

# Used Fuel Disposition Campaign

## ***Crack Growth Rates and Experimental Design***

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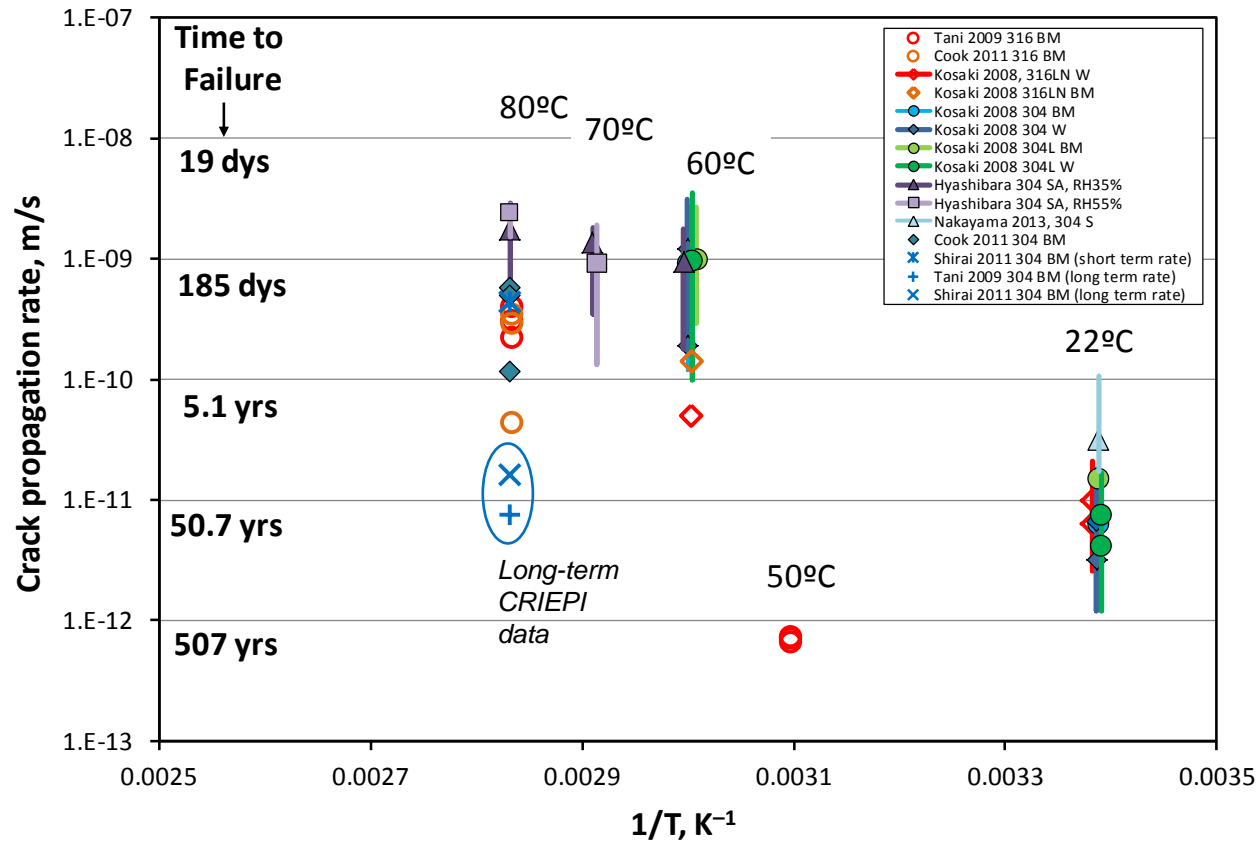
- Available SCC crack growth data
- CRIEPI data
  - *Stated Interpretation*
  - *Possible confounding factors*
    - Salt deposition method (droplet)
    - Use of a bend sample
- Implications for experimental design?

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## Literature SCC Crack Growth Rates 304 SS and 316 SS, atmospheric corrosion

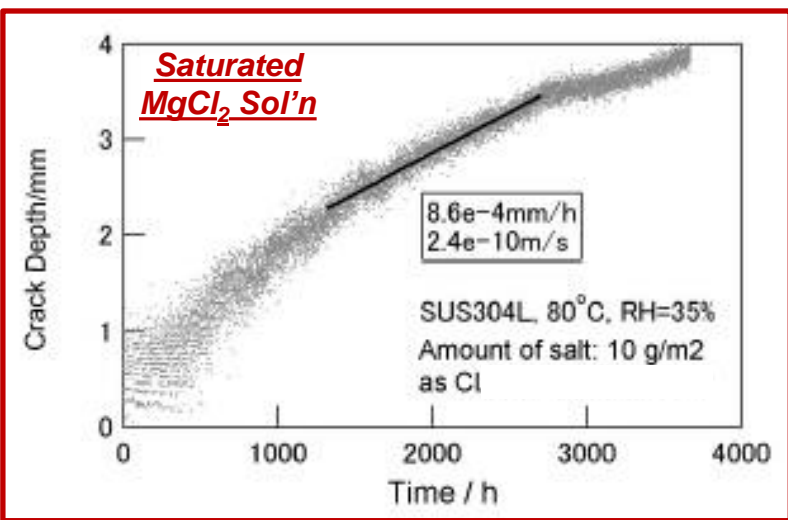
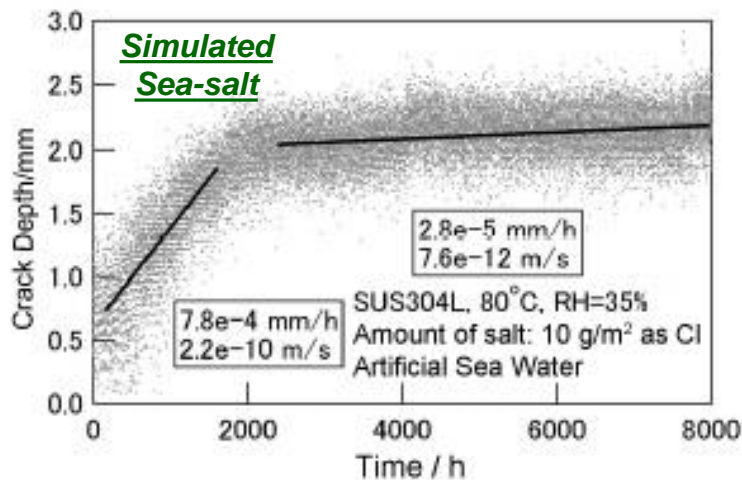
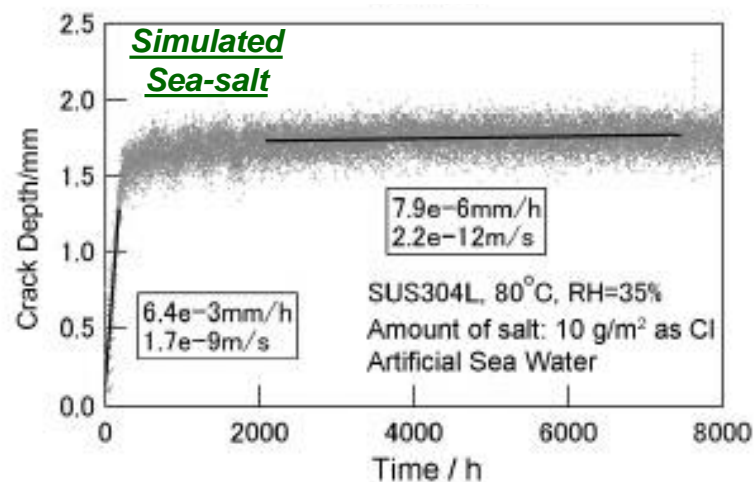
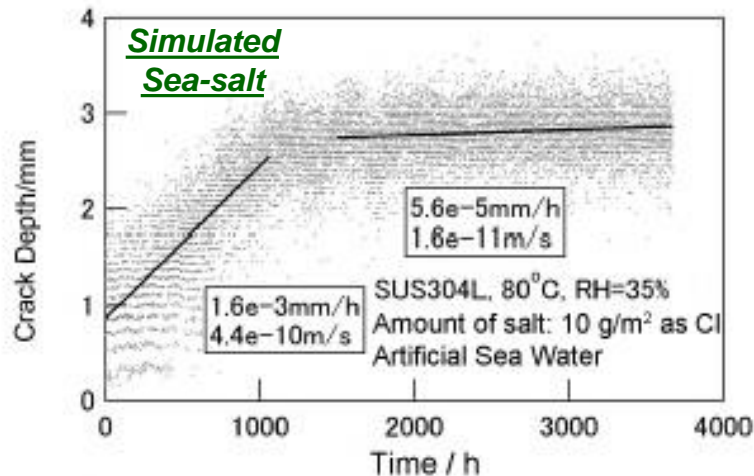
### CRIEPI Results

Long-term (>2.5-3 mm depth) crack growth rates much slower than had been previously measured. If verified, then it provides a basis for significantly reduced risk of canister penetration by SCC.



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# CRIEPI Crack Growth Rate Data



# CRIEPI Testing Mechanism

## 4-point Bend Test

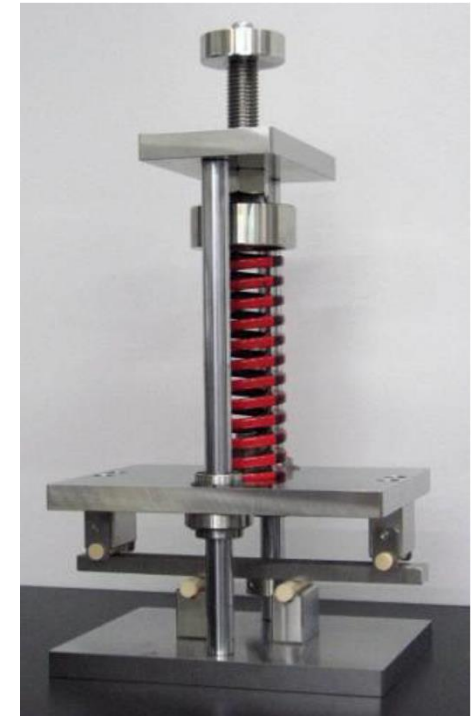
- Beam 220mm x 20mm wide x 10mm thick
- Outer fiber tensile stress = 270 MPa
- 35% RH, 80°C
- Salt (Synthetic sea salt or saturated  $MgCl_2$  solution) added as a 20  $\mu$ L droplet in the center of the beam.
- Crack growth rates measured by potential drop method (PDM)—measures crack area, rather than depth directly. Assumes constant crack aspect ratio ( $a/c$ ).

*Transition to slow growth rate attributed to limited transport between the anode (in crack) and cathode (on surface), due to small deliquesced brine volume in the sea salts.*

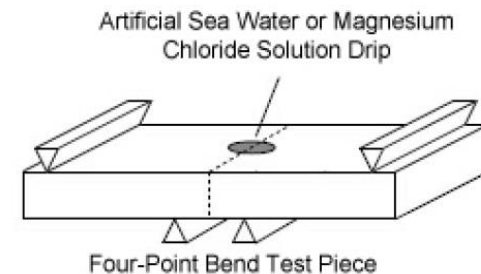
However, differences from anticipated canister conditions:

- Salt deposited as a droplet instead of a dispersed surface film
- Stress applied as a bending moment instead of uniform tension

**Did these differences affect the experimental results?**



(CRIEPI N10035)



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## Salt Deposited as a Droplet

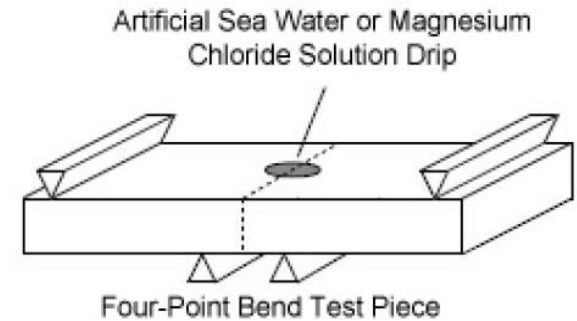
In the CRIEPI word, salt was deposited as a 20  $\mu\text{L}$  droplet, not a dispersed coating

### Size:

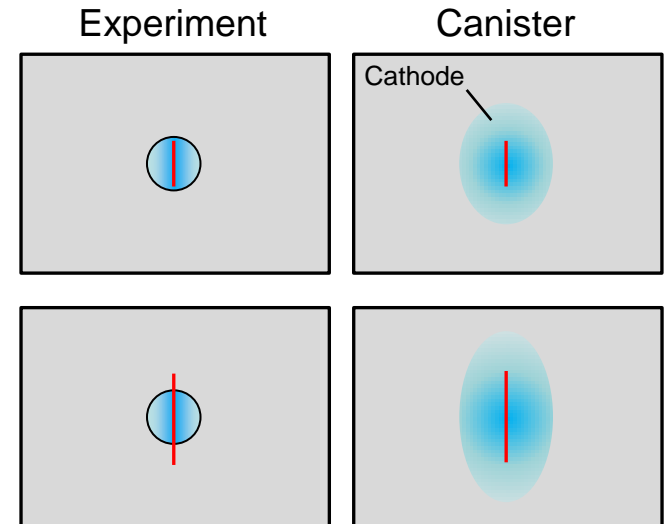
- Assuming hemispherical droplet, about 4.2 mm diameter
- Salt load described as 10 g/m<sup>2</sup>: in order to be correct, the seawater droplet would be 7 mm in diameter, the MgCl<sub>2</sub> droplet, 3 cm × 2 cm

### Possible issues?

- Could small droplet size artificially limit cathode size, limiting crack growth rate?
- CRIEPI reports final measured crack aspect ratios of  $a/c$  (depth/half width) of 1 to 2 (crack lengths from 4-12 mm). What happens when crack grows beyond droplet edge?



(CRIEPI N10035)



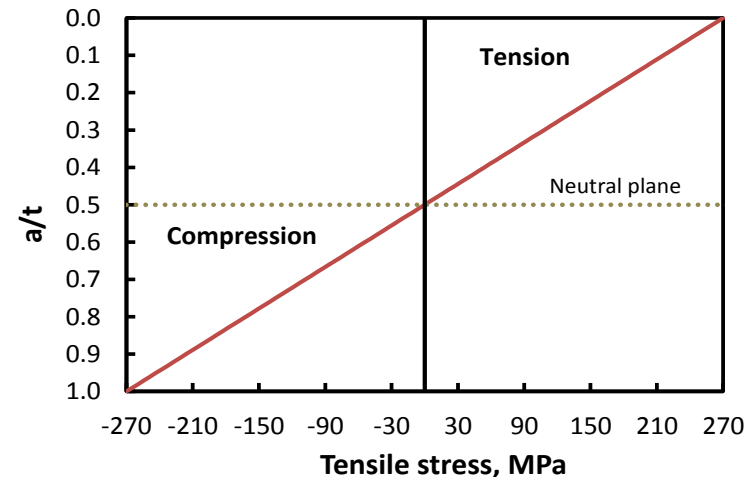
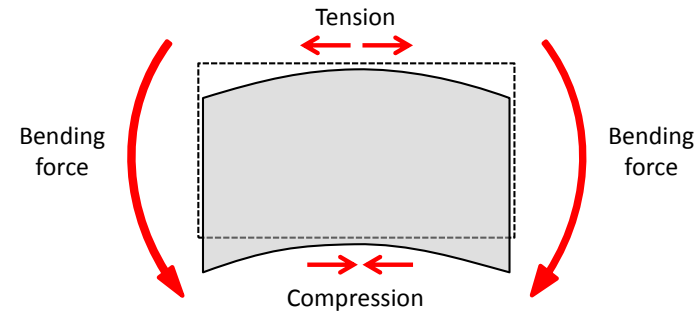
## Use of a 4-Point Bend Apparatus

### Applying stresses as a bending moment instead of uniform tension

It is well known that crack growth rates measured for bend samples may be affected by changes in stress with depth (if crack depths/sizes are large relative to the specimen size):

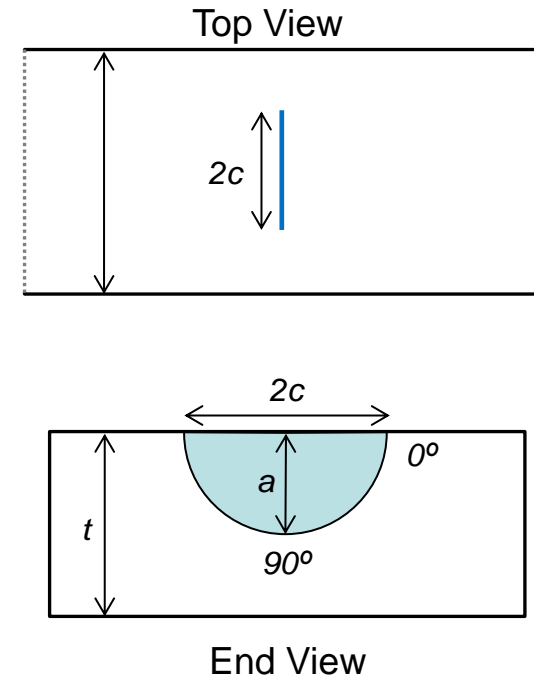
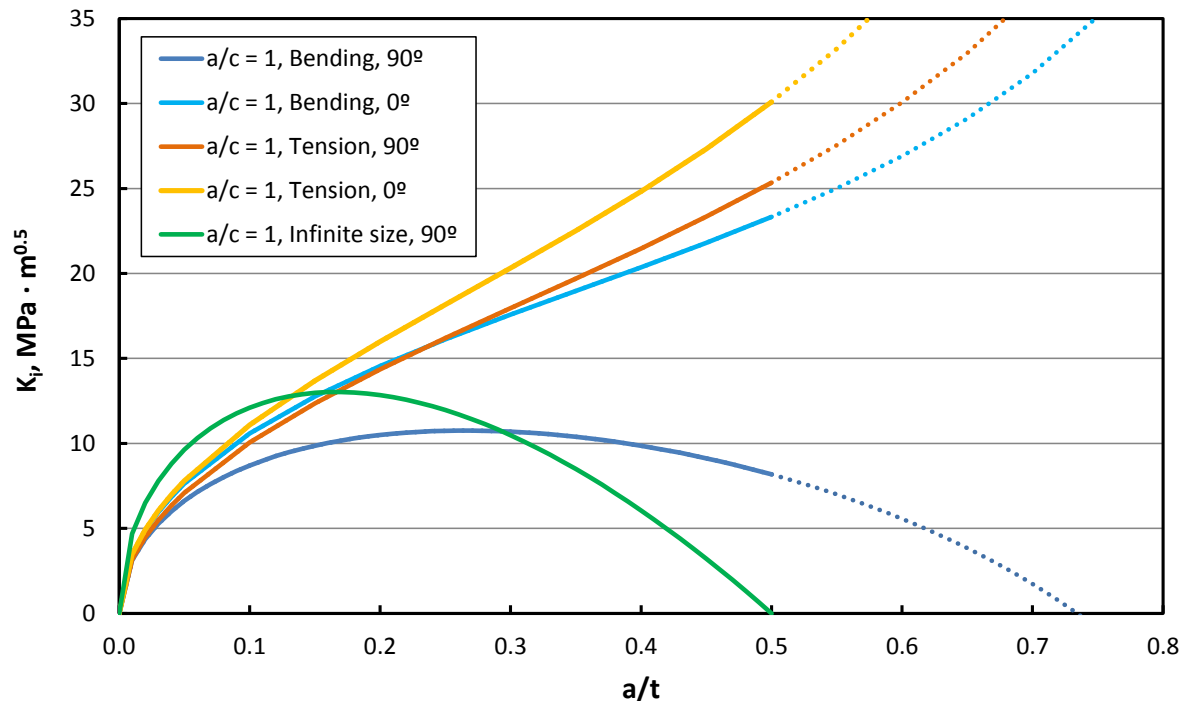
*“The four-point bend test is a constant displacement test that is performed by supporting a beam specimen on two loading rollers (bearing cylinders) and applying a load through two other loading rollers so that one face of the specimen is in tension (and uniformly stressed between the inner rollers) and the other is in compression. The stress at mid-thickness is zero and there will be significant gradients in stress through the thickness, this being most marked for thin specimens. As a consequence, cracks may initiate, but then arrest or their growth rate decrease.”*

ISO/FDIS 16540 Corrosion of metals and alloys — Methodology for determining the resistance of metals to stress corrosion cracking using the four-point bend method.



# Calculated Changes in Crack Tip Stress Intensity Factor as the Crack Grows

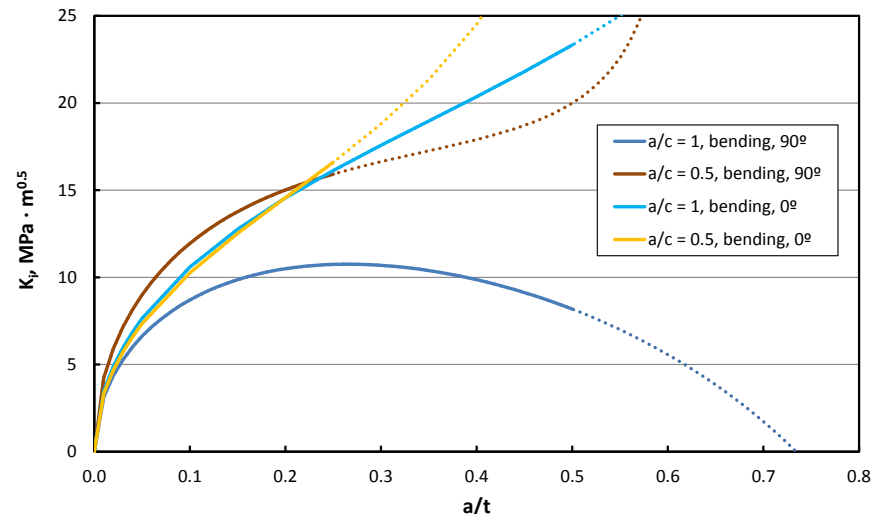
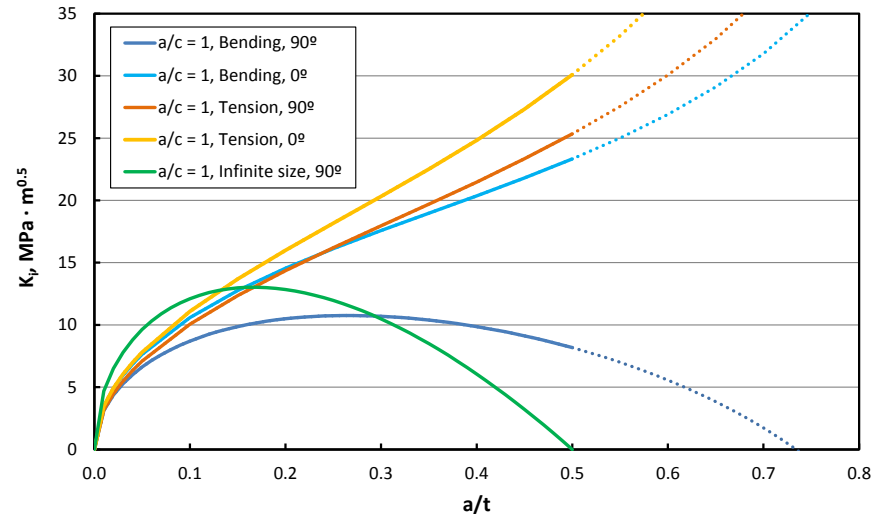
Crack tip stress intensity factors were calculated using the methods of Newman and Raju (1979). Results for the CRIEPI experimental setup, and for a sample with the same dimensions, under uniform tension, are shown below.



# Calculated Changes in Crack Tip Stress Intensity Factor as the Crack Grows

## Important features:

- $K$  at  $90^\circ$  (crack bottom) increases initially, levels between 2 and 3 mm, and then decreases at depths of  $>3$  mm.** If CGR varies with  $K$ , then CGR should begin to decrease at  $>3$  mm. *If we are on the CGR plateau, then we might see no change (EPRI conclusion).*
- $K$  at  $90^\circ$  (crack at bottom) and at  $0^\circ$  (tip at surface) vary significantly.** If CGR is a function of  $K$ , then growth rate will vary at the two locations. The crack aspect ratio will vary with time, meaning that the PDM measurements cannot be related directly to crack depth over time. (Does the same argument apply to cathodic limitation at both locations along the crack tip?)
- For a sample under uniform tension, there is little difference in  $K$  at  $0^\circ$  and  $90^\circ$**  --potentially less change in crack aspect ratio with depth. Can a bend sample be used as an analog for a uniform tension condition? Do we need to use compact tension or dogbone samples to measure relevant crack growth rates?



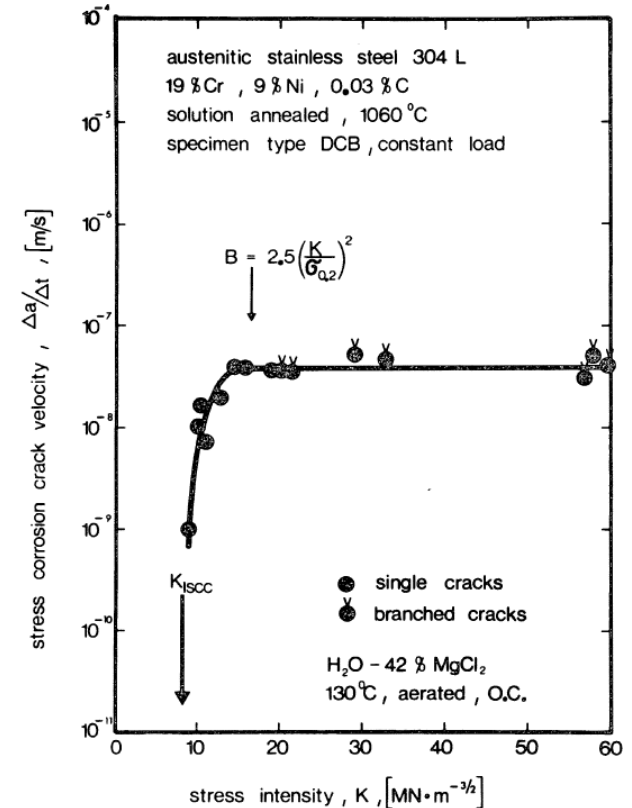
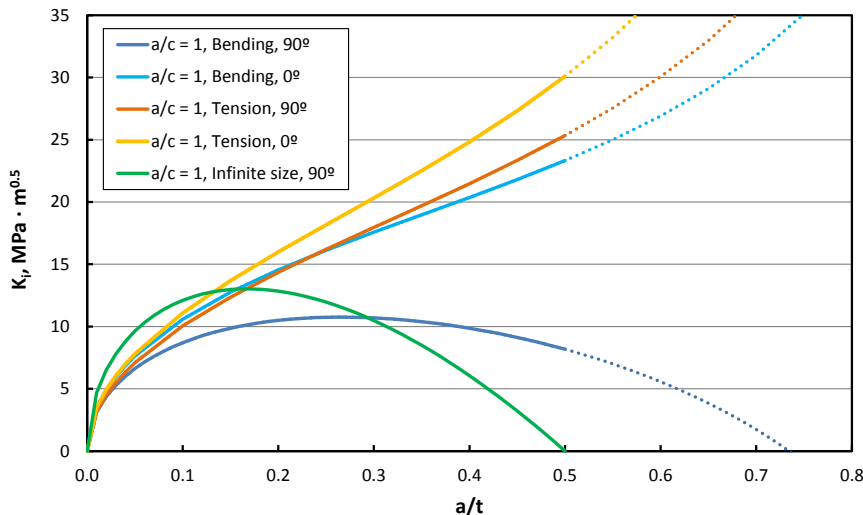
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## Crack Branching?

Does the difference in stress state between bend and uniform tension loads affect the mechanism of crack growth?

**Uniform tension:** As K values increase with depth, the crack branches; stresses at each crack tip decrease by  $\frac{1}{\sqrt{2}}$  (Spiedel (1977)). But as crack depth increases, K continues to grow. The CGR increases back to plateau rate.

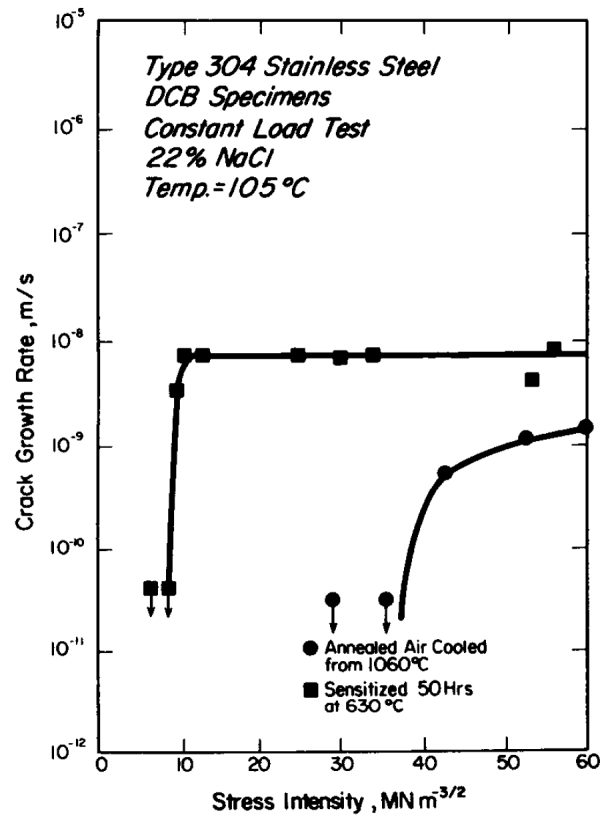
**Bend sample:** K does not change as the crack grows; will the crack branch? If a crack branches, does the overall crack growth rate slow, since K is no longer increasing with depth?



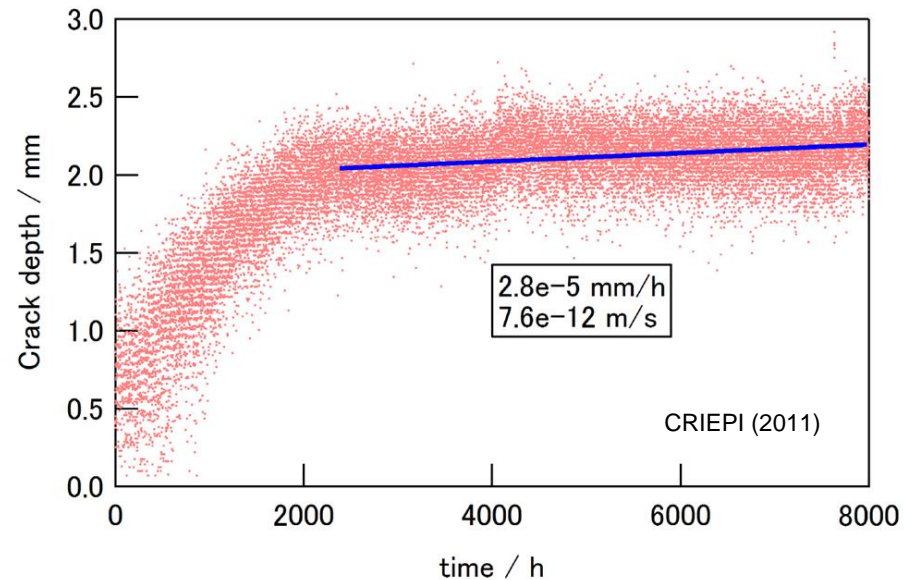
Spiedel, 1977

## Is the Proposed Mechanism Consistent with the Data?

Are these consistent?



Cragnoiano and MacDonald (1981)

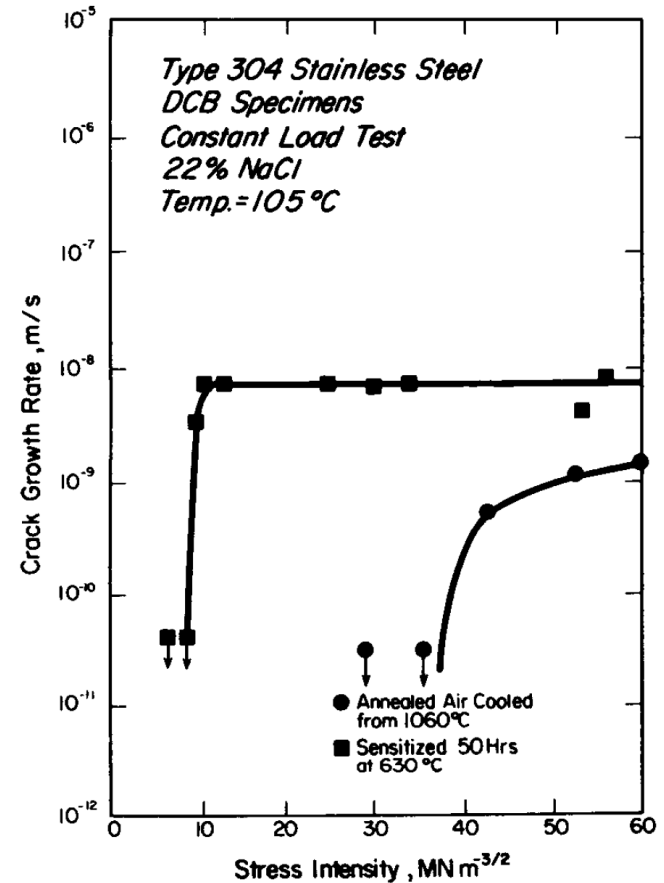
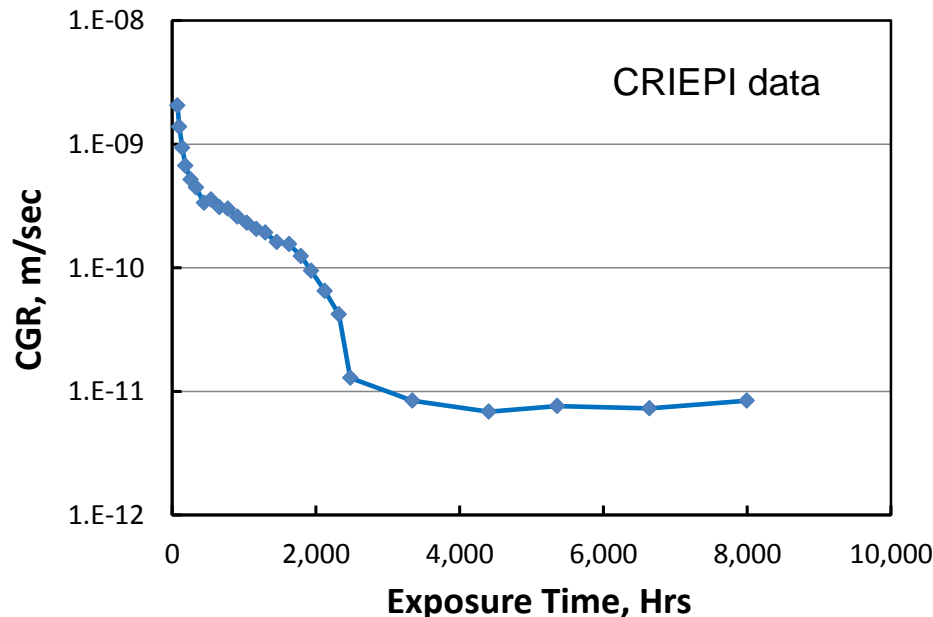


Not really...

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## Is the Proposed Mechanism Consistent with the Data?

The proposed mechanism should result in continued slowing of growth as depth increases. However, the CRIEPI long-term rate stabilizes at a low value, instead of continuing to decrease. Long-term results do not appear to be consistent with the proposed mechanism, and suggest two different mechanisms are at work.



Cragnoilano and MacDonald (1981)

Processes controlling the observed trends in the CRIEPI data are not well constrained. Possible contributing design features include:

- Salt deposition method (droplet instead of a dispersed salt coating)
- Use of a bend sample instead of a tension sample

Further research should be carried out to verify the proposed mechanism (cathodic limitation due to limited brine load) is correctly identified.

Experimental design questions:

- Can a bend specimen be used to measure relevant crack growth rates, or should a tension specimen (CT, dogbone, etc) be used?
- How do we design a test system to evaluate transport limitations (effect of salt surface load) on crack growth?
- Must it maintain the appropriate geometry (i.e., dispersed salt on a flat surface) to adequately capture the properties of the cathode?