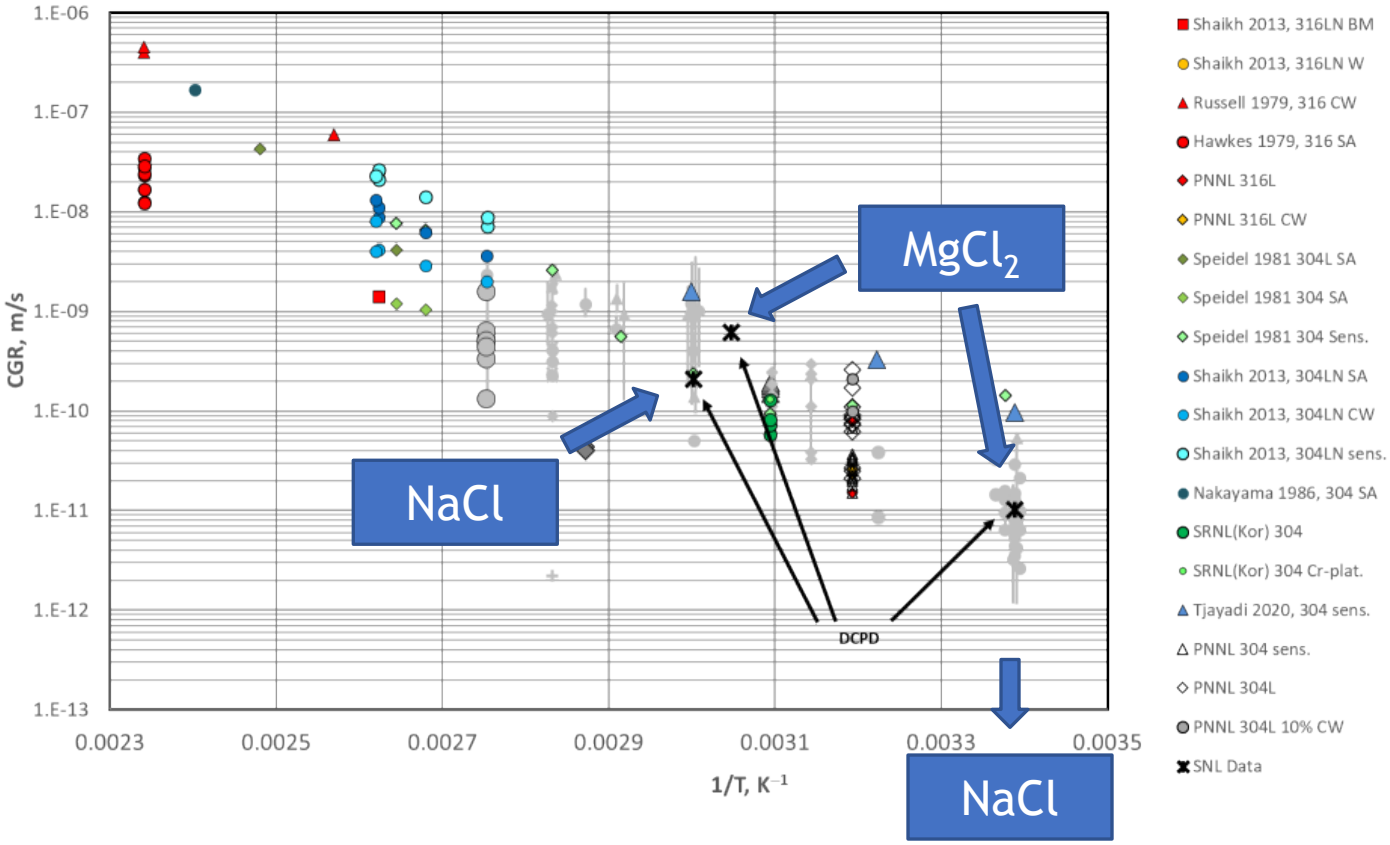


- Similar to differences in morphologies from corrosion exposures
- Potentially due to differences in cathodic reduction reaction
- Possibility for different crack tip chemistry changing pH and embrittlement



R.M. Katona et al., Journal of The Electrochemical Society, 168 (2021) 031512.
R.M. Katona et al., Corrosion Science, 177 (2020) 108935.

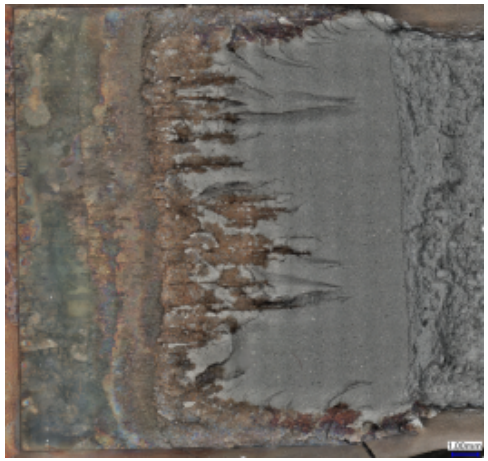
Measured Crack Growth Agrees with Literature Trends

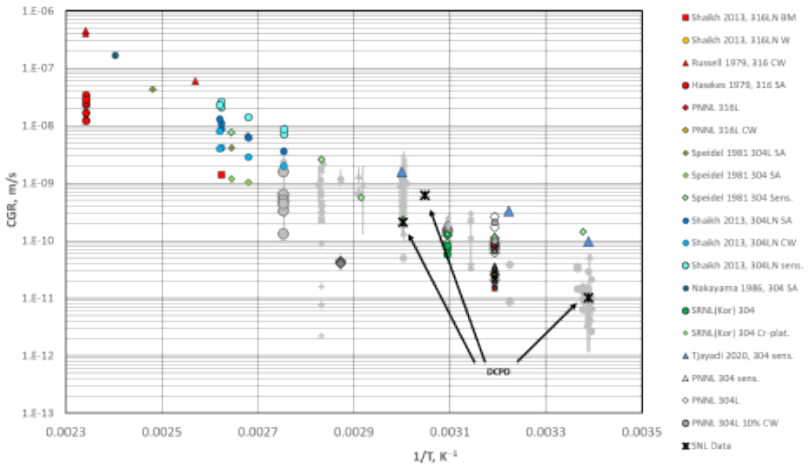


- Similar crack growth rate trend with temperature to other studies in literature
- Potential influence of solution composition on crack growth rate but does influence morphology

Key Take-a-ways

- Importance of fractography combined with DCPD
  - Can impact crack growth rate if taking DCPD average or growth of furthest protrusion
  - Can multiple tests be performed on the same sample given the ‘weird’ fracture morphologies?
- Solution, sample orientation, and material lot appear to impact crack growth and crack morphology
- Temperature has an impact on crack growth
- Is scatter due to these morphologies, **environment**, material, measurement technique, etc.?





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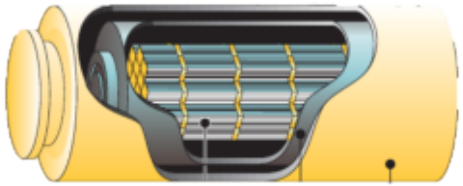
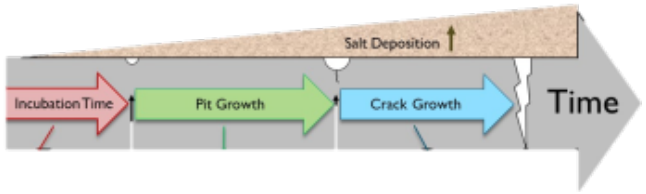
Stress Corrosion Cracking of Austenitic Stainless Steels in Concentrated Chloride Environments





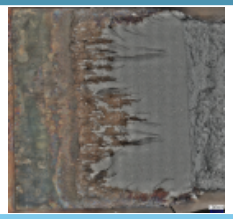


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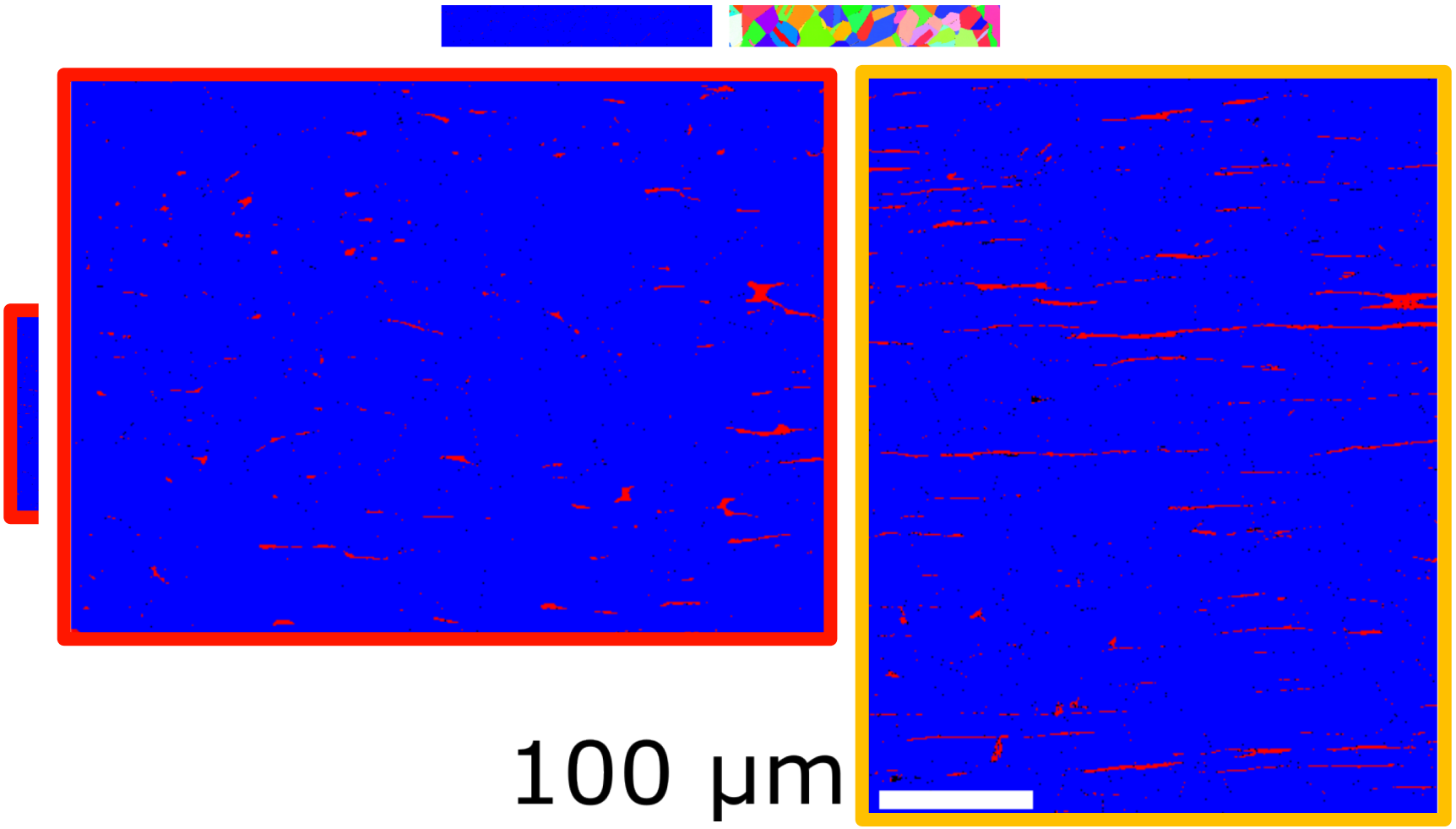
Plate Microstructure

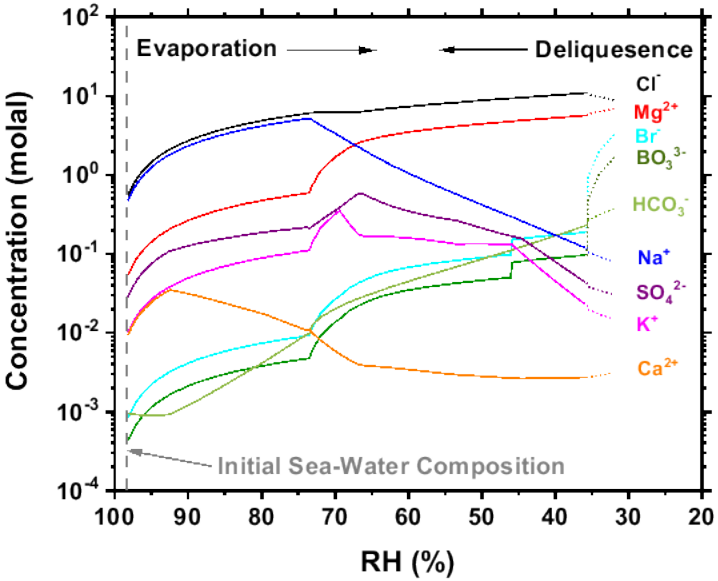


Lot Information

Lot ID	Plate #	Heat #	PNNL Reference #	UTS (Mpa)	YS 0.2% (Mpa)	Elong.(%)	HRB
LT001	206972	SD23822	n/a	647	267.516653	57.6	82.2
LT003	213104	04E28VAA	P304L1	623	292	62.9	81

	Composition													
	C	Co	Cr	Cu	Mn	Mo	N	Nb	Ni	P	S	Si	Ti	Fe
LT001	0.02	0.2	18.14	0.25	1.7	0.08	0.07	-	8.04	0.031	0.004	0.4	0.001	bal
LT003	0.017	0.234	18.1	0.412	1.782	0.414	0.08	0.014	8.03	0.037	0.001	0.236	0.002	70.7

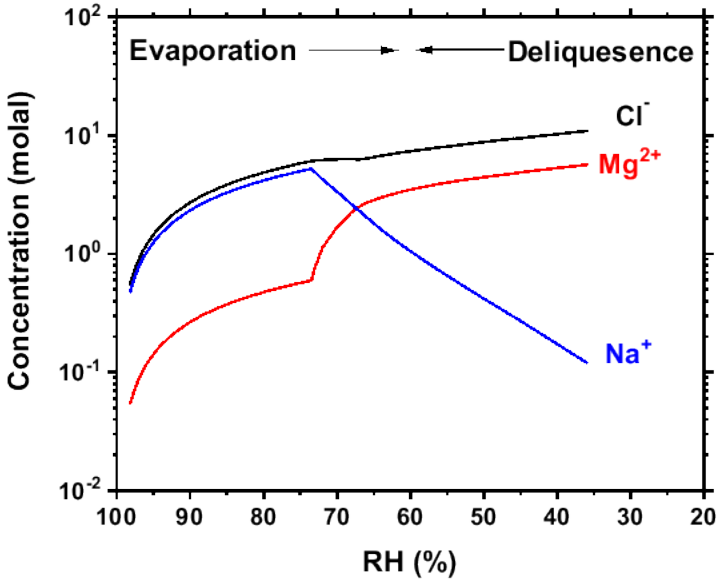
Salt Composition and Concentration Change with RH

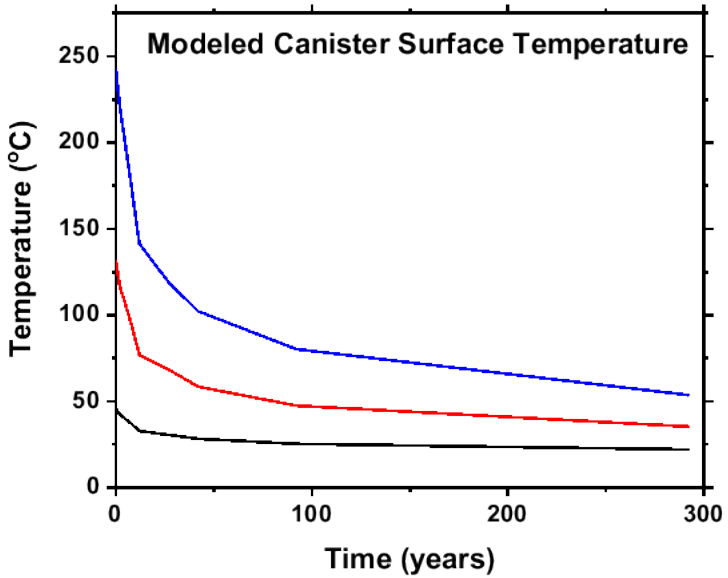


- Initial assumption of sea water brine

C.R. Bryan et al., Science of the Total Environment, Under Review, (2022)

Salt Composition and Concentration Change with RH





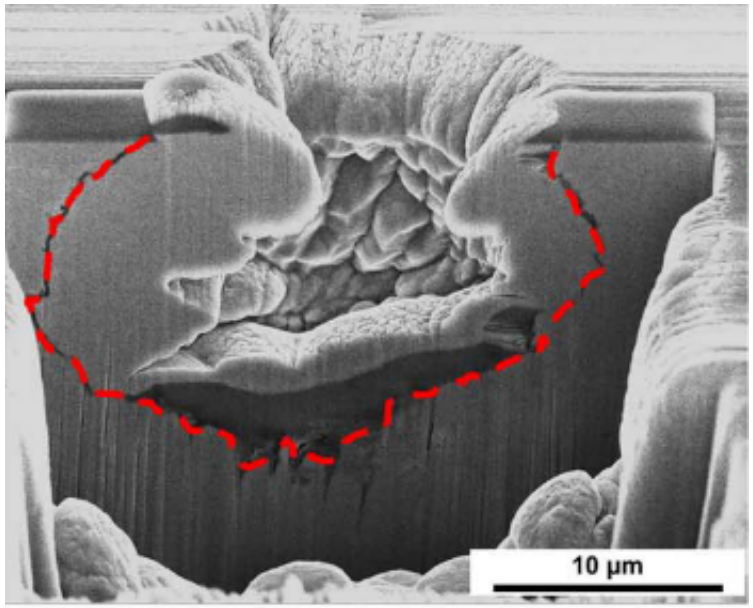
- Initial assumption of sea water brine
- Evaporation of sea water:
  - Concentration of chloride (Cl^-)
  - Change in brine composition (~ 75 % RH)
- Canister surface physically hot

Need to inform upon localized corrosion across a wide range of chloride concentration (dilute NaCl to saturated $MgCl_2$) and temperature (20 – 55 ˚C)

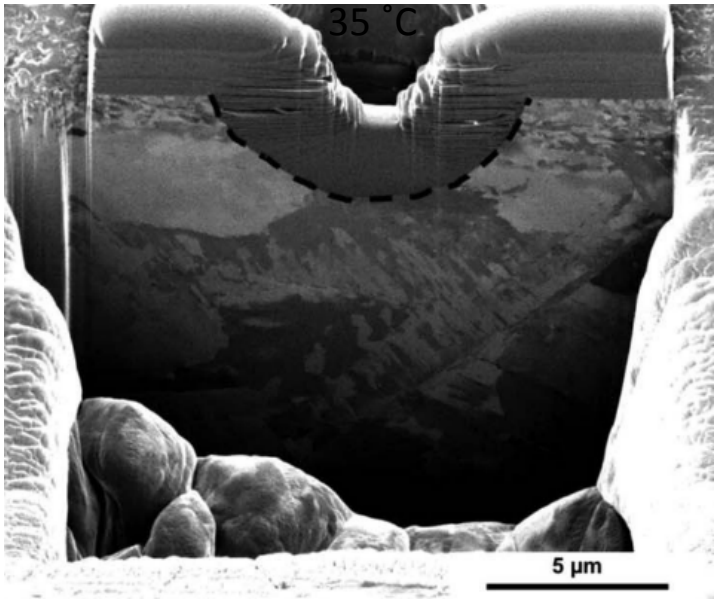
C.R. Bryan et al., Science of the Total Environment, Under Review, (2022)

Future Consideration of Anode Shape

Sample exposed at **40 % RH** and 35 ˚C



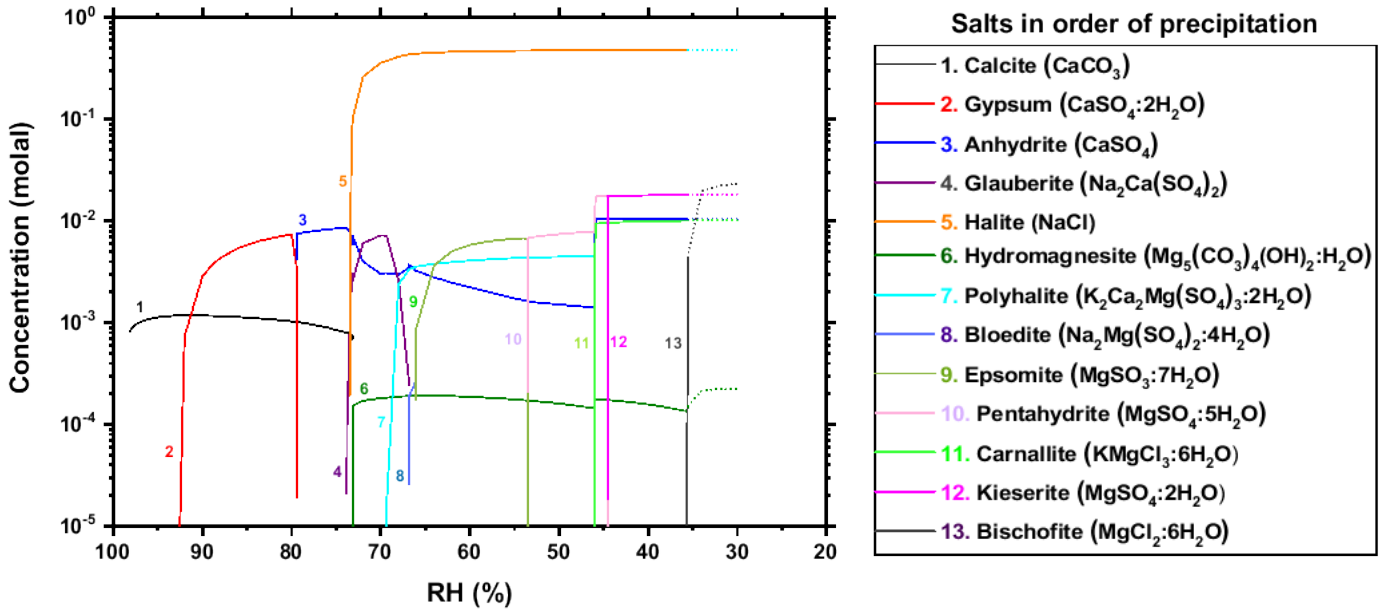
Sample exposed at **76 % RH** and 35 ˚C



- Anode shape dependent upon RH
- Potential influence on diffusion and whether or not propagation is under a salt film
- Pit kinetics are a function of position (what is the bounding case?)

T.D. Weirich, et al., Journal of The Electrochemical Society, 166 (2019) C3477-C3487.

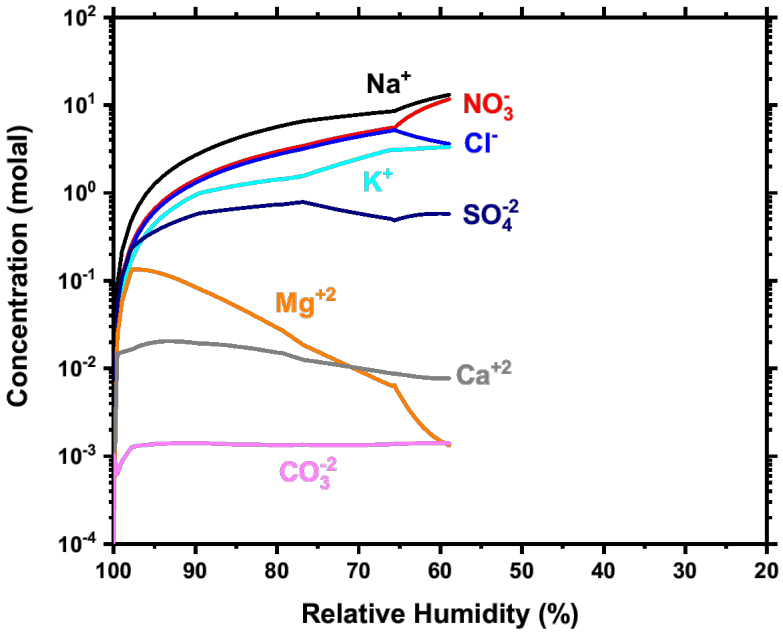
Future Consideration of Precipitated Species in Cathode

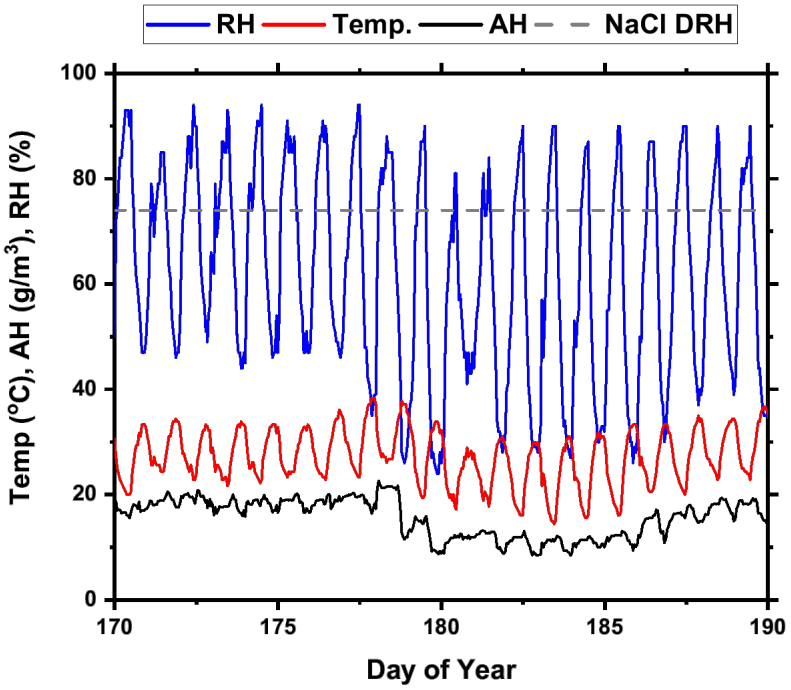


C.R. Bryan et al., Science of the Total Environment, Under Review, (2022)

R.M. Katona et al., Electrochimica Acta, 370 (2021) 137696.

Salt Composition and Temperature Vary by Location





- Composition and deliquescence RH change by geolocation
- Daily/Seasonal temperature and RH changes

Model can be adapted to predict pit size as a function of location and daily fluctuations

Framework can be combined with kinetic information