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# Task 3: Cracking of Nickel Alloys and Welds – CGRs of Ni-alloy Welds in Primary Water

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*Experimental Effort: Ed Listwan and Loren Knoblich*

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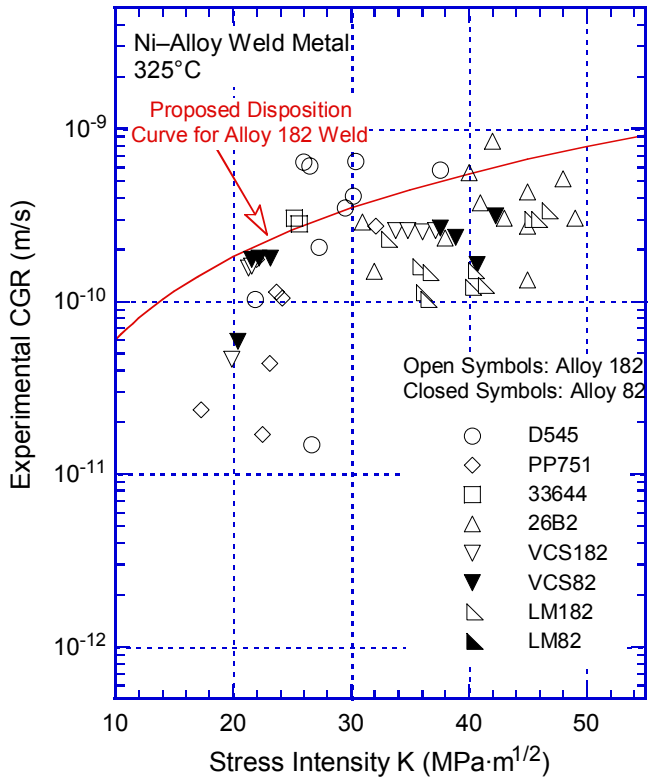
# *Outline*

- Background
  - Proposed disposition curve, selection criteria
  - CGR testing at ANL, participation in the Round-Robin testing of Alloy 182
- CGR of Laboratory-prepared Alloy 182
- CGR of Field Welds (Davis-Besse Alloy 182, V.C. Summer Alloys 182/82)
- Determination of the activation energy for SCC crack growth
- CGR of Laboratory-prepared Alloy 152

# Background

- Proposed disposition curve[1]:




$$\dot{a}_{Ni-weld} = \alpha \exp\left[-\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] K^{\beta}$$

$\alpha = 1.5 \times 10^{-12}$ m/s

$Q = 130$ kJ/mol

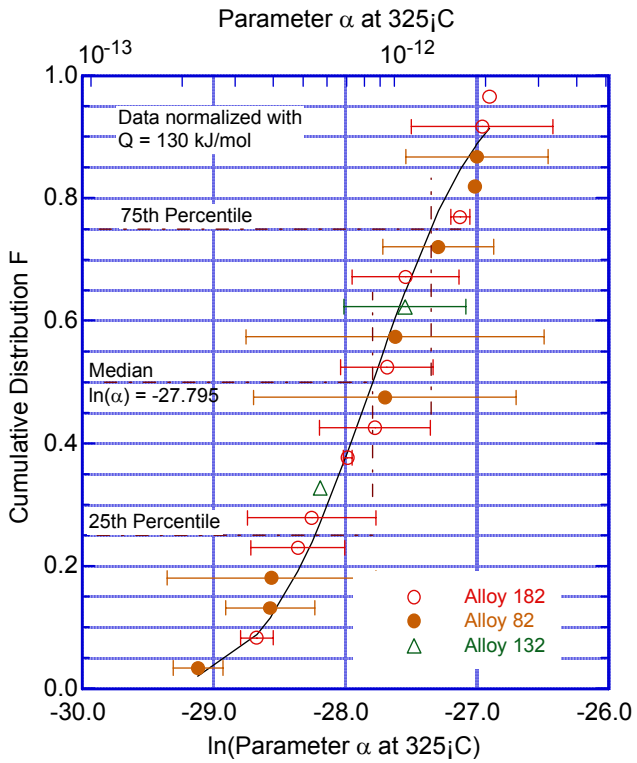
$T_{ref} = 325°C$

[1]White, G., J. Hickling, and C. Harrington, EPRI Alloy 600 Conference, 2005

# Background

- Data analysis[1]

- Divide by the engagement fraction to allow for incomplete initiation
- Normalize all CGRs to 325°C using Q=130 kJ/mol
- Multiply the CGRs for TL orientations by 2 to account for orientation effects
- Multiply the CGRs for Alloy 82 welds by 2.6 to account for the effects of alloy type.




[1]White, G., J. Hickling, and C. Harrington, EPRI Alloy 600 Conference, 2005

# *Testing Facilities*

- Autoclave (up to 350°C)
- Water loop
- Hydraulic test frame with Instron digital control
- Crack growth measuring system by the DC potential method
- LabView data acquisition

# *Experiment*

- Temperature: 290°C - 350°C
- PWR Water (<10 ppb DO, 1000 ppm B, 2 ppm Li)
- Flow Rate: ≈55 mL/min
- Conductivity: ≈23 μS/cm
- Precracking carried out in the PWR environment to facilitate the transition from transgranular fatigue cracking to intergranular SCC cracking before conducting the constant load test
- Load Ratio R: 0.3–precrack; 0.5–sawtooth with up to 1000s rise time; 1.0–constant load

# *The Analysis of Cyclic CGR Data for Ni-weld Alloys*

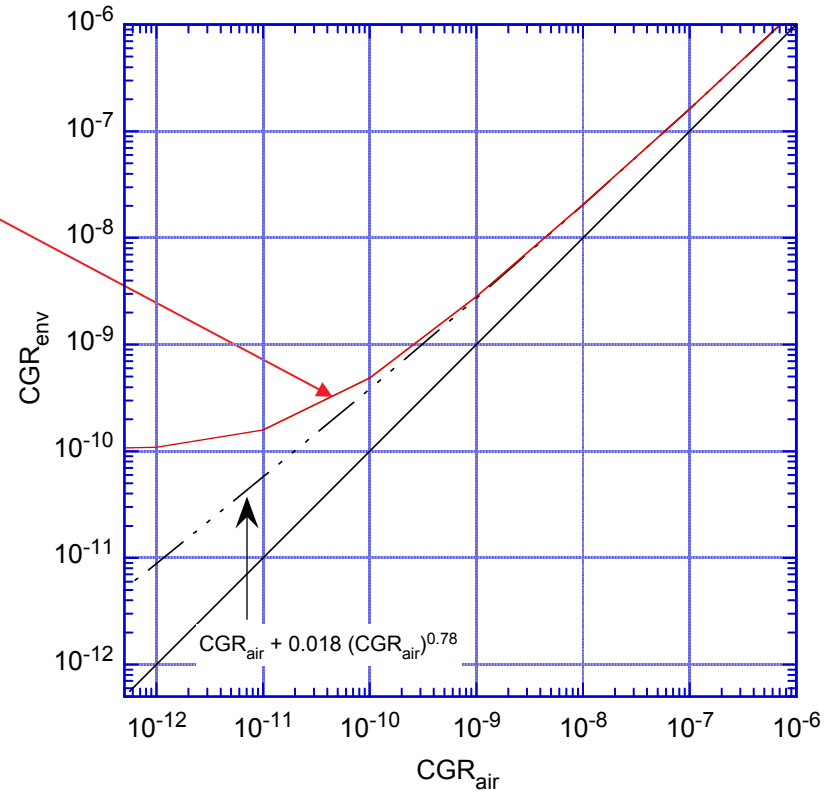
- Superposition model (Kassner & Shack)

$$\dot{a}_{env} = \dot{a}_{air} + \dot{a}_{CF} + \dot{a}_{SCC}$$

- For Ni-welds:

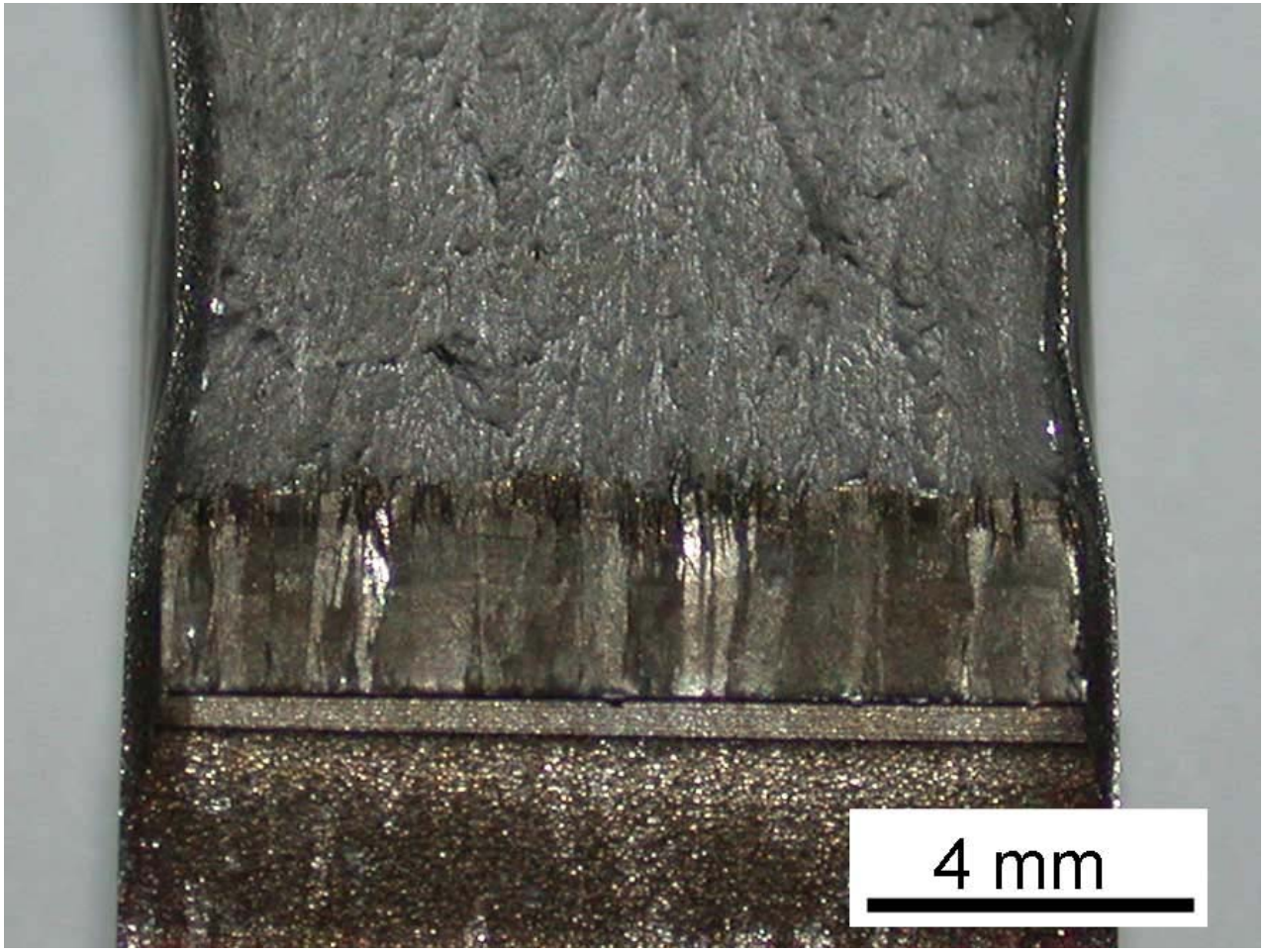
$$\dot{a}_{air} + \dot{a}_{CF} = \dot{a}_{air} + 0.018 \cdot \left(\dot{a}_{air}\right)^{0.78}$$

$$\dot{a}_{SCC} = \alpha \exp\left[-\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] K^{\beta}$$

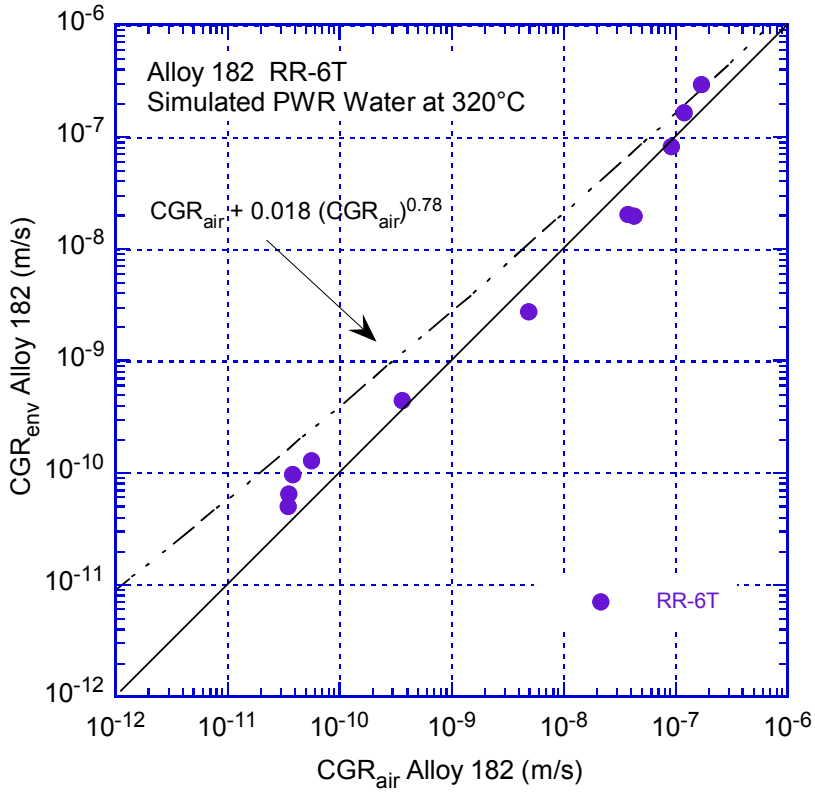


# *Round-robin CGR Test*

# *Alloy 182 Round Robin – Specimen 6T (ANL)*

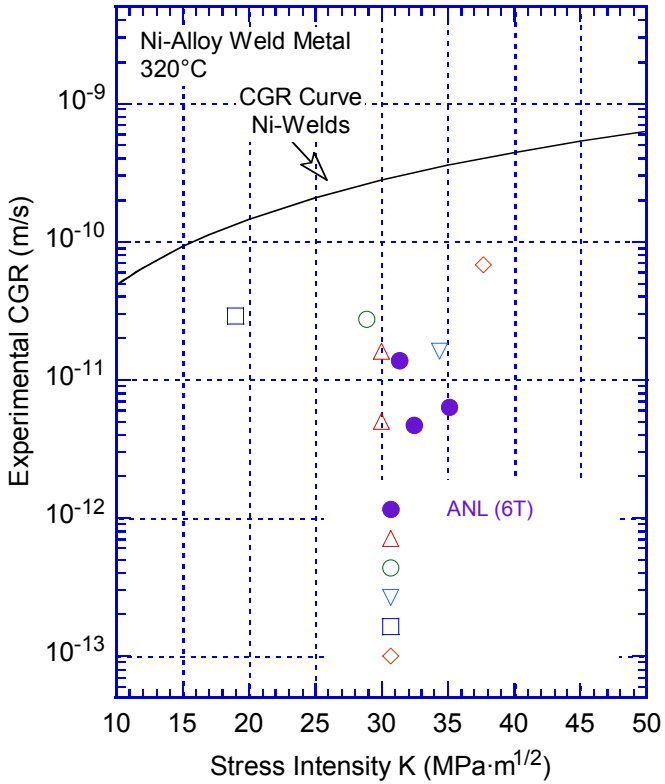


# *Cyclic CGRs of the Round Robin Alloy 182*




- No environmental enhancement

# SCC CGRs of the Round Robin Alloy 182

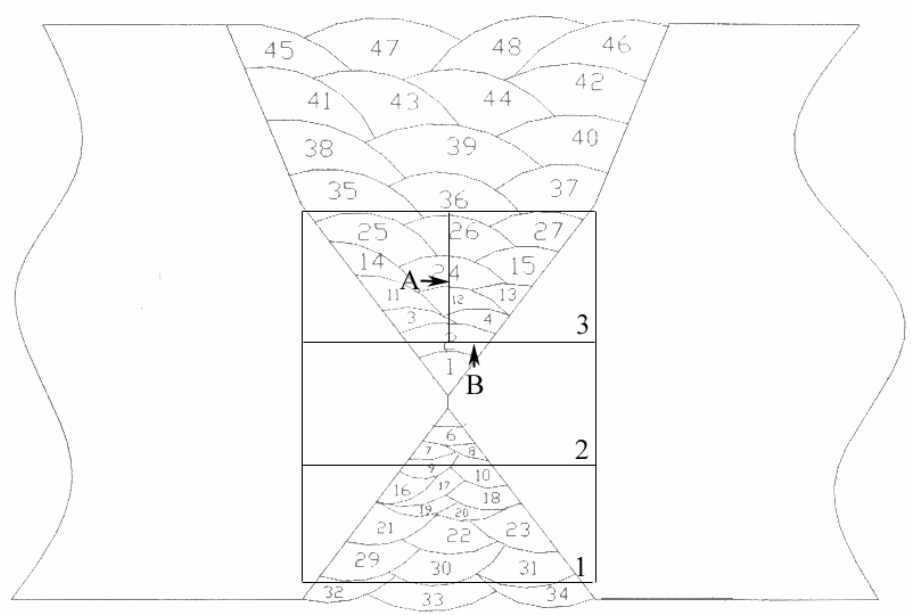



- Very good agreement with other participants

# *Cracking of Laboratory-prepared Alloy 182 Weld*

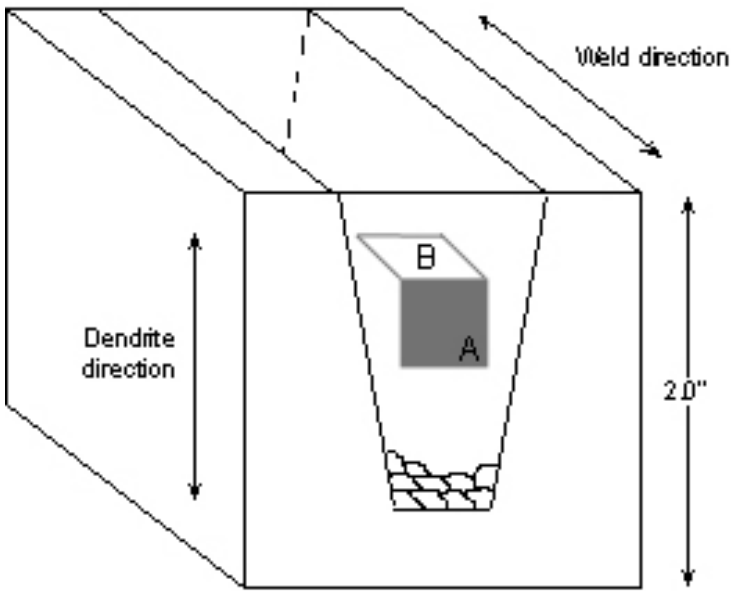
# *Alloy 182 Weld Specimens*

## Double-J weld



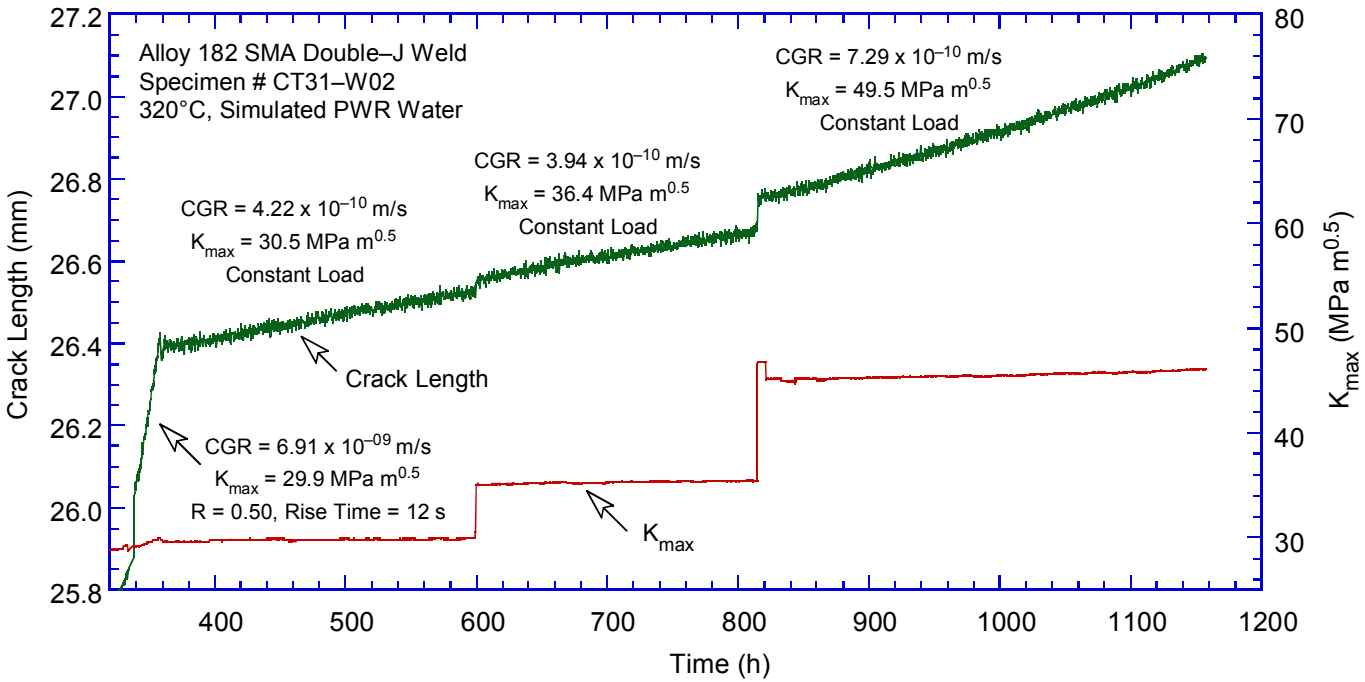

**CT31-W01 TS**
**CT31-W02 TS**

## Deep-groove weld

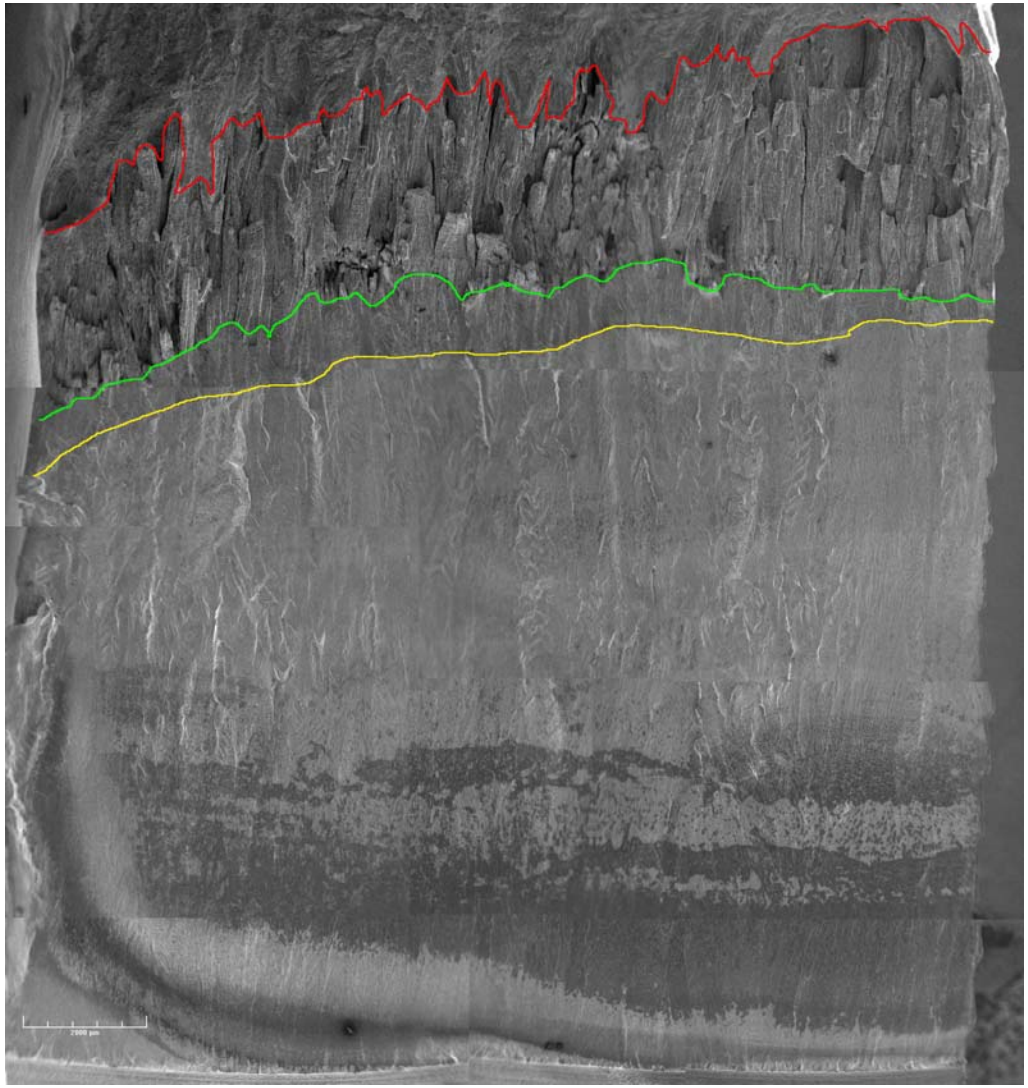



**CT933-01 TS**
**CT933-TL1**
**CT933-LS**

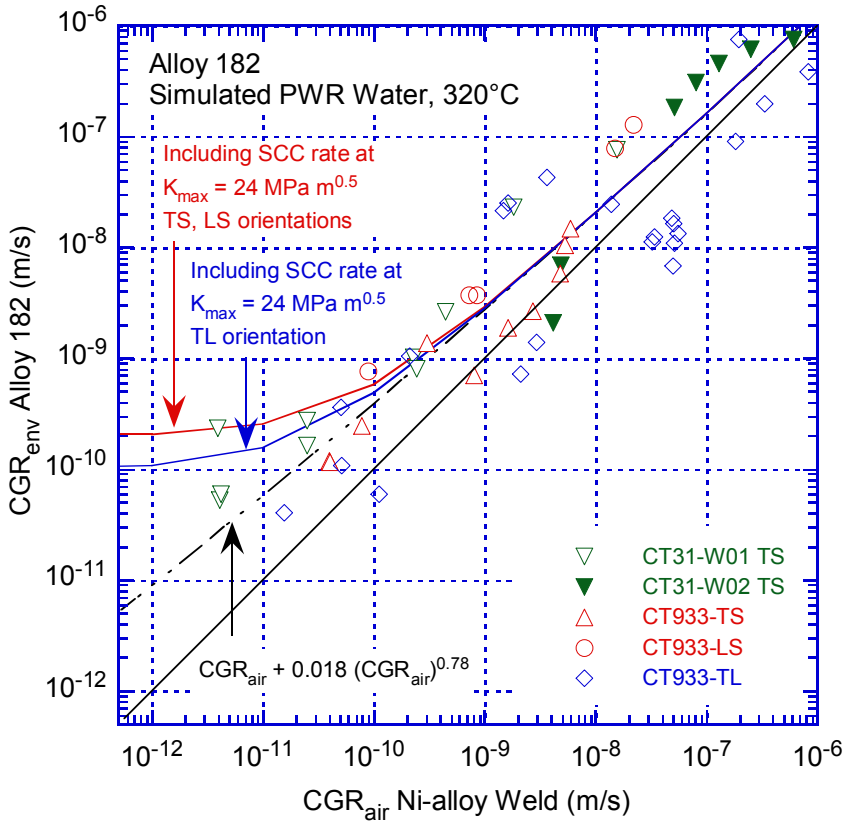
# *Double-J Alloy 182 Weld Specimen CT31-W02 TS*



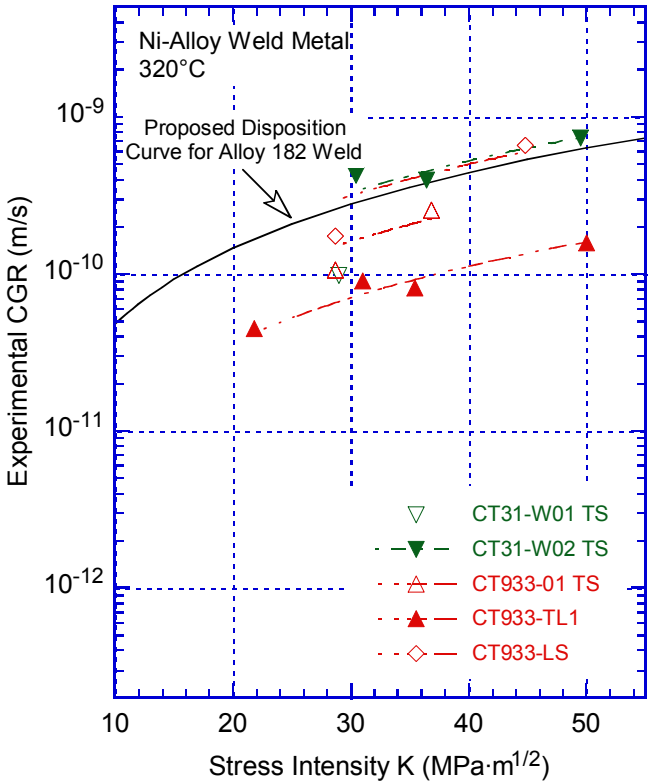
# *Fracture Surface of CT31-W02 TS*

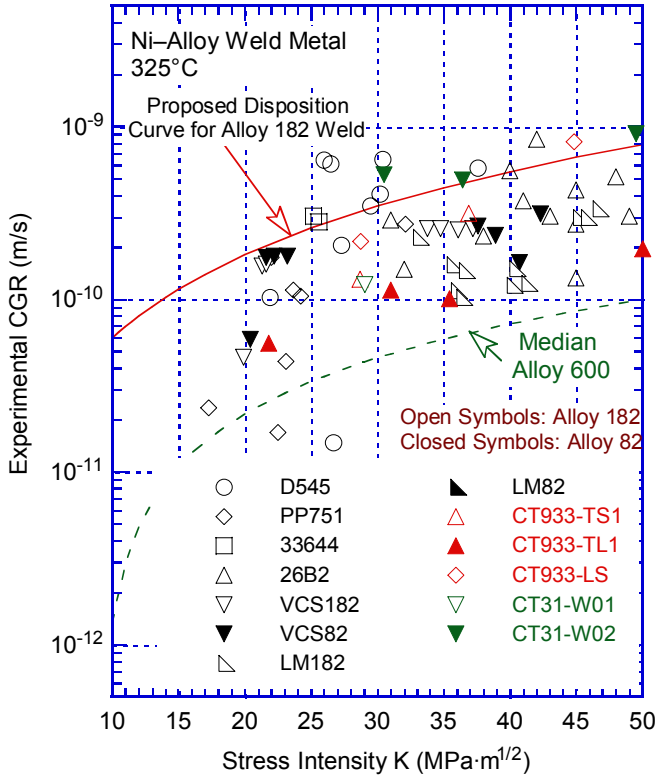


# Cyclic and SCC Data for Laboratory Welds



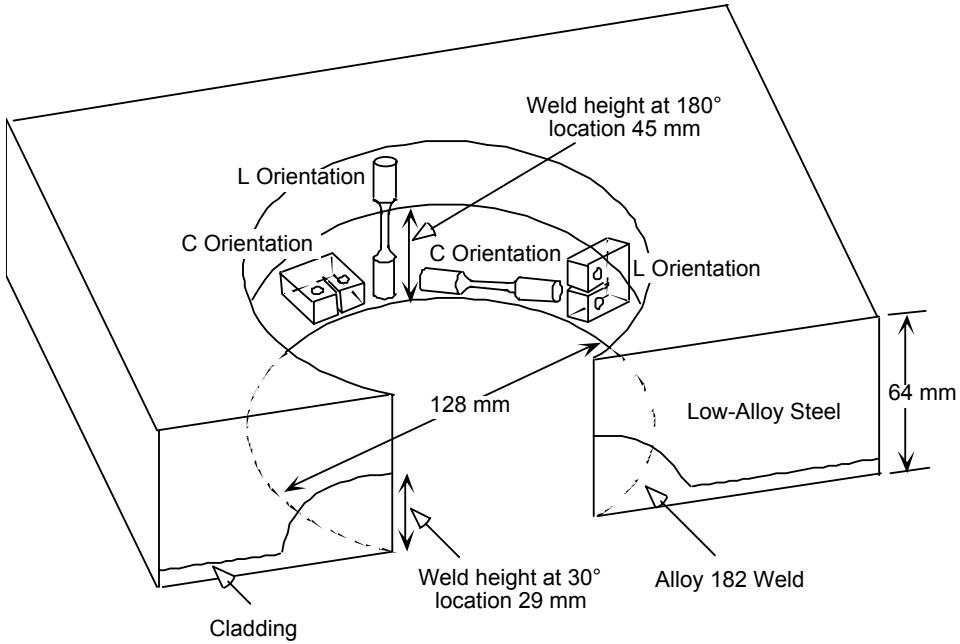
# SCC CGRs of Laboratory-prepared Alloy 182 Welds



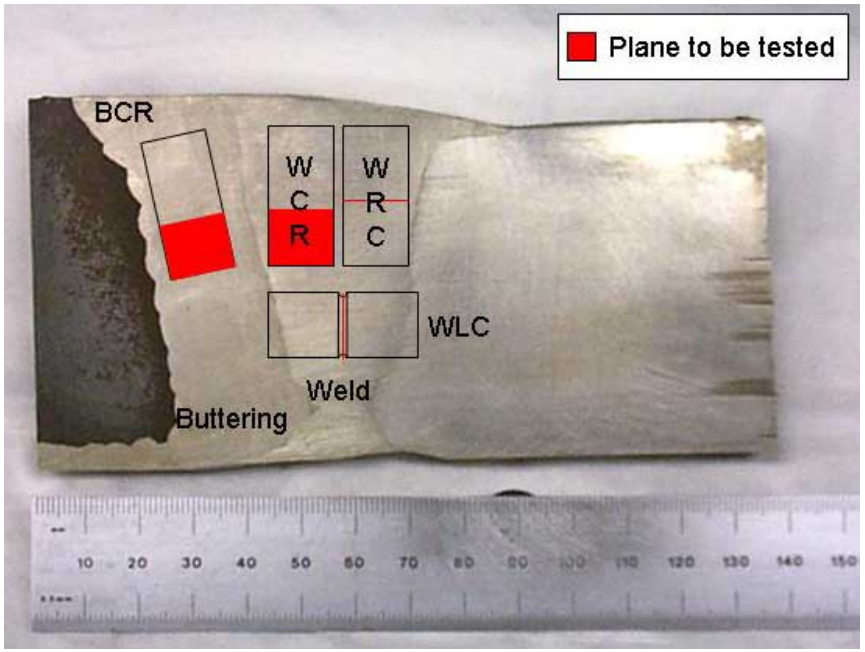



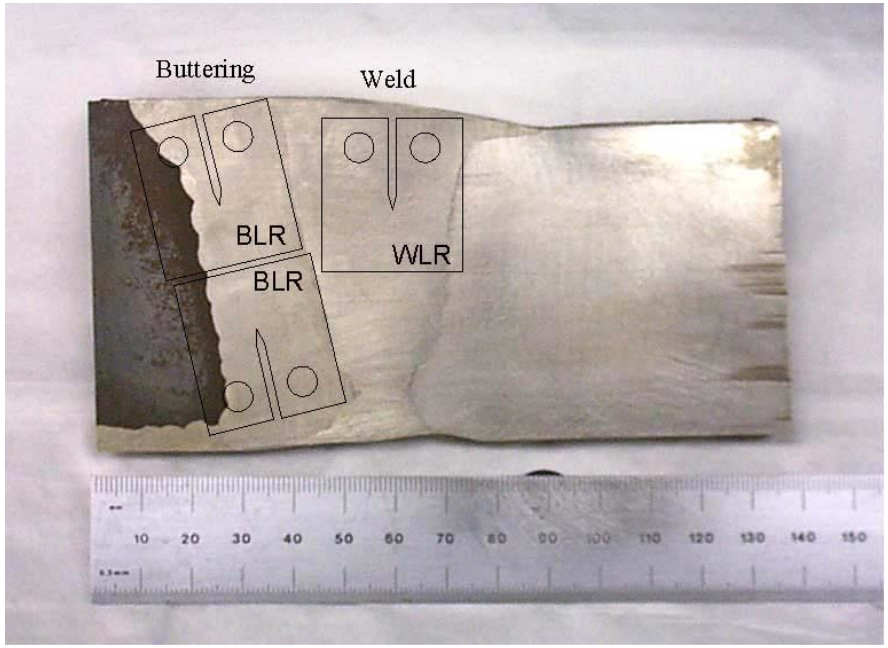
## *Cracking of Field Weld Alloys (Davis-Besse and V.C. Summer)*

# *Location of Specimens – Alloy 182 J-groove Weld of Nozzle #11 from Davis-Besse*

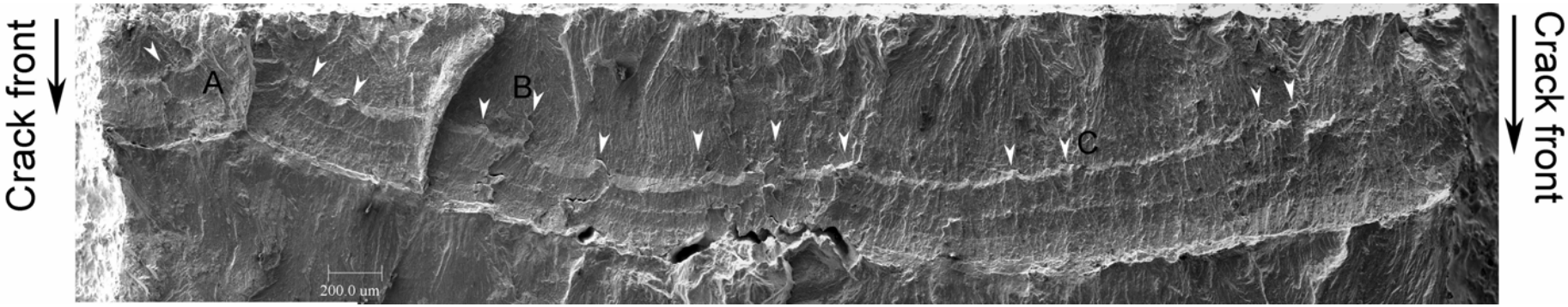



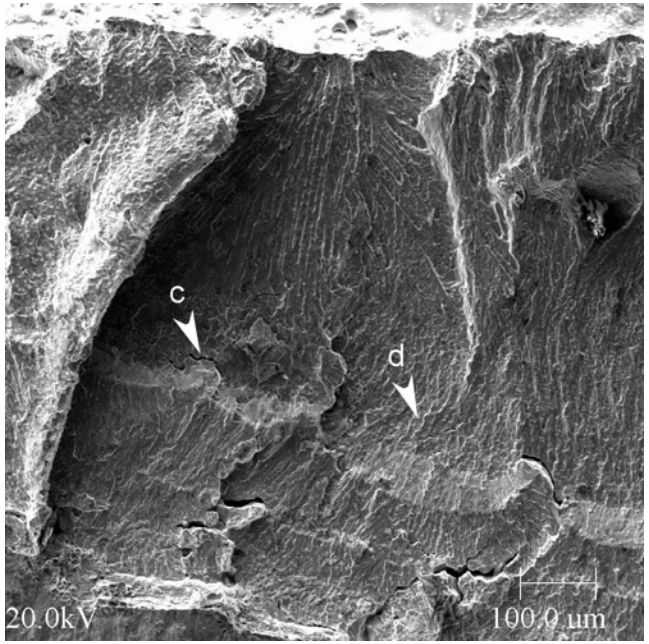
# *Location of specimens – V.C. Summer reactor vessel nozzle–to–pipe weld*

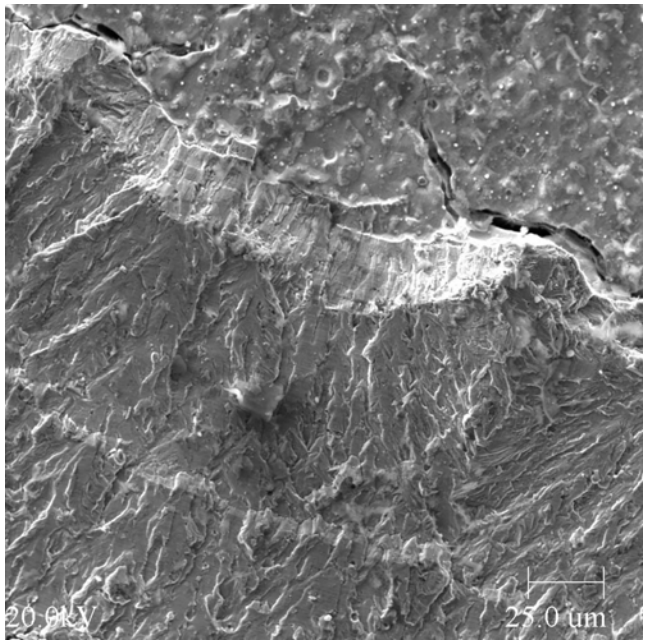


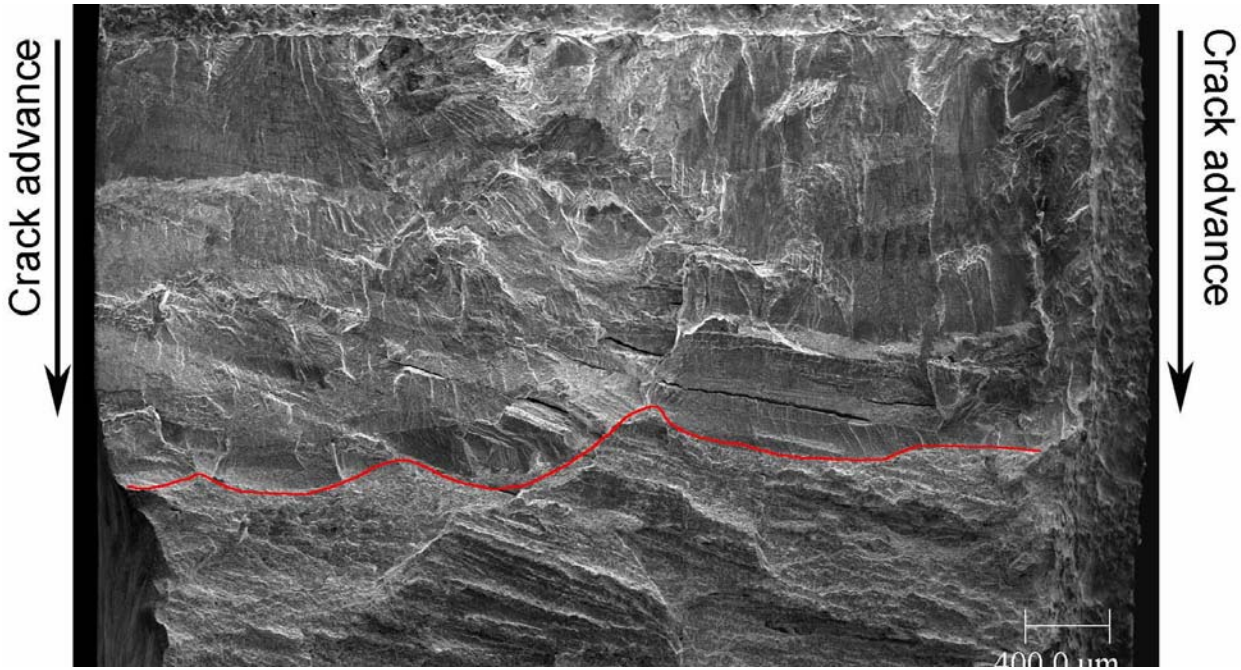
# *Fracture Surface of Alloy 182 Specimen J11CC-1 (Davis-Besse)*

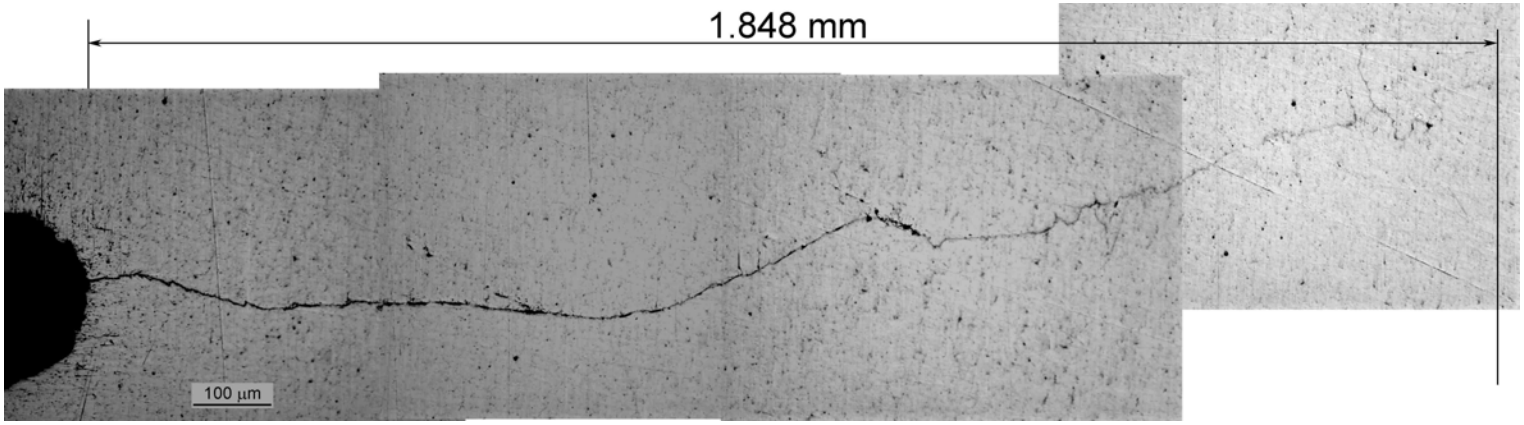


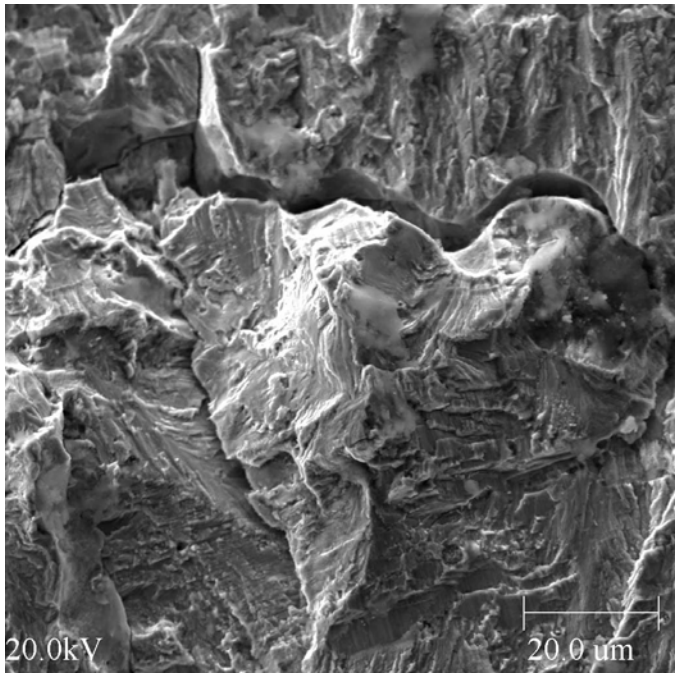



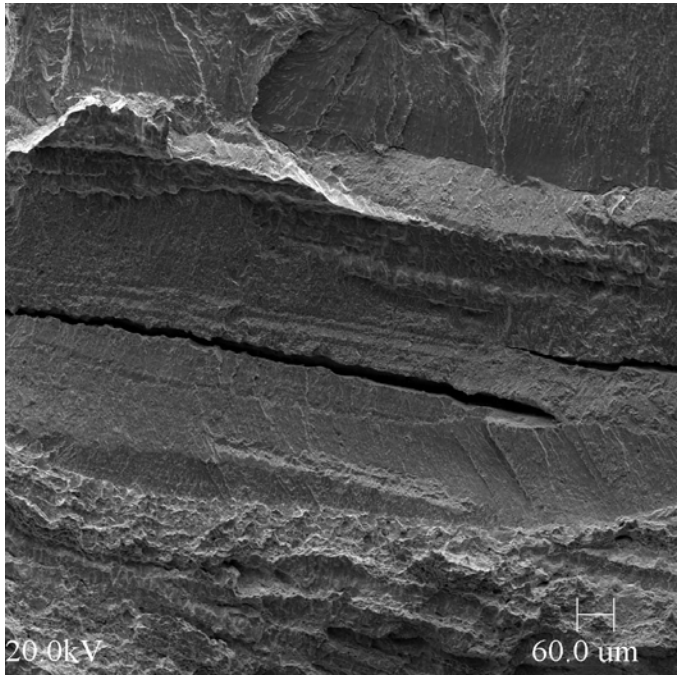
# *Fracture Surface of Alloy 182 Specimen BCR-01 (V.C. Summer)*



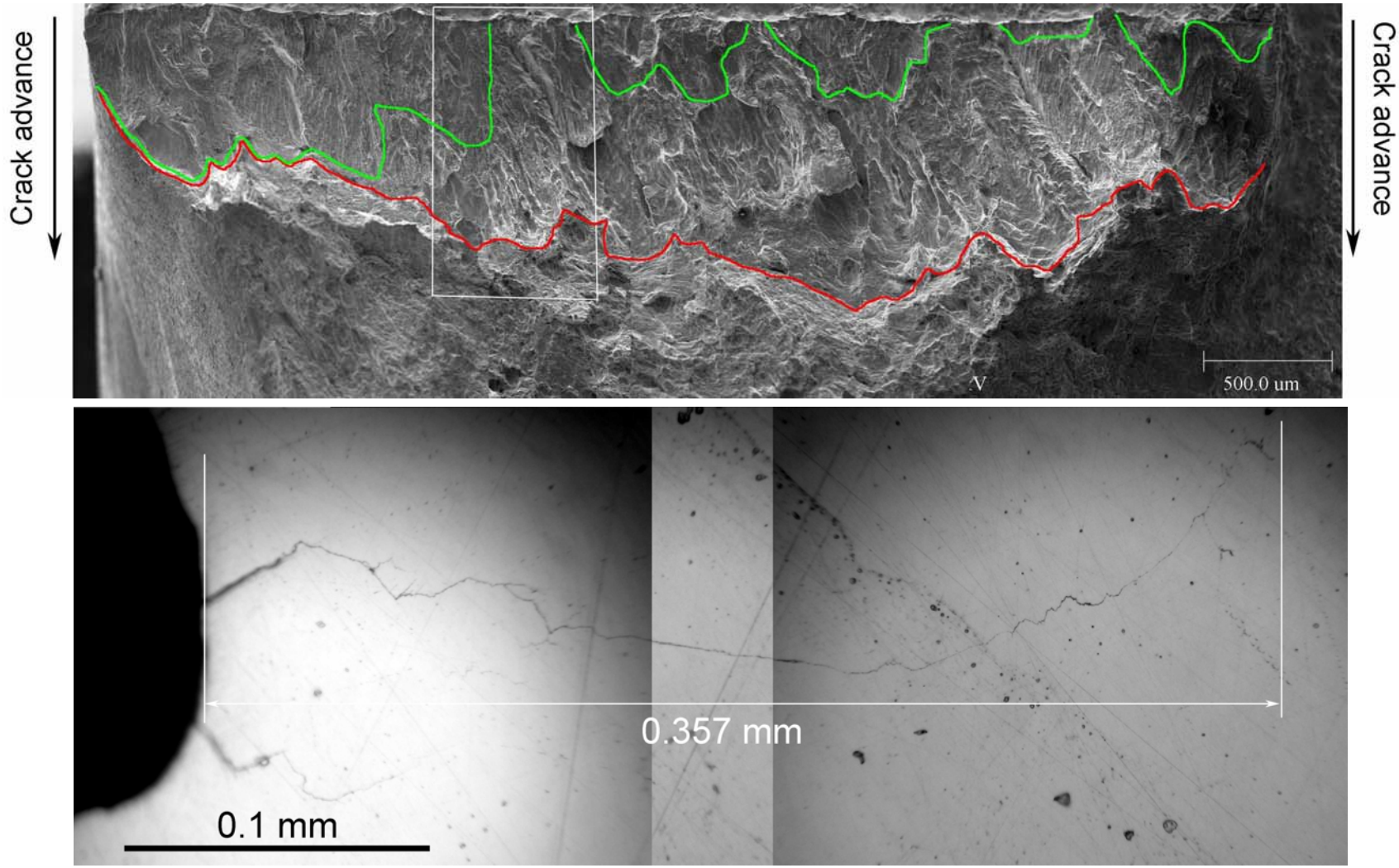
# *Fracture surfaces of J11CC-1 and BCR-01 (Alloy 182)*



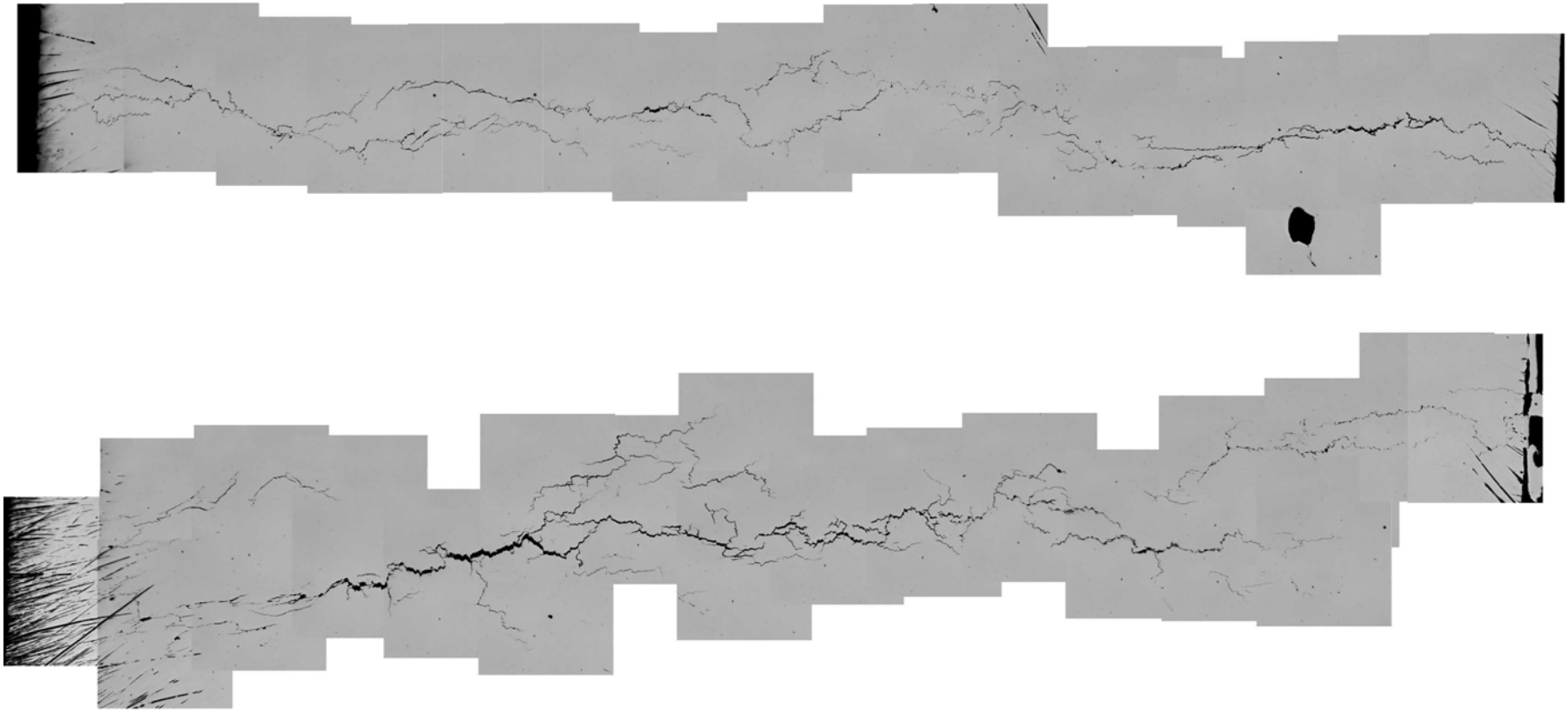

- Secondary cracks across the propagation front

# *Fracture Surface of WCR-01 (A82)*



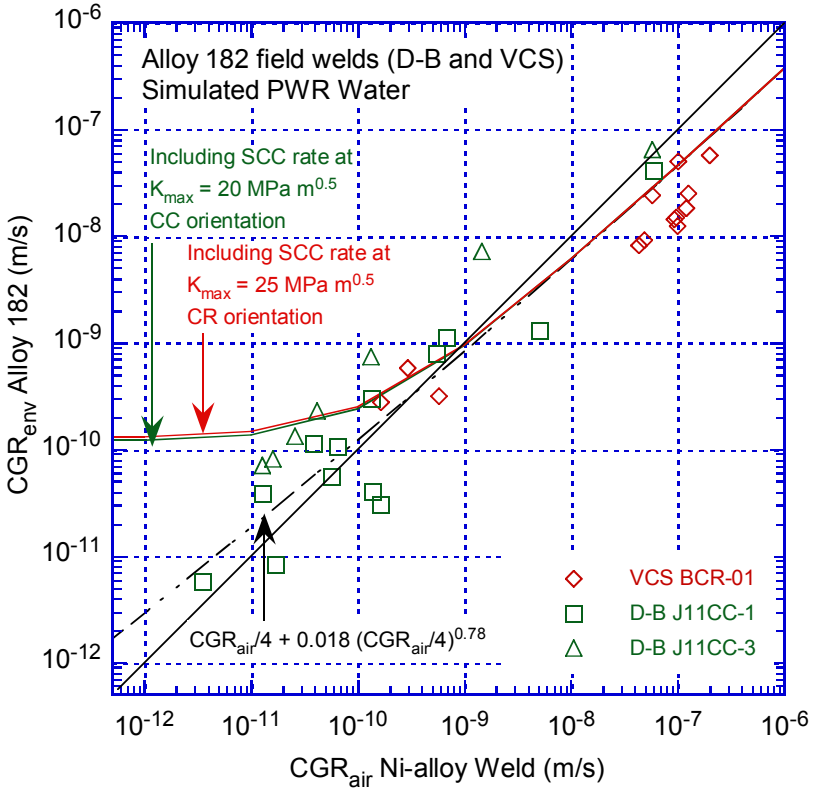

- Crack branching (secondary cracks observed on the fracture surface, across the propagation front)

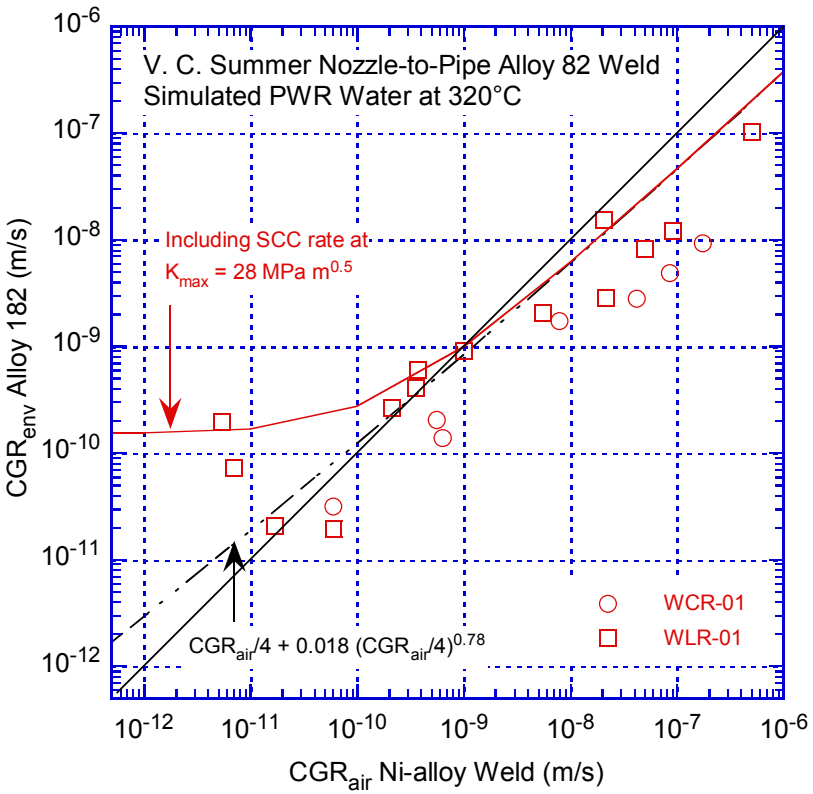
# North Anna Unit 2 Nozzle #31 – Destructive Examination (PNNL)



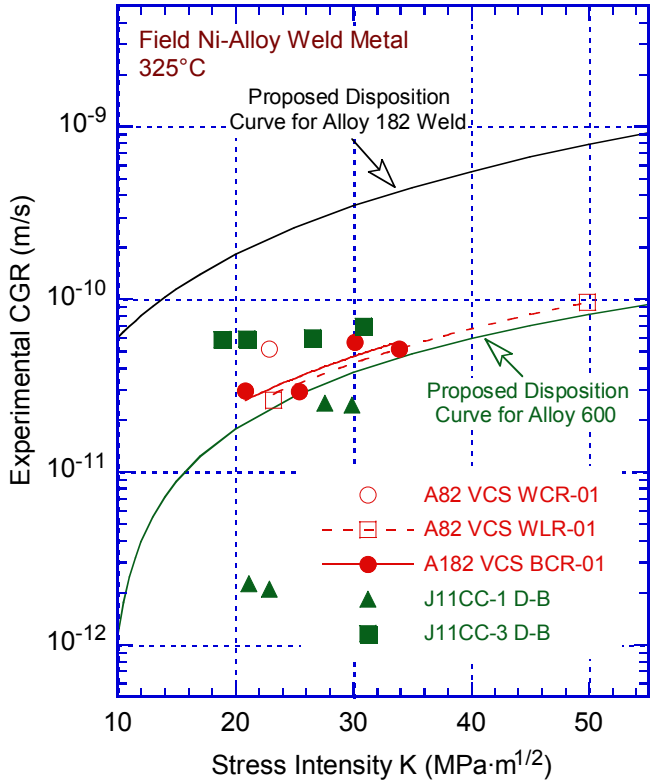
- **Extensive branching**

# Cyclic CGRs for Field Welds (Davis-Besse and V.C. Summer)



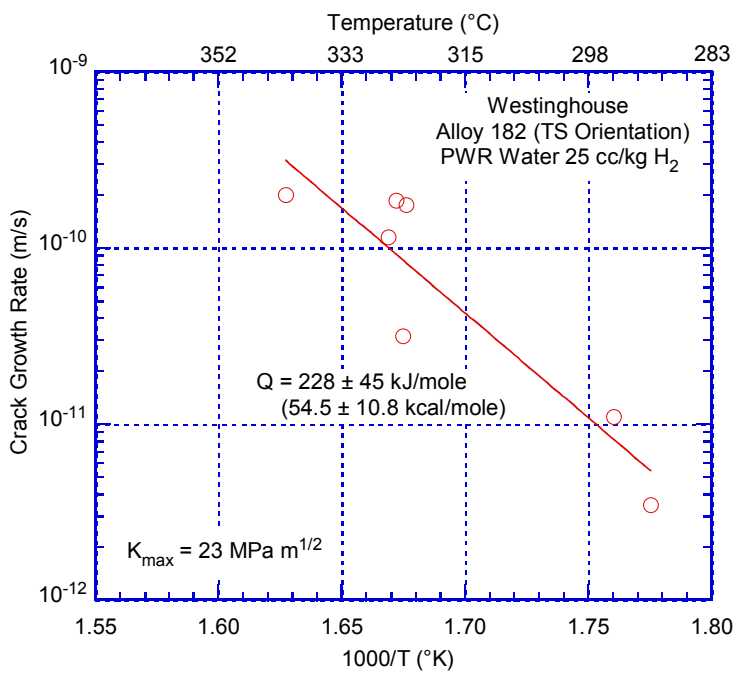
# *SCC CGRs for Field Welds (Davis-Besse and V.C. Summer)*

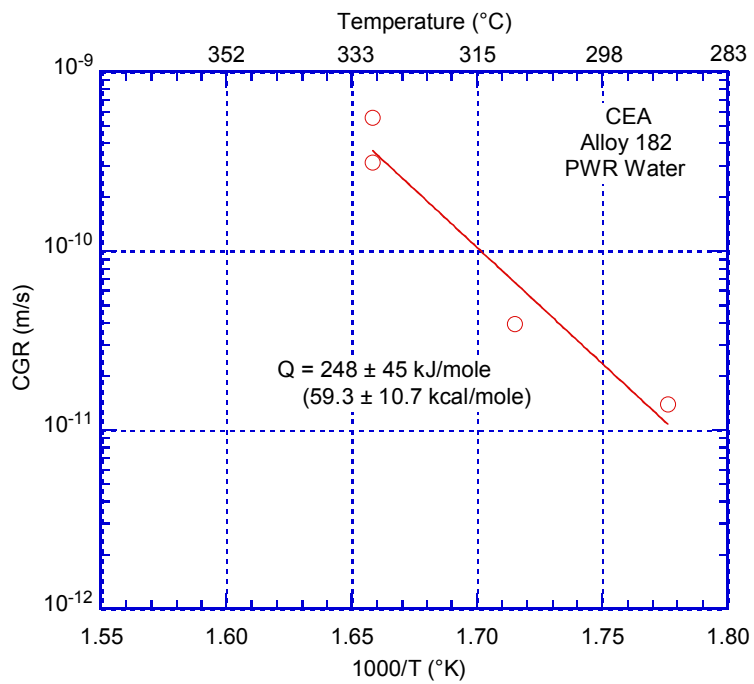



- **All CGRs well below the proposed disposition curve**

# *Determination of the Activation Energy for SCC Crack Growth of Alloy 182 Weld*

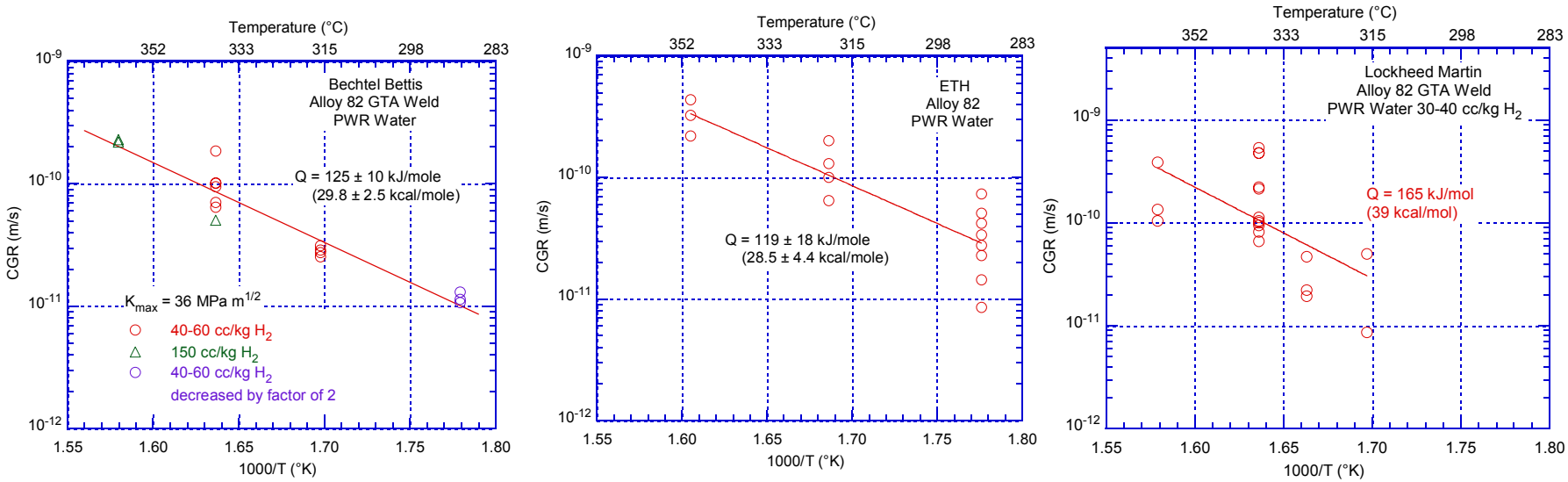
# *Literature Data: Alloy 182*




- Larger than the proposed value of 130 KJ/mol

# Literature Data: Alloy 82




- Large scatter: 119-165 kJ/mol

# *Approach*

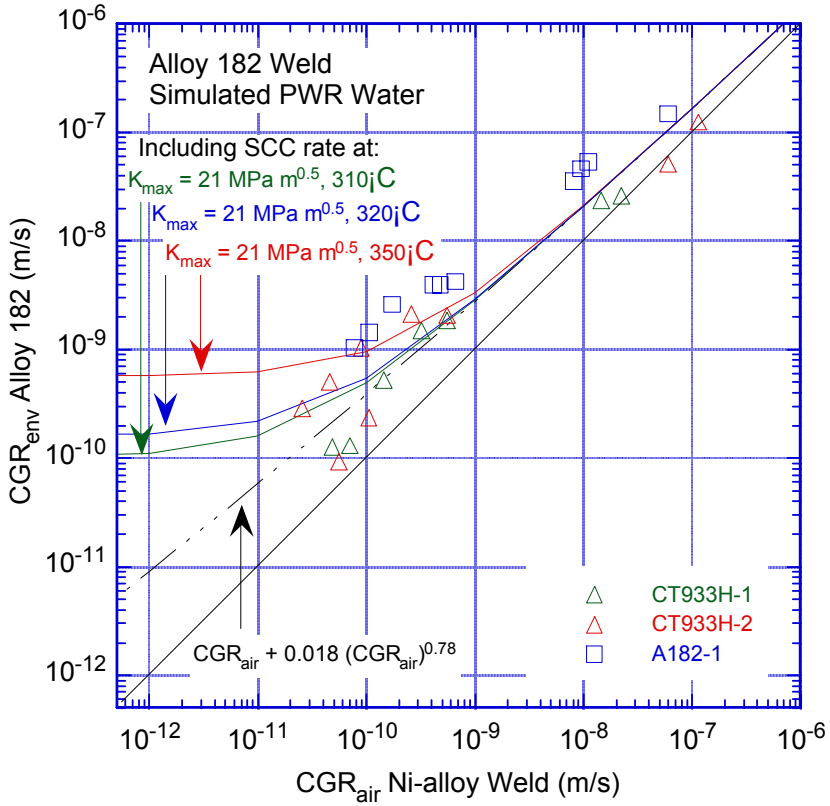
- Conduct tests in PWR environment at different temperatures
- Use one specimen for up to three temperatures to observe the effect of temperature on a crack that is already propagating
- Maintain $\Delta E$ from the Ni/NiO line by adjusting the hydrogen overpressure

# *Composition (wt.%) of Alloy 182 Welds*

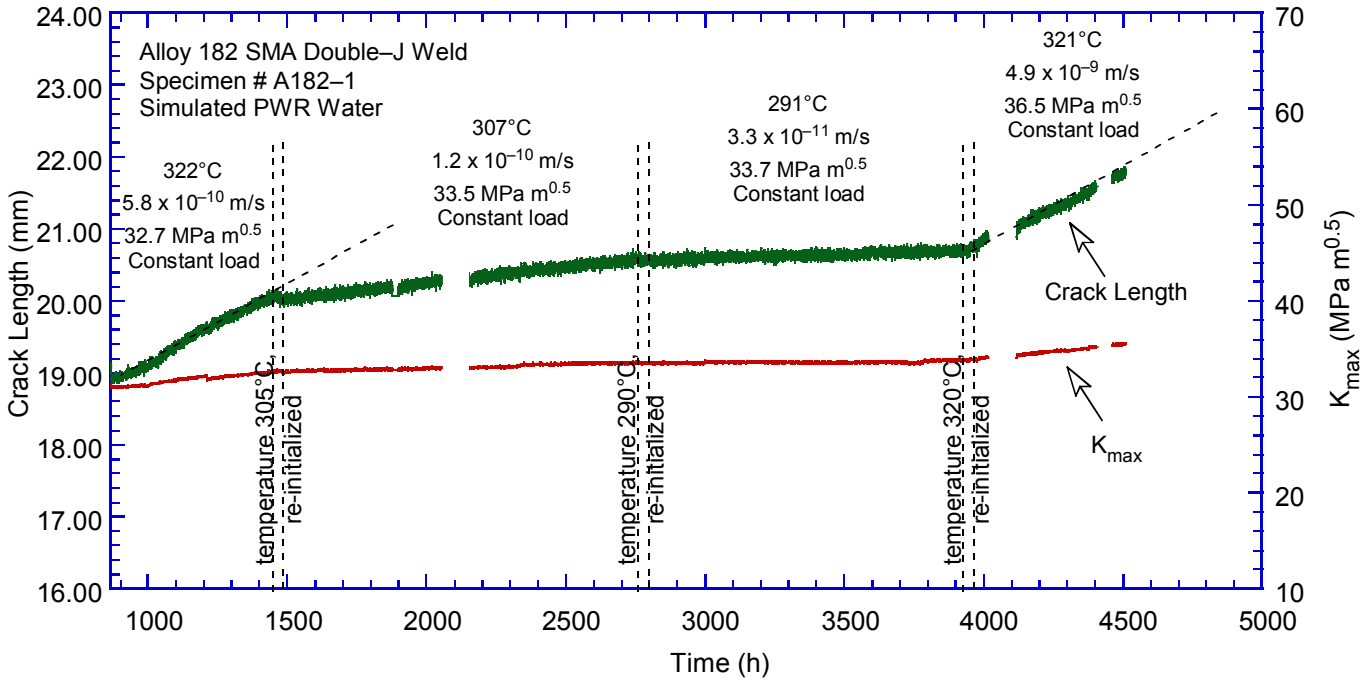
| Alloy ID (Heat) | Analysis | C | Mn | Fe | S | P | Si | Cu | Ni | Cr | Ti | Nb | Co |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A 182 | Spec. | 0.10* | 5.0-9.5 | 6.0-10.0 | 0.015* | – | 1.0* | 0.5* | Bal | 13.0-17.0 | 1.0* | 1.0-2.5 | 0.12* |
| A 182 Double-J | ANL | 0.0415 | 7.095 | 6.005 | 0.008 | 0.06 | 0.53 | 0.03 | 65 | 14.35 | 0.43 | 1.585 | 0.03 |
| A 182 Deep Groove | ANL | 0.04 | 7.08 | 6.82 | 0.005 | 0.025 | 0.35 | 0.03 | 70.44 | 13.81 | 0.30 | 1.06 | 0.02 |

- Three Alloy 182 weld specimens (all TS orientations) were tested:
  - 1T CT Specimen A182-1: 320°C - 305°C - 290°C- 320°C
  - 1/2T CT Specimen CT933H-1: 310°C - 300°C - 290°C- 310°C
  - 1/2T CT Specimen CT933H-2: 350°C - 310°C - 290°C- 350°C

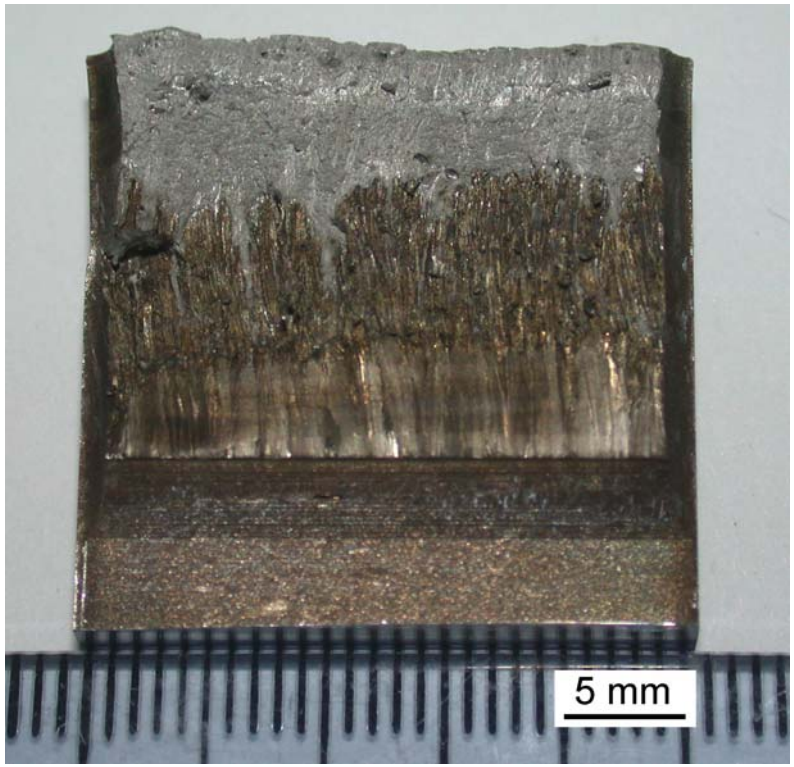
# *Cyclic CGRs for Laboratory-prepared Alloy 182 Welds*

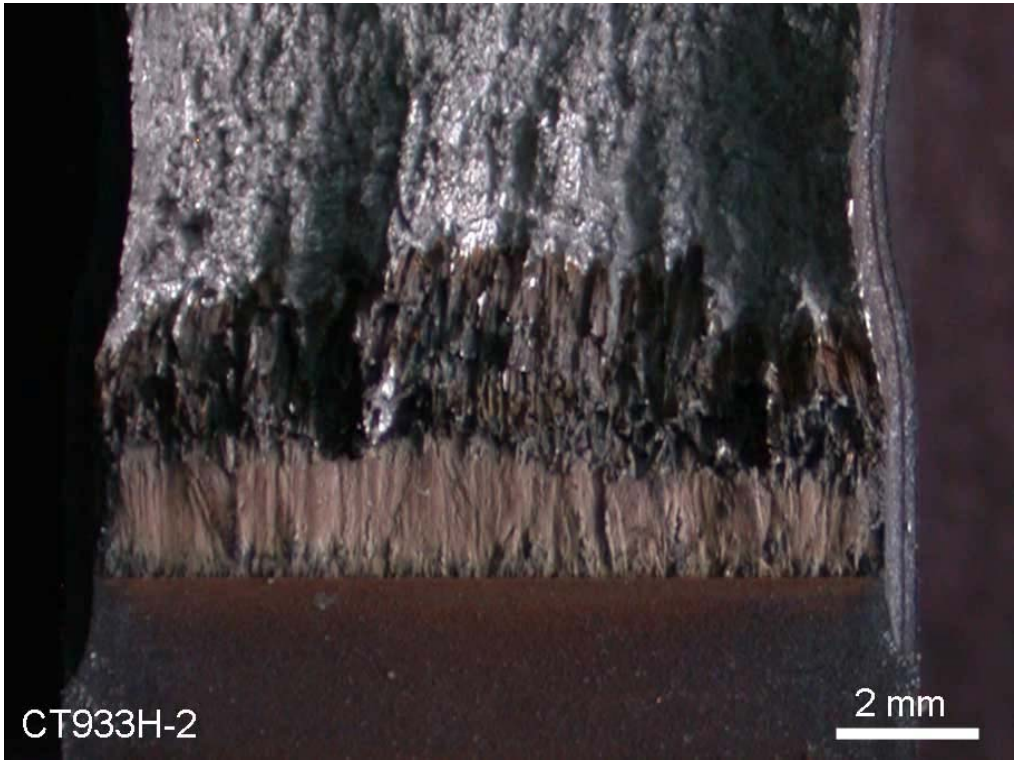


# SCC CGR vs. temperature for Specimen A182-1



## *Fracture Surfaces*

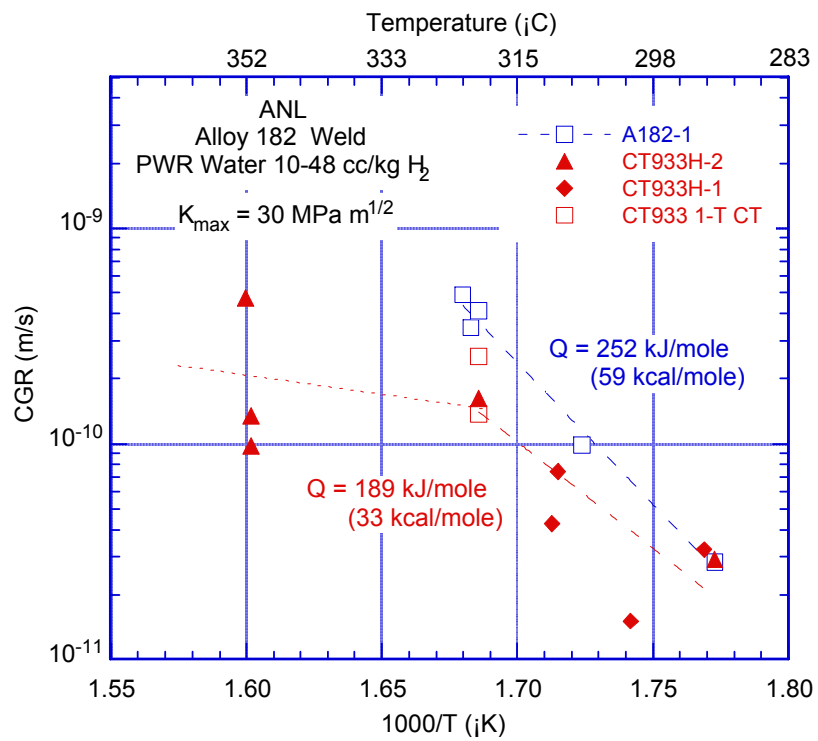



- 1T CT Specimen A182-1:
320°C - 305°C - 290°C- 320°C

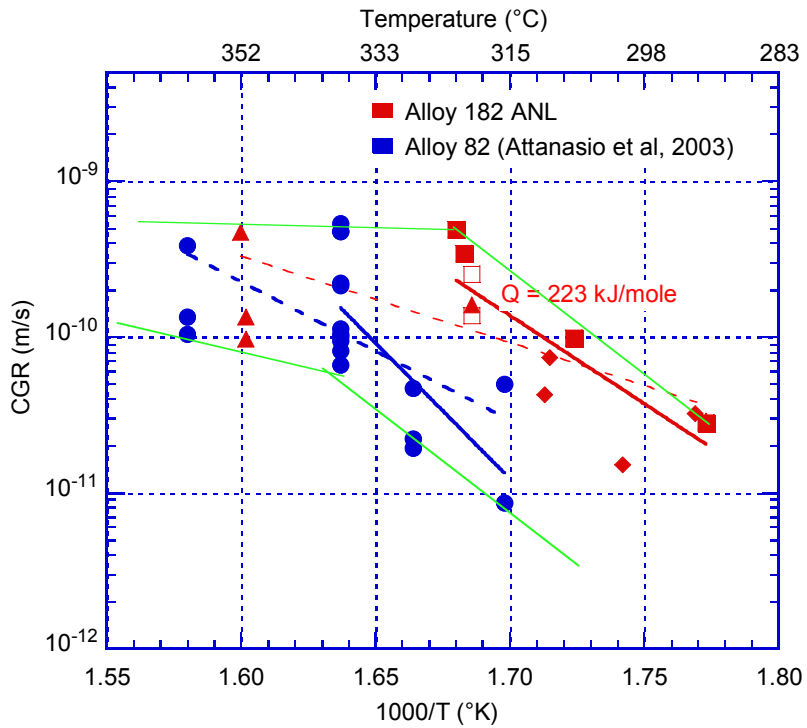
- 1/2T CT Specimen CT933H-2:
350°C - 310°C - 290°C- 350°C

# *Determination of the Activation Energy for SCC Crack Growth in Alloy 182 Weld*




- Q = 252 kJ/mol for double-J weld, 189 KJ/mol for deep groove weld

# *Comparison with Alloy 82 data*



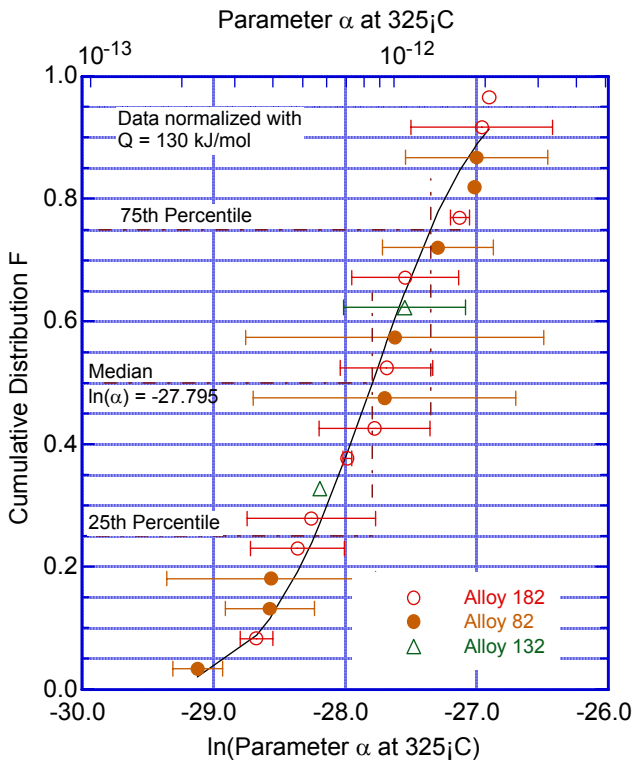

- Alloy 82 appears to be more resistant to SCC crack growth than Alloy 182

# *The Consequences of Using a Larger Activation Energy*

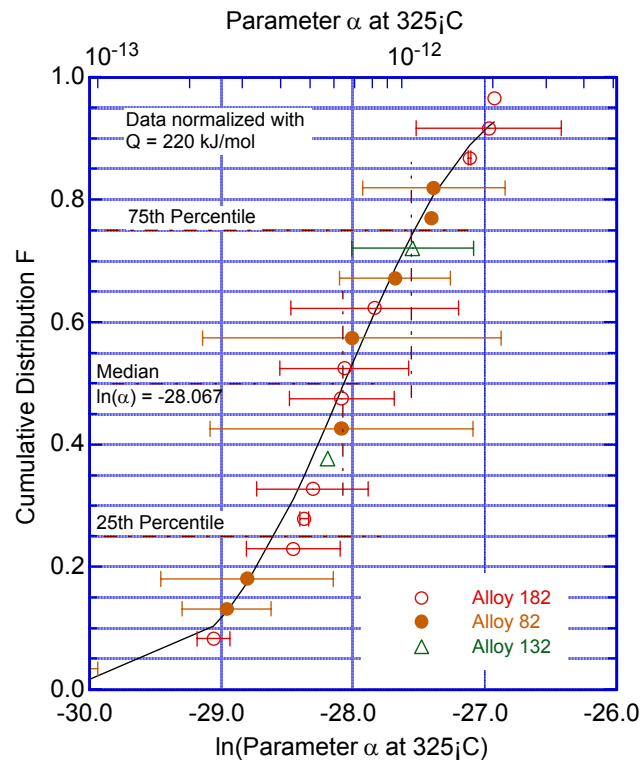
$$\dot{a}_{Ni-weld} = \alpha \exp\left[-\frac{Q}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]K^{\beta}$$

- Cumulative distribution of parameter $\alpha$, when data normalization uses:

Q =130 kJ/mol



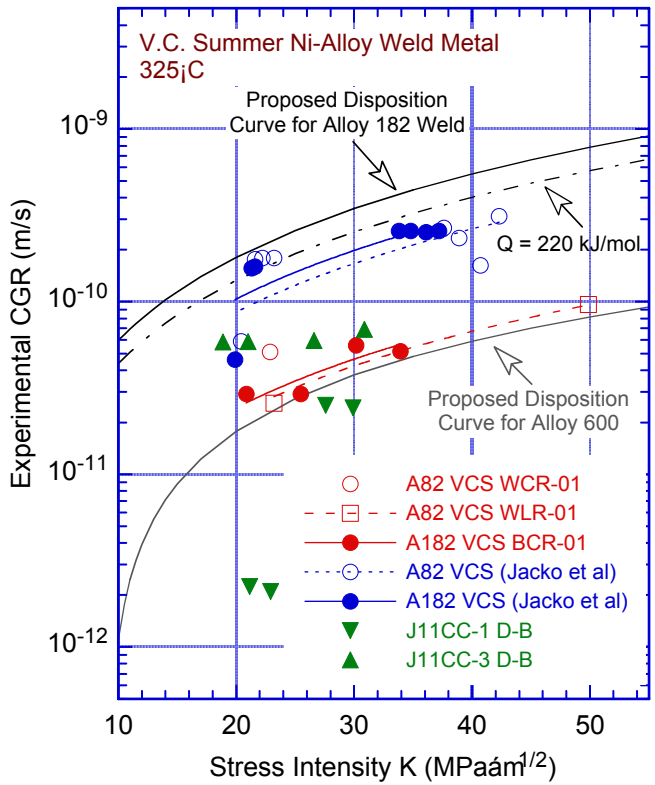

Q = 220 kJ/mol




- $\alpha = 1.5 \times 10^{-12}$

$\alpha = 1.1 \times 10^{-12}$ (36% lower)

# *The Consequences of Using a Larger Activation Energy*

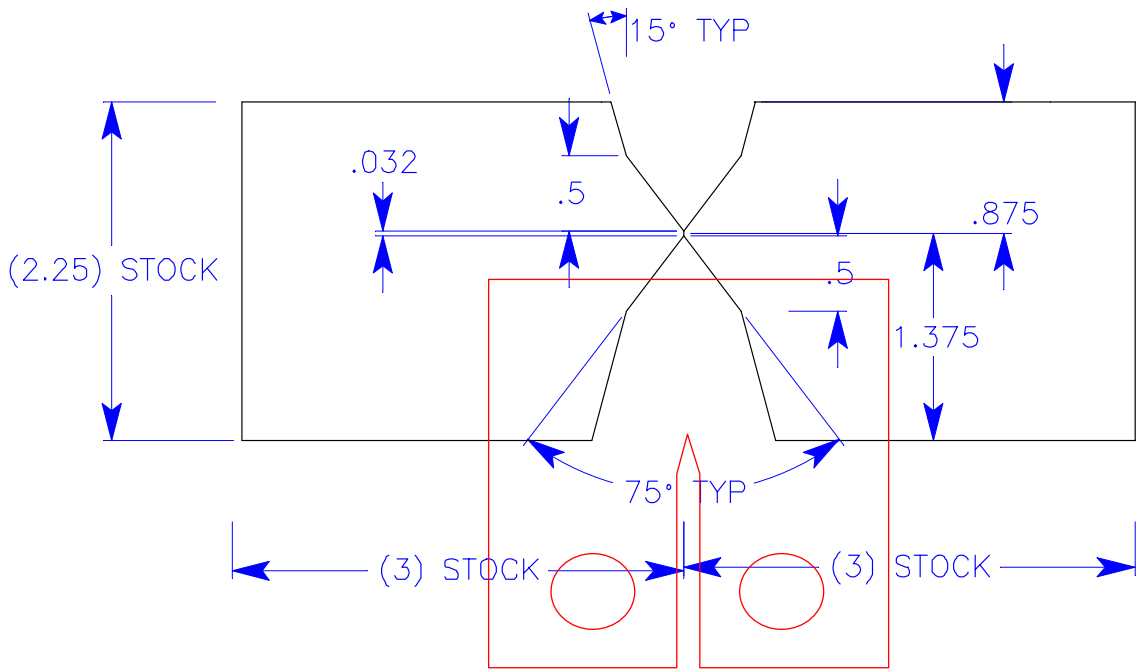



$$\dot{a}_{Ni-weld} = 1.1\times10^{-12}\exp\left[-\frac{Q}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]K^{1.6}$$

- If Q = 220 kJ/mole is used, the disposition curve for Alloy 182 becomes 36% less conservative

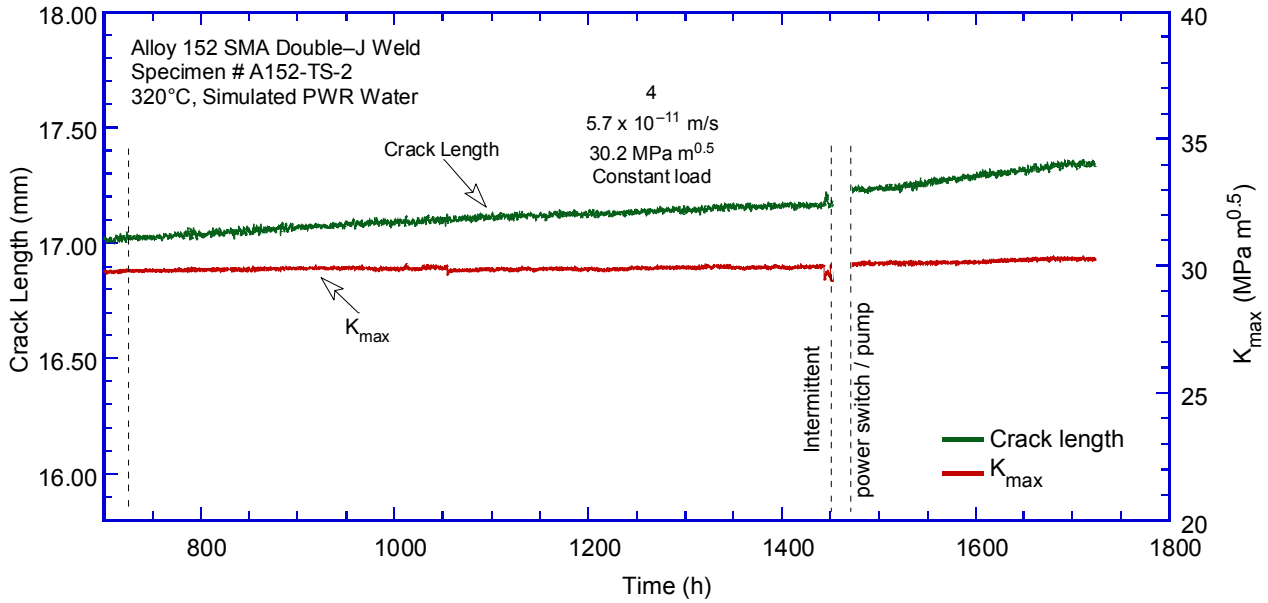
# *Determination of the Activation Energy for SCC Crack Growth of Alloy 182 Weld*

# *Alloy 152 specimens (A152-TS-2 and A152-TS-4)*

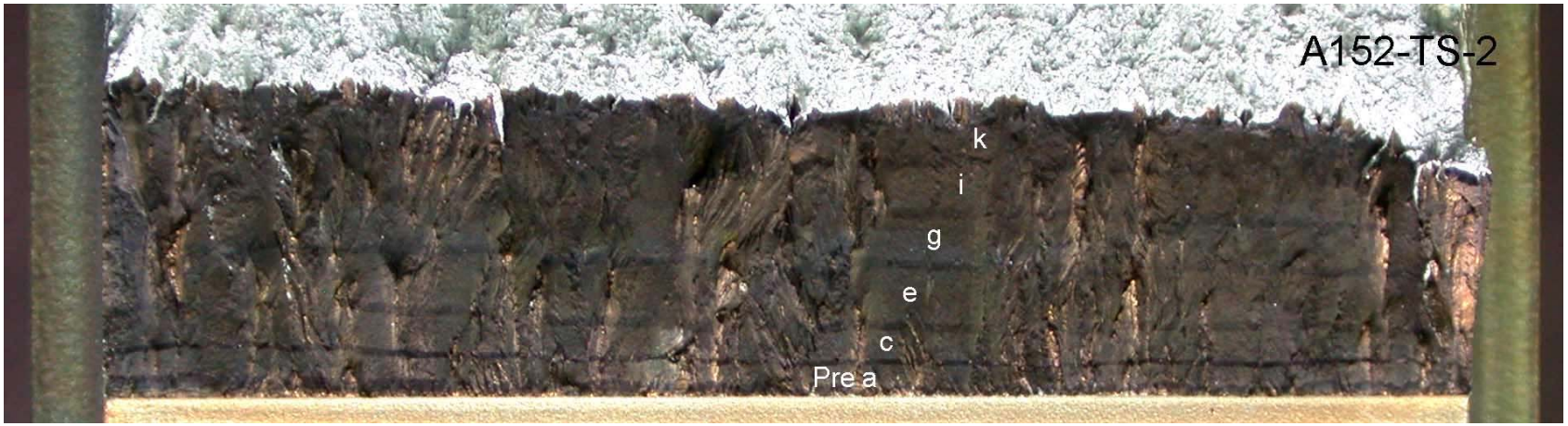


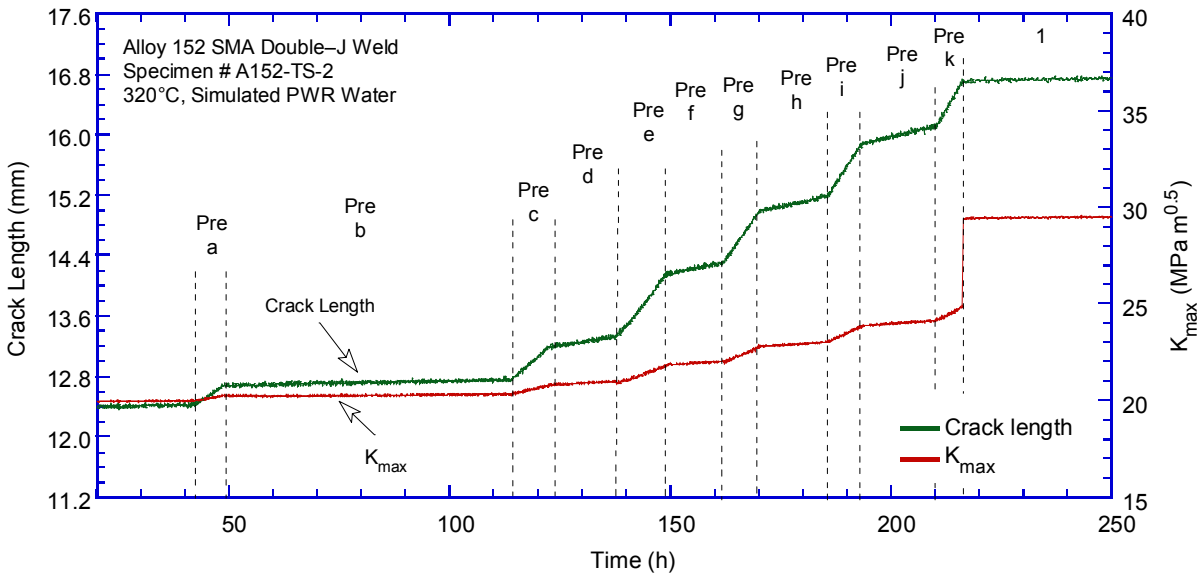

- A152-TS-4 test in progress

# Results - Alloy 152 specimen A152-TS-2

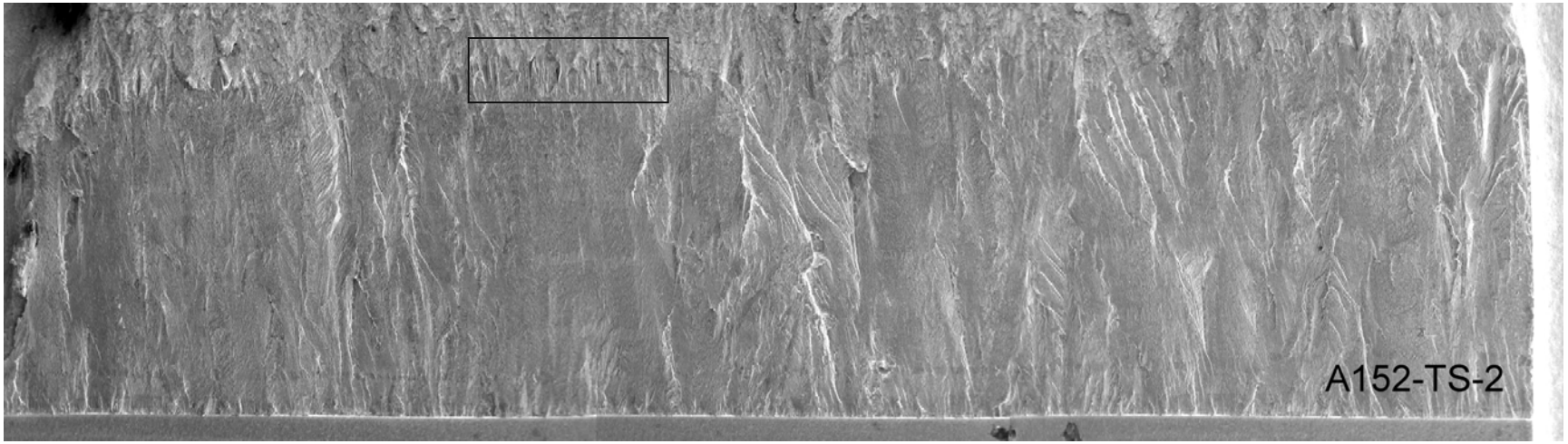


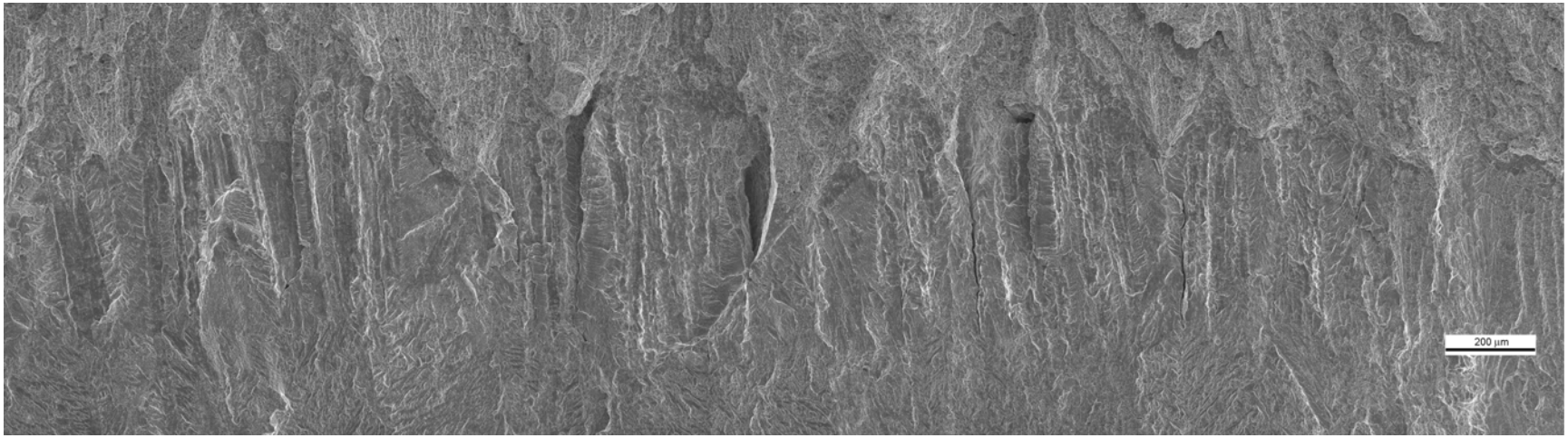
# Fracture surface of A152-TS-2



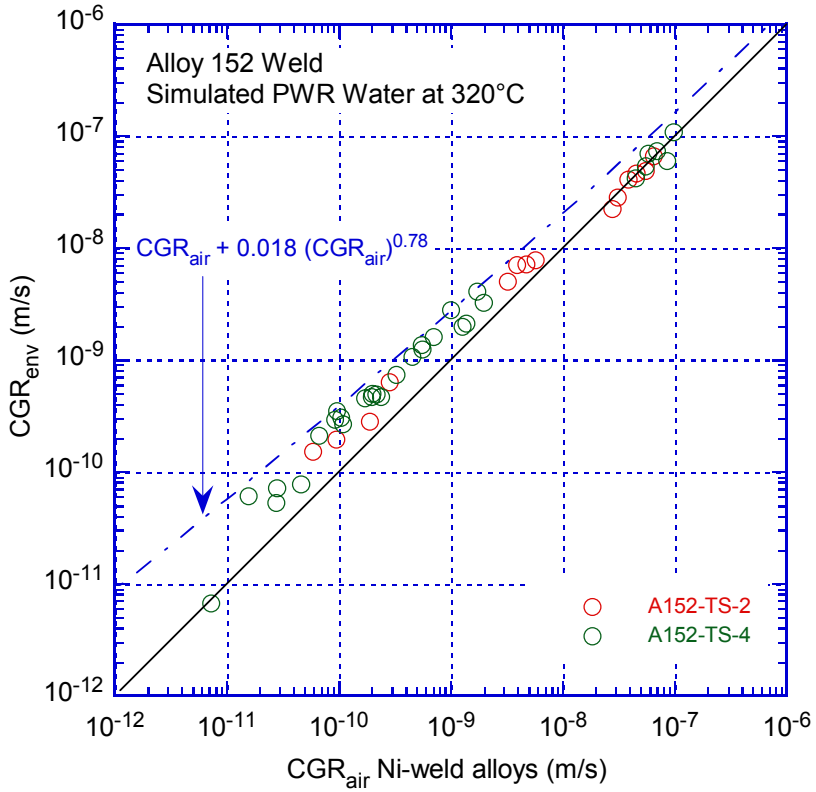



# *Fracture surface of A152-TS-2*



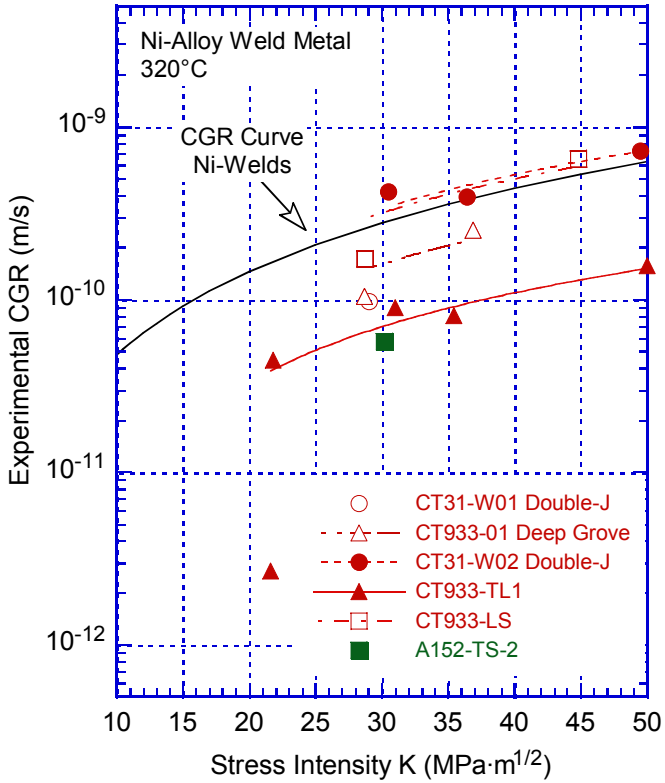



# *Cyclic CGR data for A152-TS-2*




- A152-TS-4 rates are not corrected

# *SCC CGRs for A152-TS-2 and Alloy 182 vs. K*




- A152-TS-4 rates are not corrected

# *Summary*

*General*

- Experimental procedure assured transition to IG fracture mode, superior IG engagement, and relative straight crack fronts (field and laboratory 182/82, 152)
- The environmental enhancement of cyclic CGRs is minimal for all weld alloys

*Laboratory-prepared welds (Alloy 182)*

- SCC CGRs consistent with other laboratory data
- The activation energies for SCC crack growth were 252 kJ/mol (double-J weld), and 189 kJ/mol for the deep-groove weld
- The use of the larger activation energy (220 kJ/mol vs. 130 kJ/mol) for CGR data analysis for Alloy 182 welds leads to a less conservative disposition curve disposition curve

*Field welds*

- Defects were found in the field welds
- SCC CGRs lower than those for laboratory-prepared welds
- Crack branching was observed on both fractures surfaces and cross sections

*Alloy 152*

- SCC CGRs was as high as $5.4 \times 10^{-11}$ m/s for $K_{max}$ = 30.2 MPa $m^{1/2}$