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SCC CGRs of Alloys 690 and 152 Weld in PWR Water

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Outline

- CGR of Alloy 690
  - comparison with data reported by Bettis (similar alloy condition, and similar deformation levels)
- CGR of Alloy 152 Weld
  - comparison with Alloy 182
- Future work
- Possible discussion topic
  – transitioning to SCC

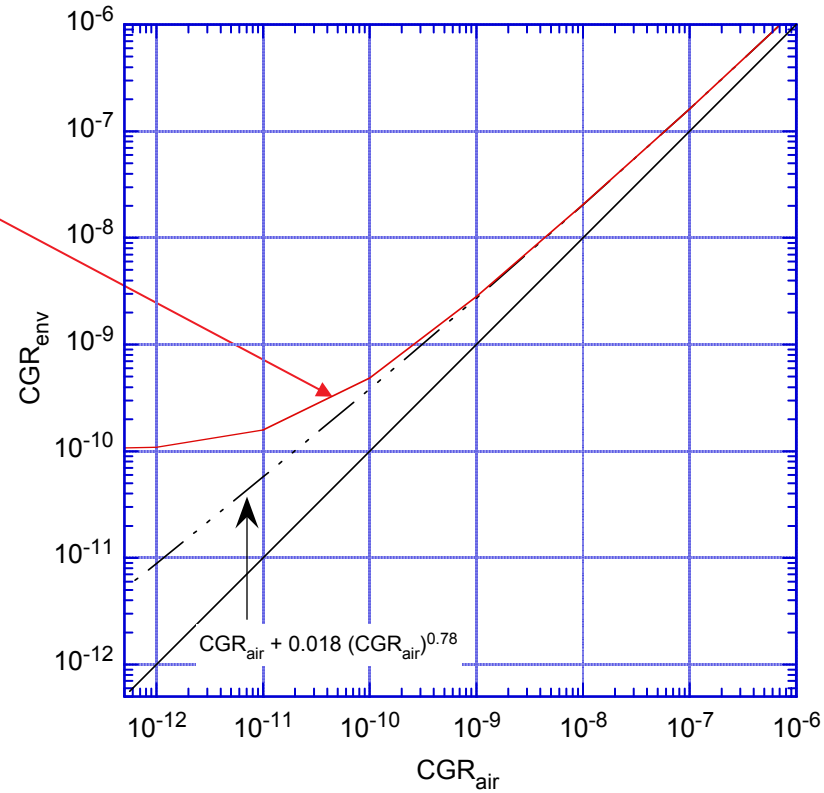
Experiment

- Temp: 320°C
- PWR Water (<10 ppb DO, 1000 ppm B, 2 ppm Li, ≈23 cc/kg hydrogen)
- Flow Rate: ≈55 mL/min
- Conductivity: ≈20 μS/cm
- Loading history to facilitate the transition from transgranular fatigue cracking to intergranular SCC cracking:
  - Precracking carried out in the PWR environment
  - Load Ratio R: 0.3–precrack;
    0.5-0.7–sawtooth with up to 1000s rise time;
    1.0–constant load

*The Analysis of Cyclic CGR Data**

- Superposition model (Kassner & Shack)

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



- For Ni-welds:

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

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

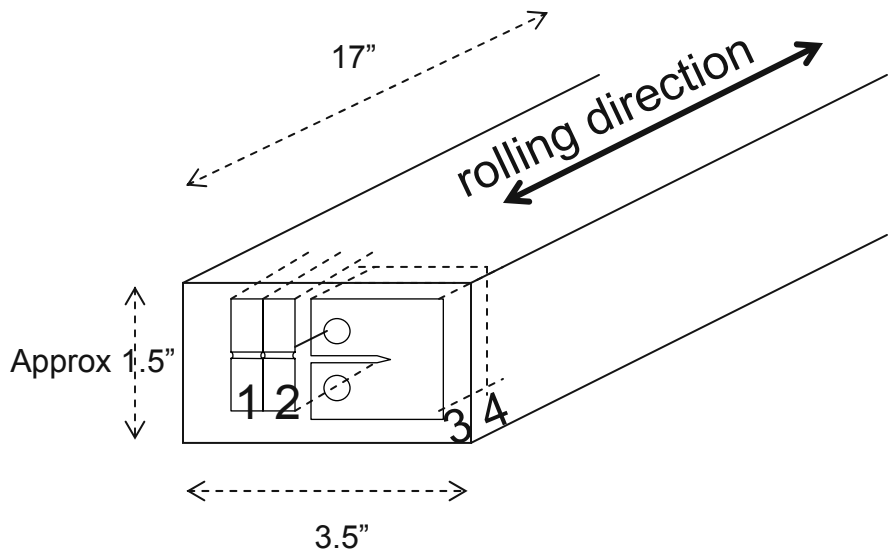
* Example shown is for Ni-alloy welds, the approach for Alloy 690 is similar

Alloy 690 Specimens

- Alloy 690 in plate form (MIL-DTL-24802*)

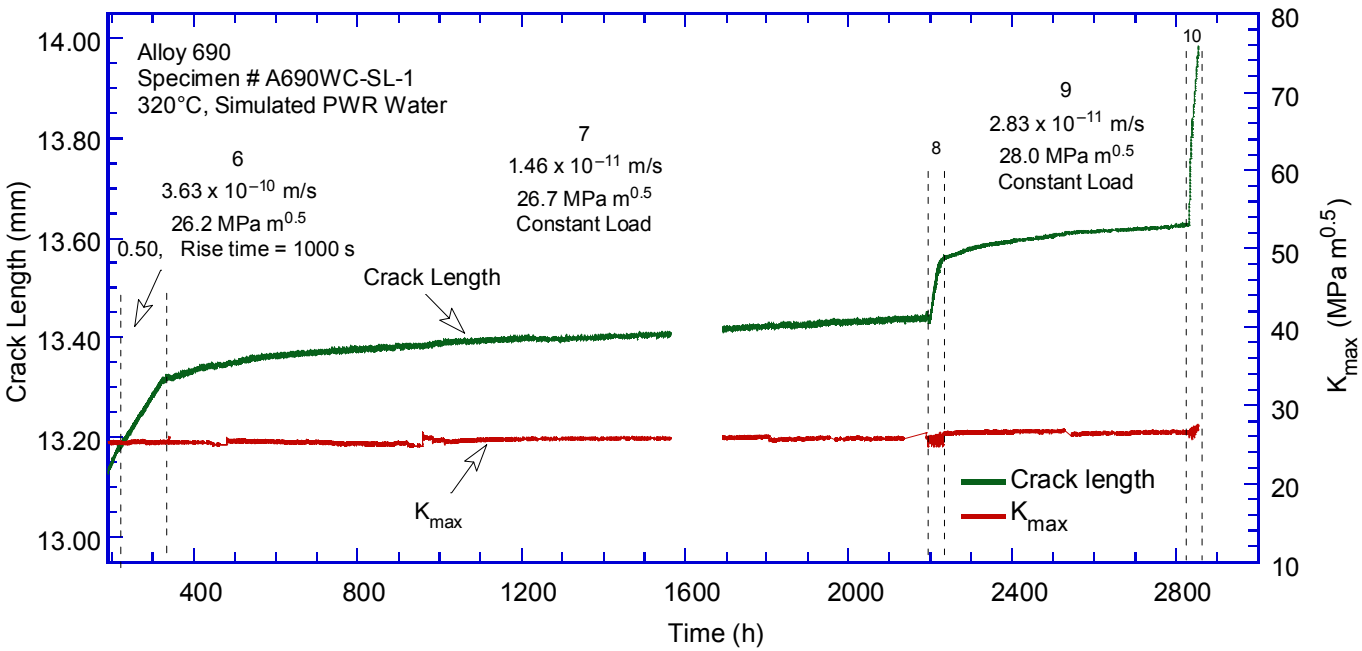
Alloy ID (Heat)	Analysis	C	Mn	Fe	S	P	Si	Cu	Ni	Cr	Ti	Nb	Co
A 690WC (NX3297HK12)	Vendor	0.03	0.20	9.9	<0.001		0.07	0.01	59.5	29.5			
	ANL	0.04	0.33	8.53	0.001	0.003	0.02	0.04	59.67	30.82	0.47	0.01	<0.01

- Cold-rolled in three passes to achieve approx. 26% reduction in thickness
- Specimens cut in both SL and ST orientations

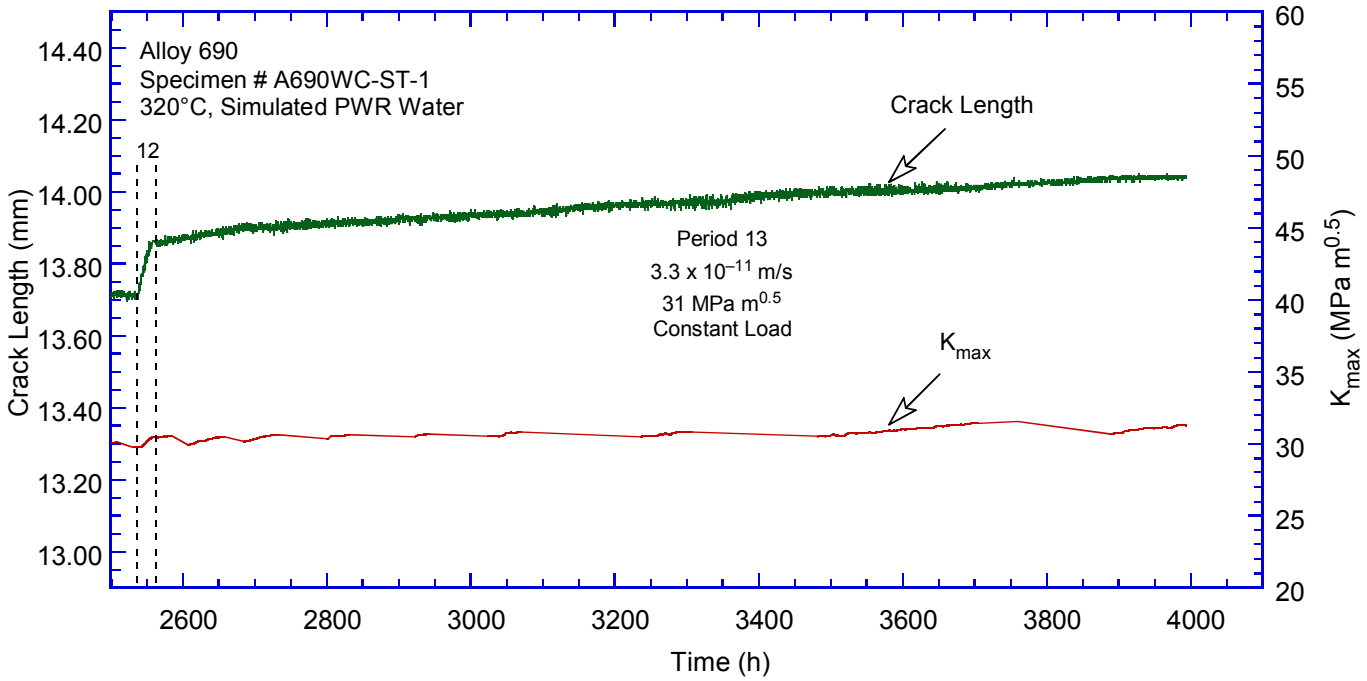


- *MIL-DTL-24802
  - vacuum induction - melted
  - electro slag - removed
  - hot - rolled
  - de-scaled
  - annealed at 1900F for 2h
  - air-cooled

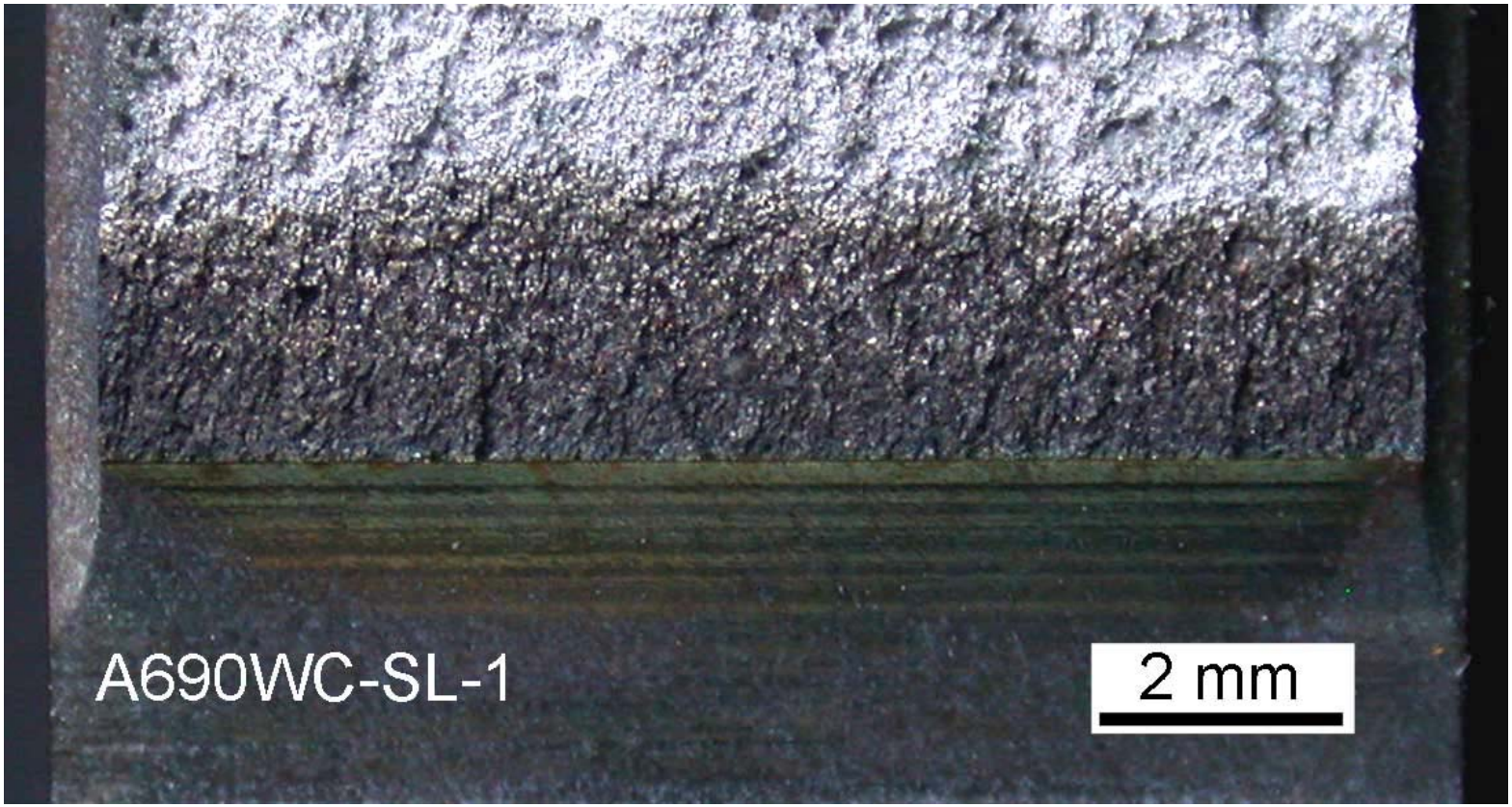
Results - Alloy 690 specimen A690WC-SL-1



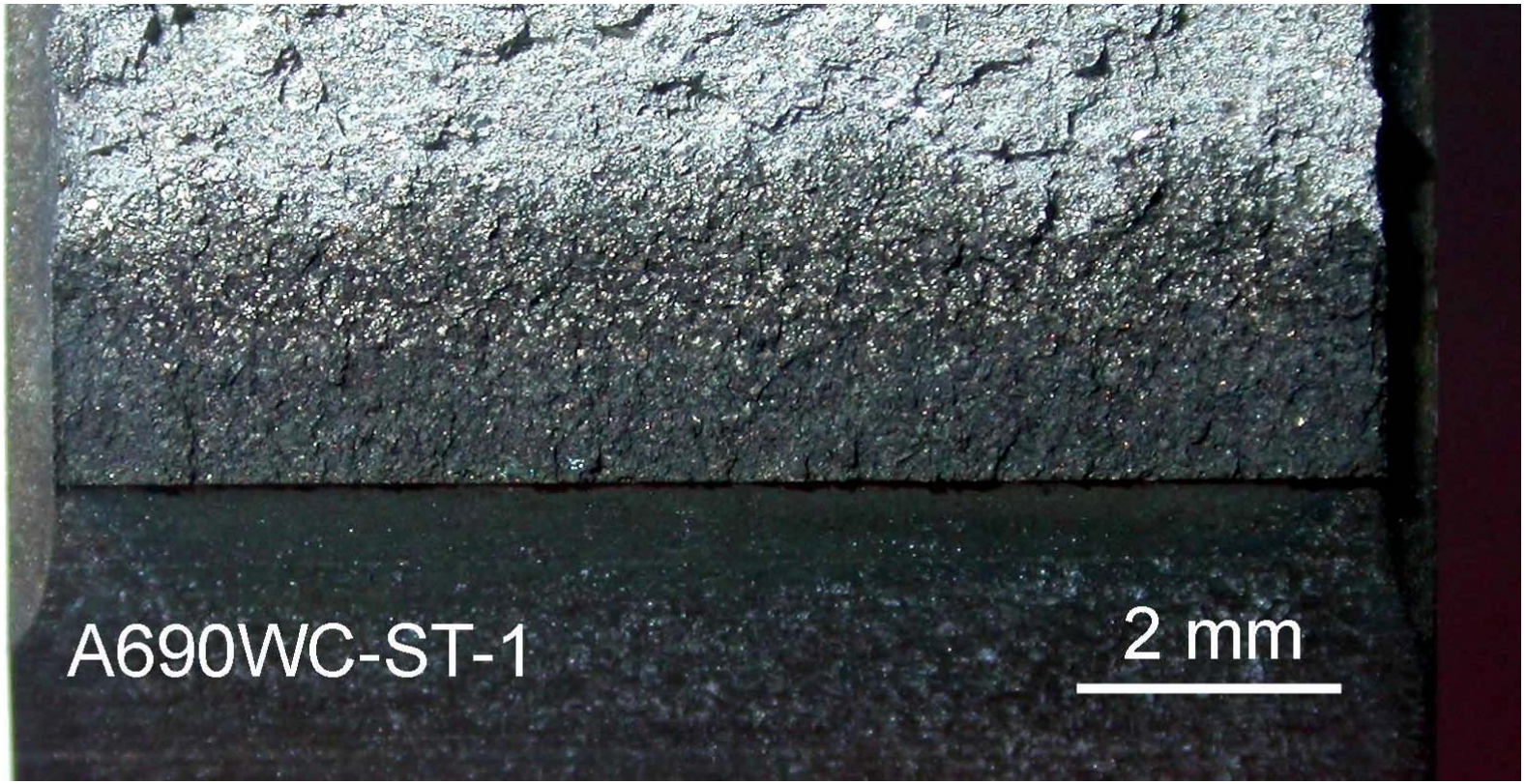
Results - Alloy 690 specimen A690WC-ST-1



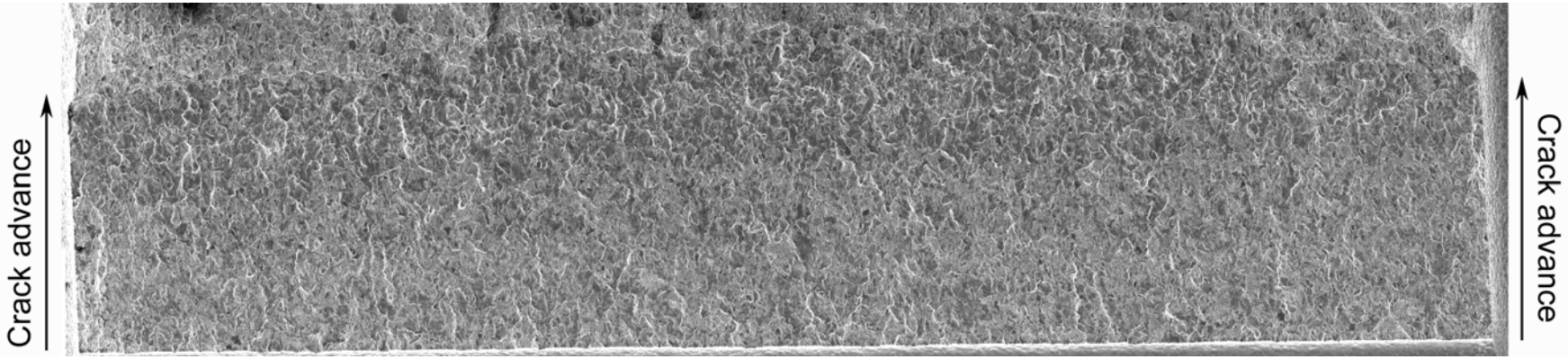
Fracture surface of A690WC-SL-1

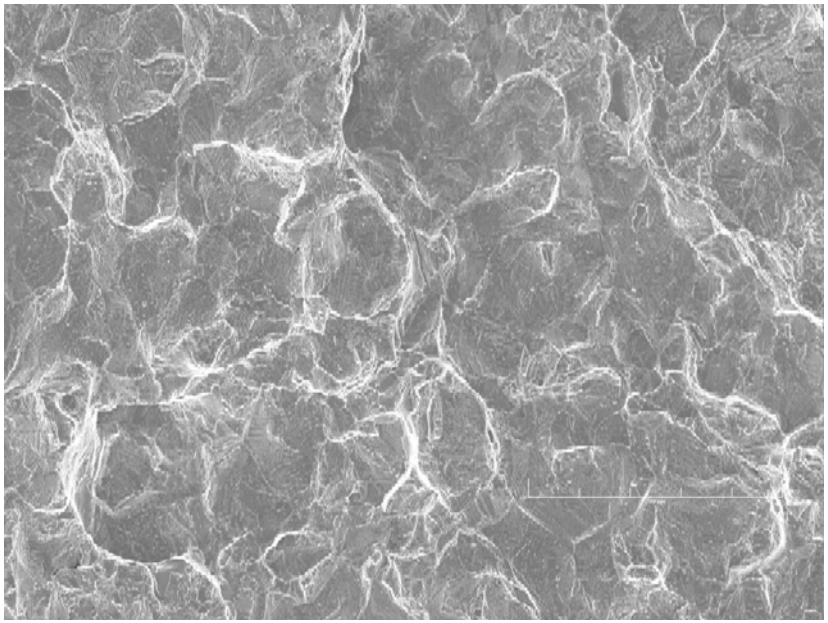


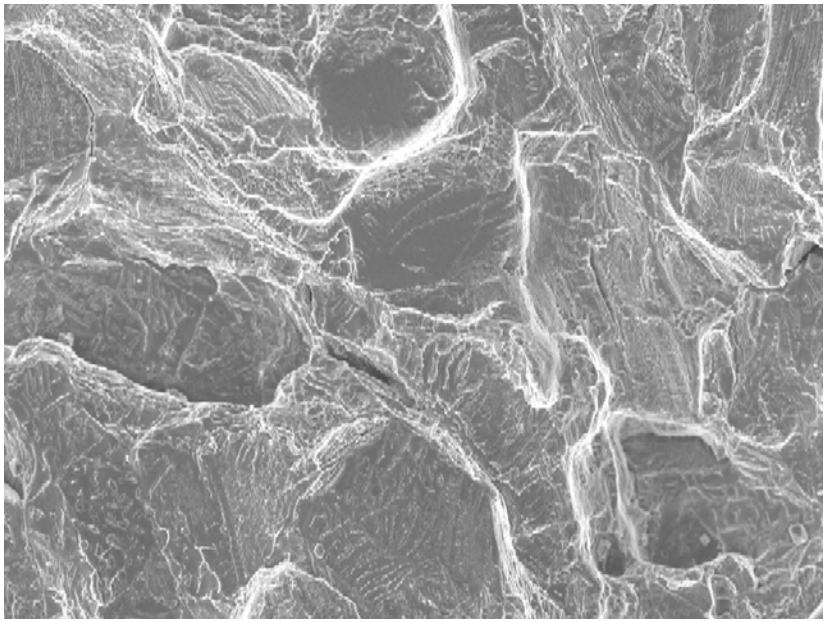
Fracture surface of A690WC-ST-1



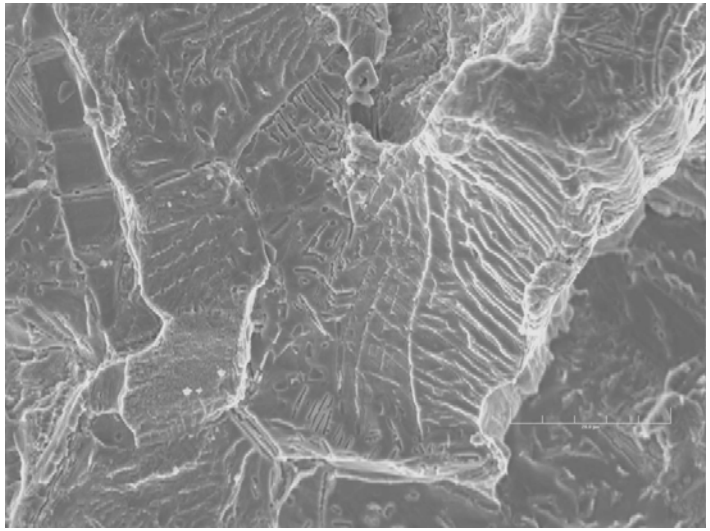
Fracture surface of A690WC-SL-1

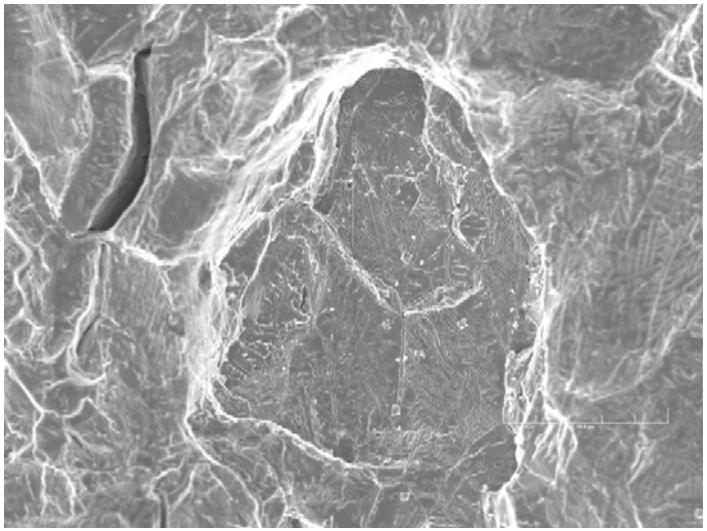


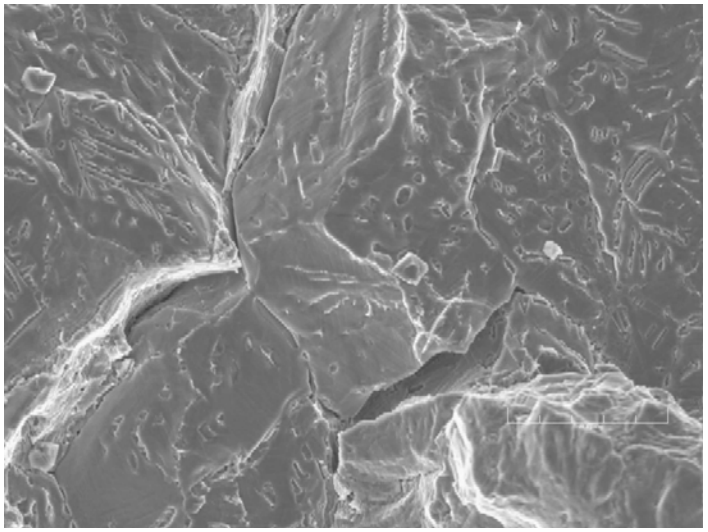




Fracture surface of A690WC-SL-1

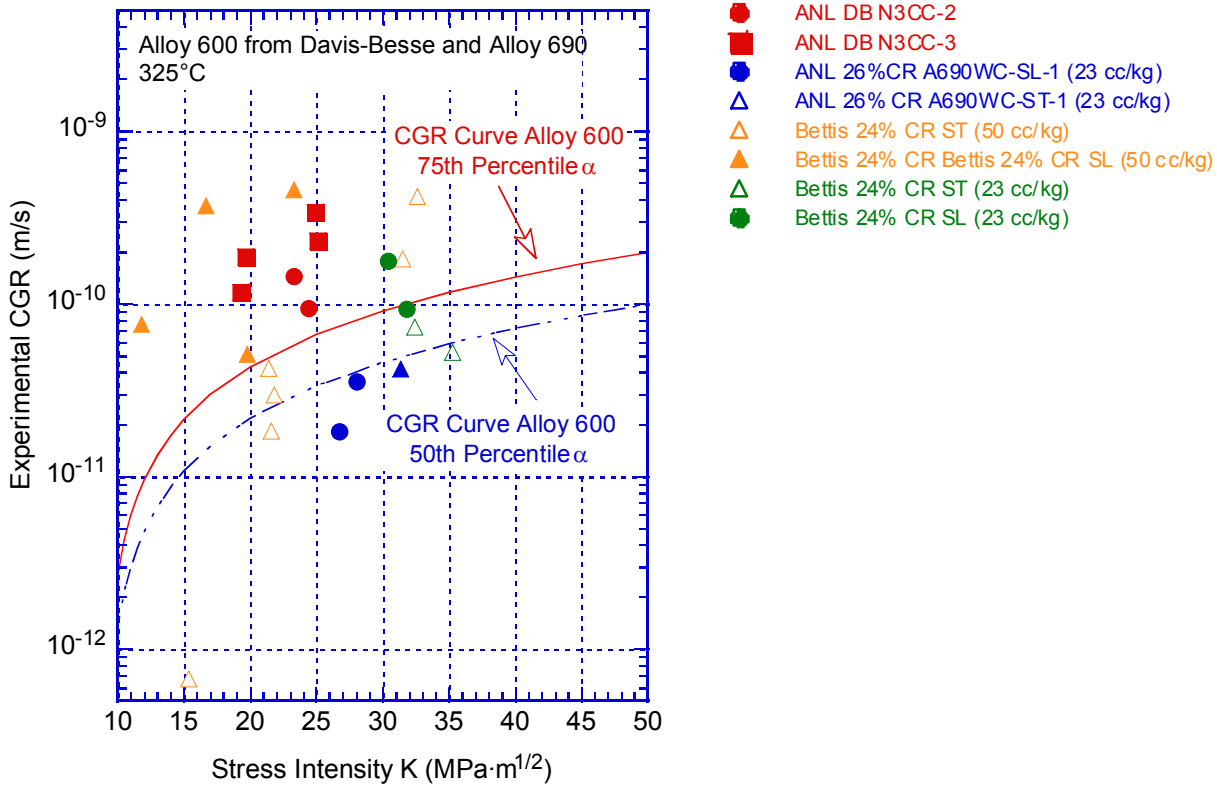






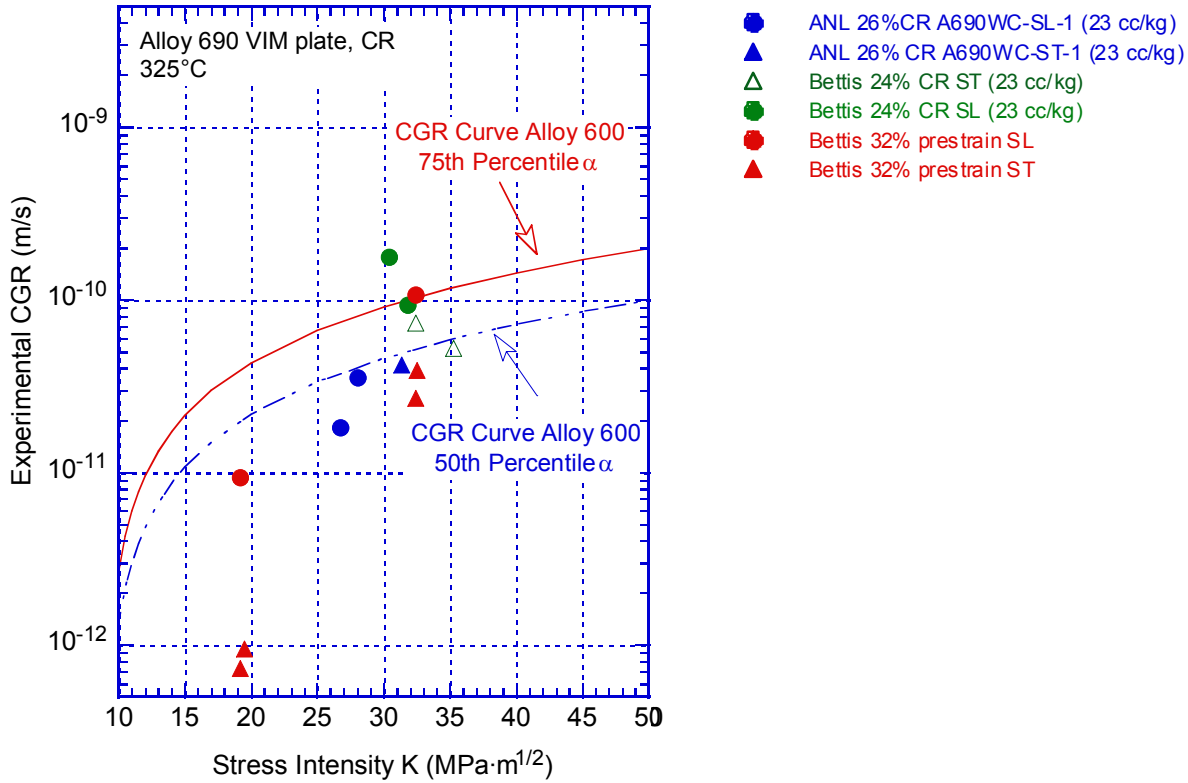
SCC CGRs for Alloy 690 vs. K

- Also included is data from Davis-Besse Nozzle #3 Alloy 600
- Bettis data obtained on similar VIM plate, 24% CR obtained at 338°C (normalized using Q = 130 kJ/mol)



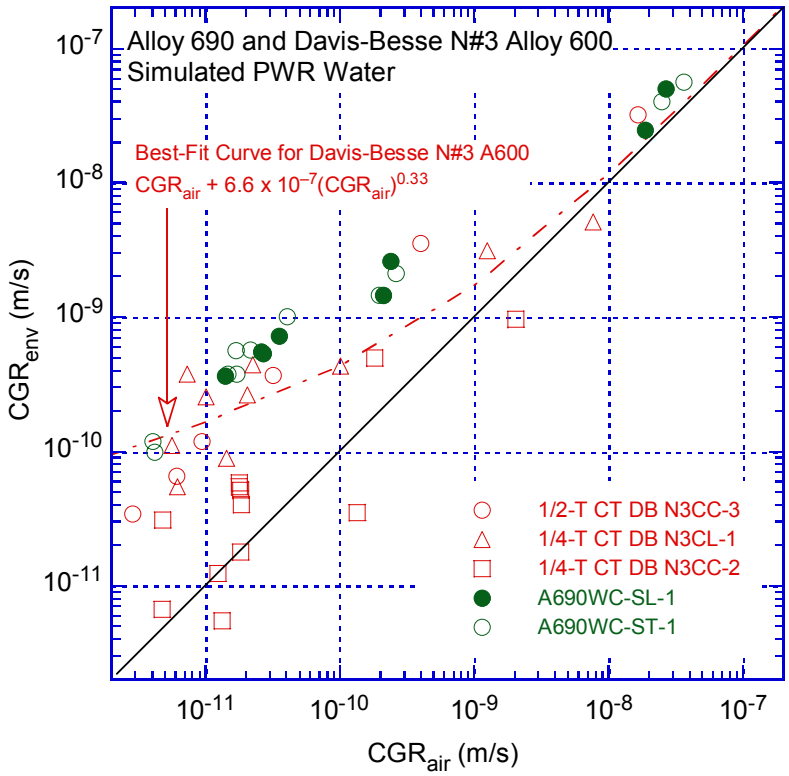
- Bettis: SL orientation is very high (comparable to Davis-Besse Nozzle #3 Alloy 600)
- Bettis: SCC CGRs are higher for 50 cc/kg than for 23 cc/kg of hydrogen
- ANL data: no apparent difference between the SL and ST orientations
- ANL and Bettis agreement (where hydrogen level was also the same, 23 cc/kg)

SCC CGRs for Alloy 690 vs. K



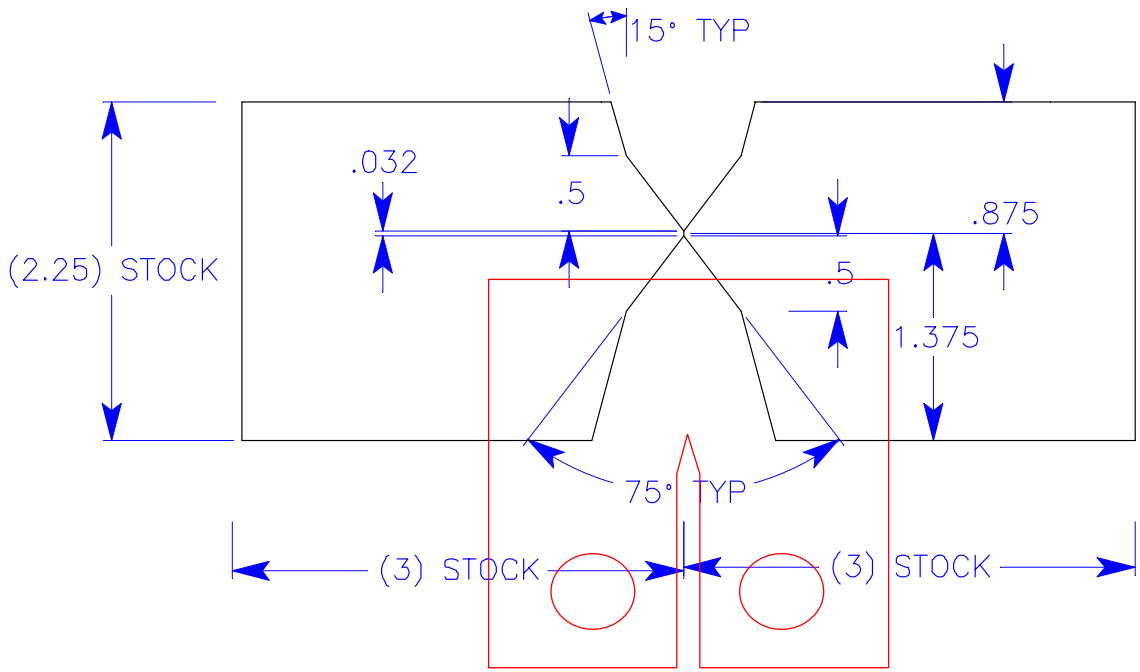
- Good agreement with Bettis data at the same hydrogen level (23 cc/kg)

Cyclic CGR data for 26% Cold-Rolled Alloy 690 and Davis-Besse Alloy 600



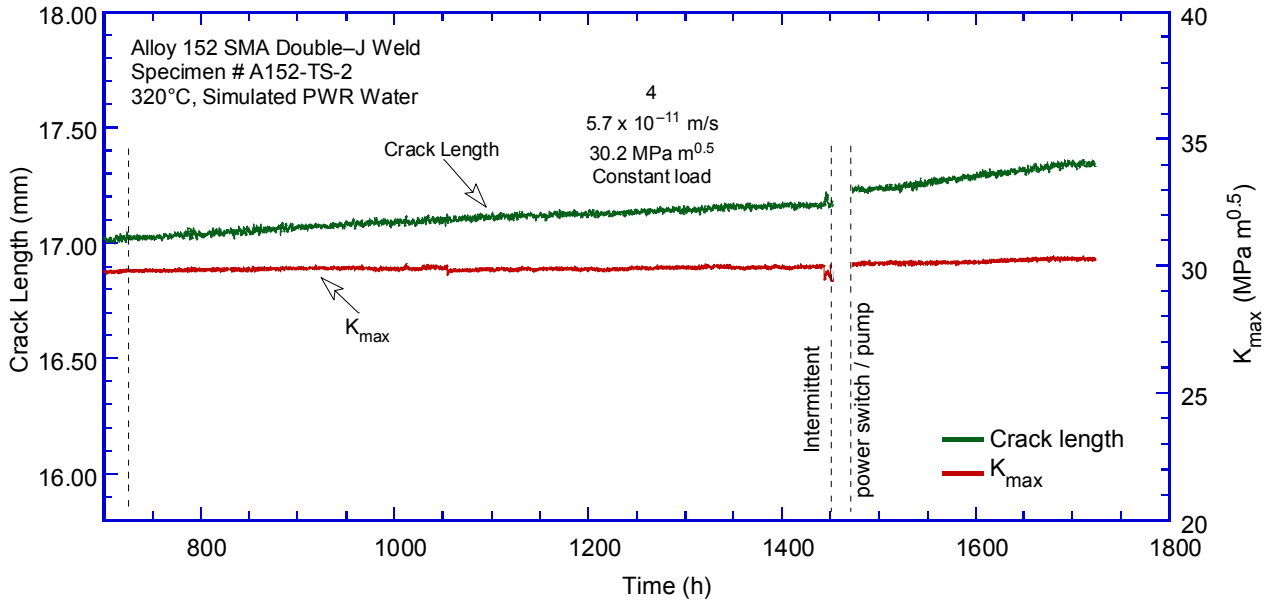
- Alloy 690 cold-rolled shows significant environmental enhancement (transitioning to SCC was expected)
- Good agreement with Davis-Besse Nozzle #3 Alloy 600 data
- Consistent with Bettis observation of “no incubation time”

Alloy 152 Specimens (A152-TS-2 and A152-TS-4)

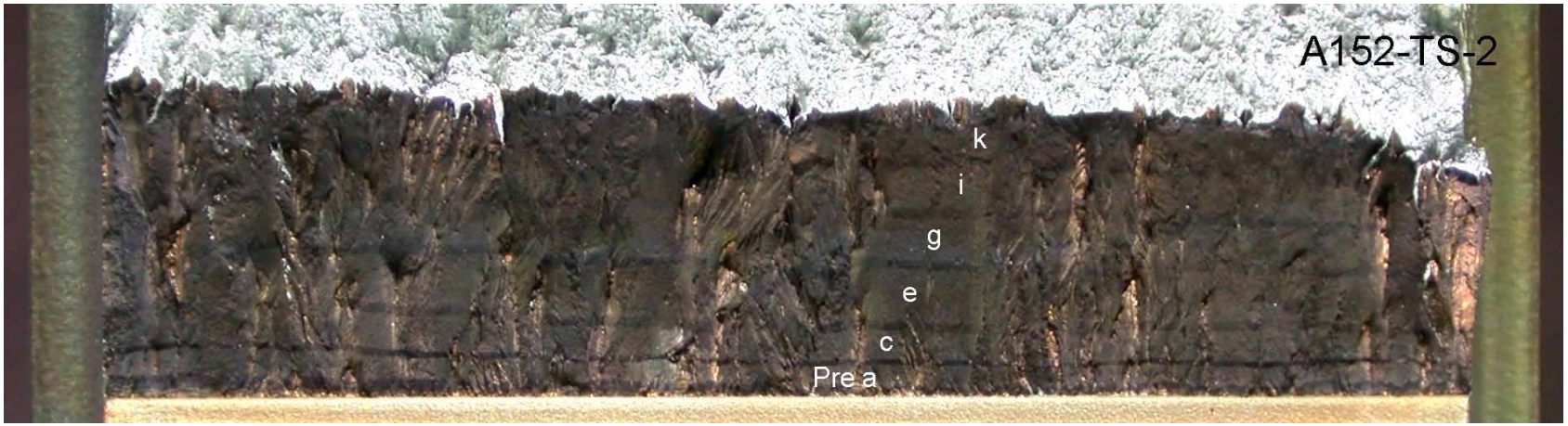


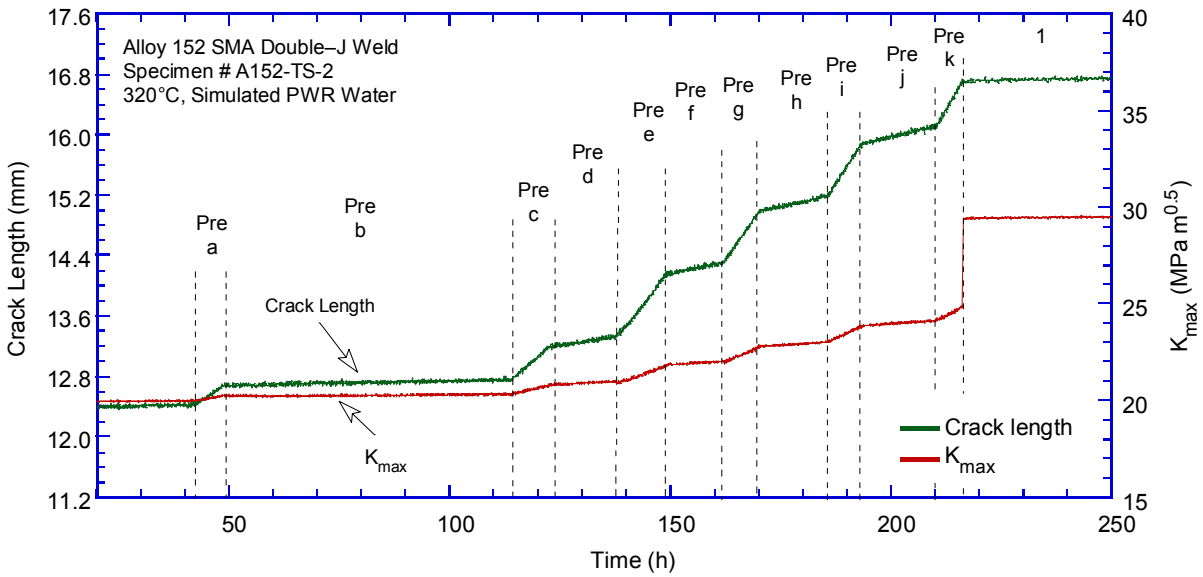
- A152-TS-4 test in progress

Alloy 152 specimen A152-TS-2

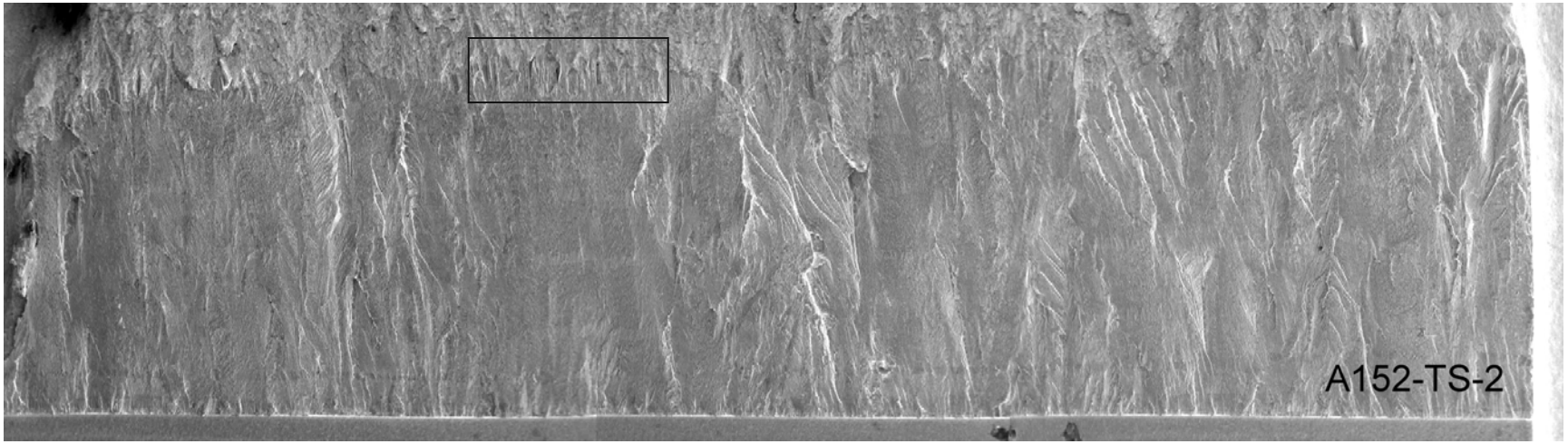


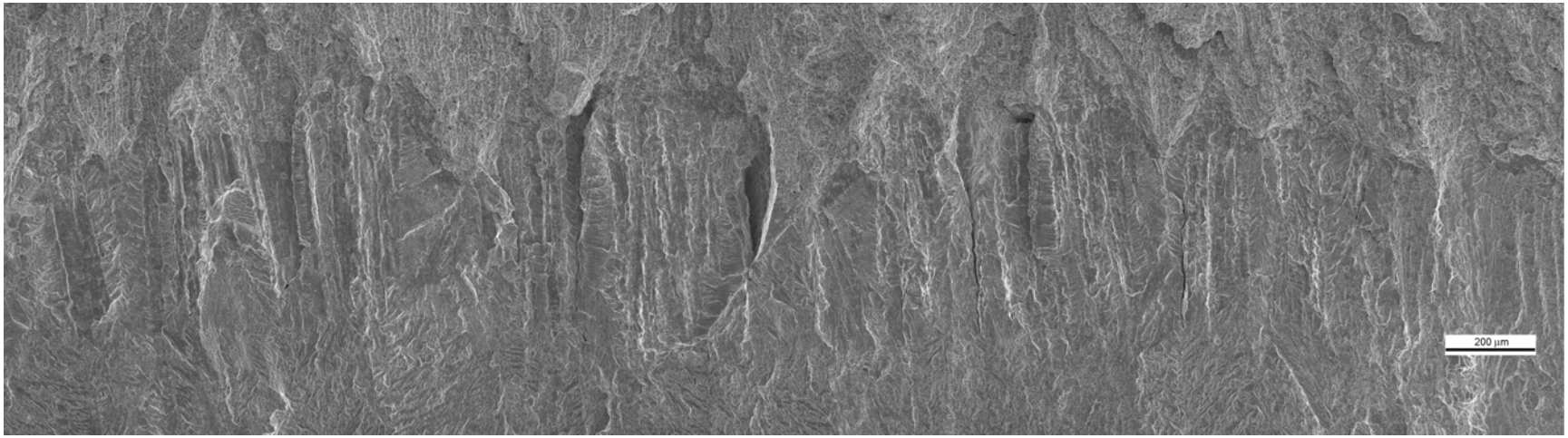
Fracture surface of A152-TS-2



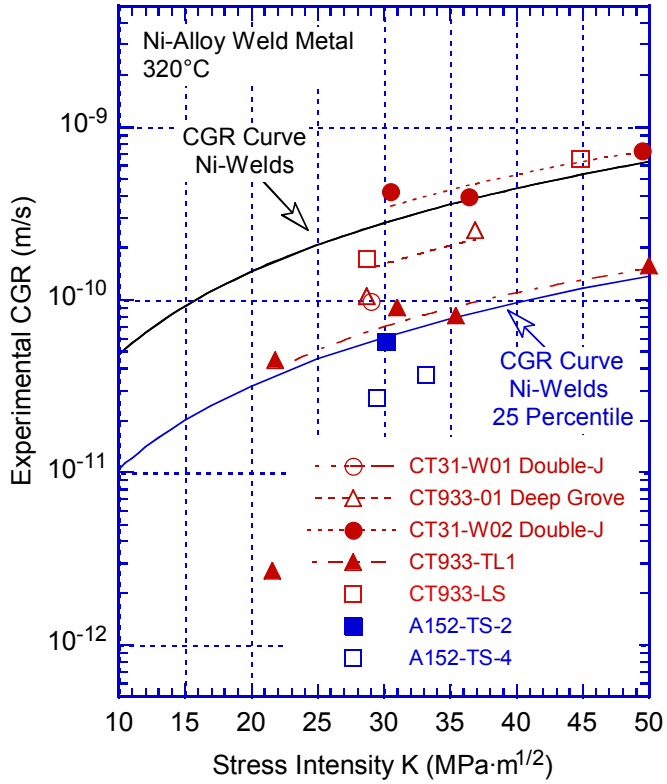


Fracture surface of A152-TS-2



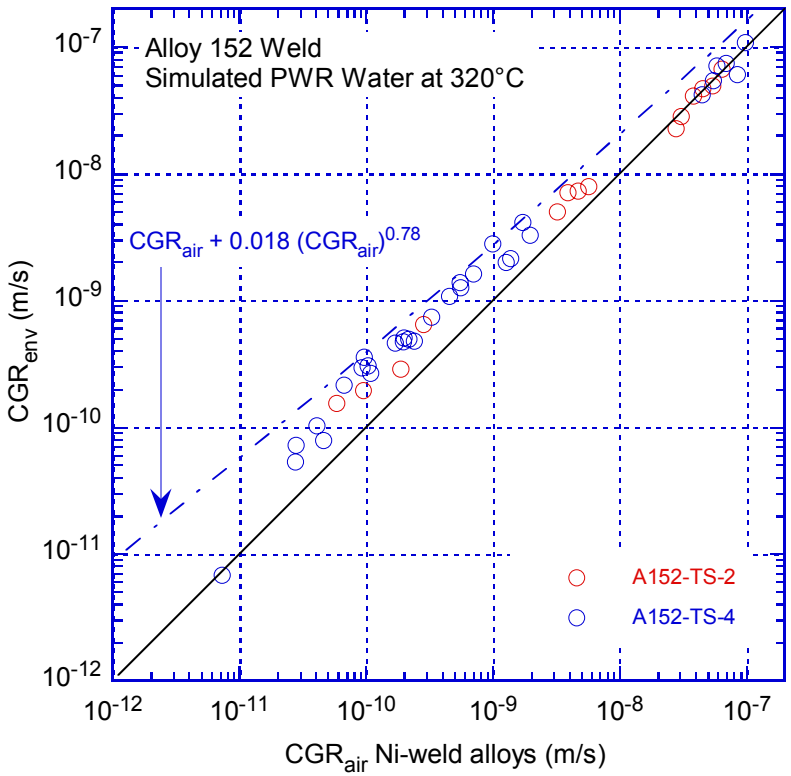


SCC CGRs for A152 and Alloy 182 vs. K



- A152-TS-4 rates are not corrected

Cyclic CGR data for Alloy 152 Weld



- A152-TS-4 rates are not corrected
- Conditions selected for transitioning from TG to IG SCC appear to be critical

Summary of Testing Results

- Fracture surfaces were uniform for both Alloy 690 and 152 specimens; the experimental approach facilitated transitioning to SCC
- The cyclic CGRs of cold-rolled Alloy 690 show significant environmental enhancement
- The environmental enhancement of cyclic CGRs is minimal for Alloy 152
- The SCC CGRs in simulated PWR water at 320°C were as high as:

  $2.8\text{-}3.3 \times 10^{-11}$ m/s for K_{max} = 28-31 MPa $m^{1/2}$ for Alloy 690

  5.4×10^{-11} m/s for K_{max} = 30.2 MPa $m^{1/2}$ for Alloy 152

Future Work - Objectives

1. Determine the SCC CGR for Alloys 690, Alloy 690 HAZ, and Alloy 152/52 Welds

2. Determine the activation energy for SCC CGR for Alloys 690, Alloy 690 HAZ, and 152/52 Weld

Future Work – Alloys

- Alloy 690 on hand:

1. Alloy 690 in plate form (including 26% cold rolled, Wah Chang)
2. 20% cold-rolled Alloy 690 in plate form (exchange with Peter Andresen, GE)
3. CRDM Alloy 690TT (2 tubes); 2941-Heat WP142, Valinox Nucleaire also used for Alloy 690 HAZ testing

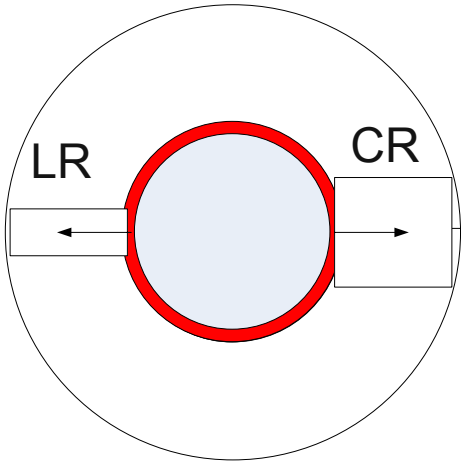
- Alloy 152 on hand:

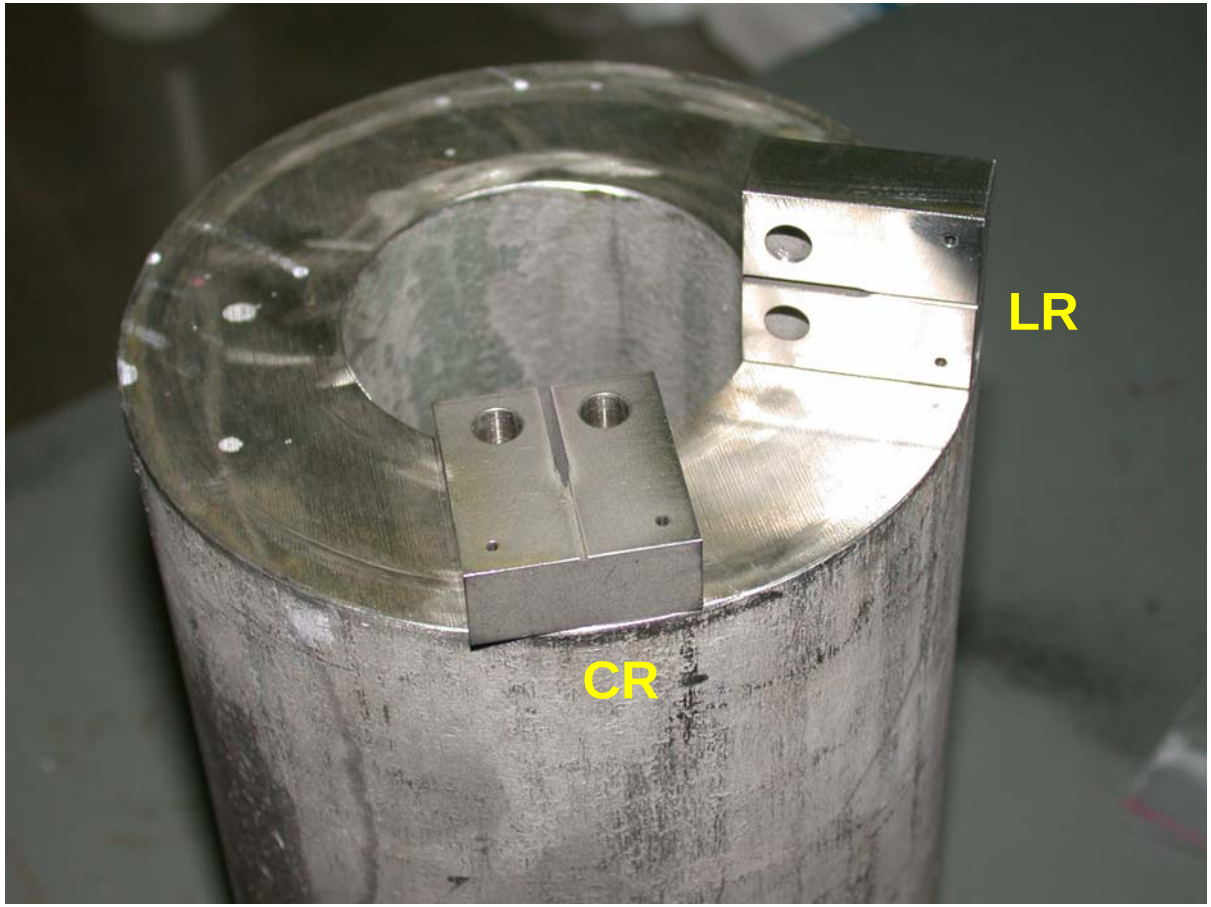
1. Double-J weld mock-up (ANL), currently used in CGR tests, also used for tensile testing vs. temperature
2. B-P7 Alloy 152 weld on CRDM Alloy 690TT (2941-Heat WP142, Valinox Nucleaire)

- Planned:

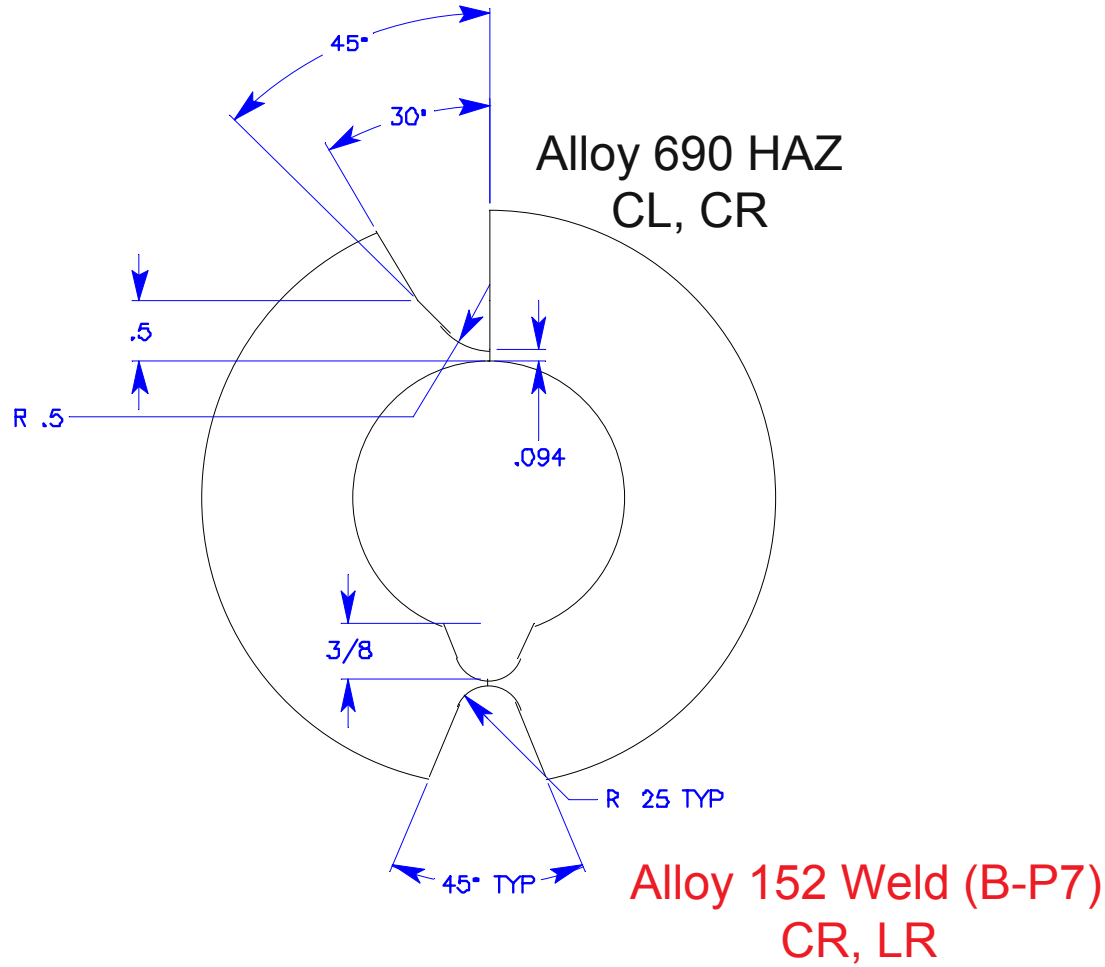
1. Double-V weld mock-up 690/152/LAS, also for aging studies
2. CRDM Alloy 690 tube /152(52)/Alloy 690 plate mock-up

CGR testing of CRDM Alloy 690





CGR testing of Alloys 690, Alloy 690 HAZ and Alloy 152 Weld



Approach

- Use CGR testing in simulated primary water
  - precracking conducted in the environment
  - loading sequence to facilitate transition from fatigue TG to SCC IG
  - monitor cyclic CGR for environmental enhancement
- The approach results in uniform SCC engagement and straight crack fronts)

Significant Milestones

Complete CGR tests on CRDM nozzle Alloy 690TT as a function of orientation in PWR water (12/08)

Provide an interim report detailing the experimental results from the crack growth rate testing of Alloy 690 and Alloy 152. (04/09)

Milestones for FY 2010

Complete CGR tests on Alloy 690TT in PWR water to determine the activation energy for PWSCC. (11/09)

Complete CGR tests on Alloy 690TT HAZ material as a function of loading and temperature in PWR water. (06/10)

Milestones for FY 2011

Complete CGR tests on CRDM nozzle Alloy 152 weld as a function of orientation. (11/10)

Complete CGR tests on Alloy 152 weld to determine activation energy for PWSCC (08/11)

Conclude CGR tests on Alloy 690 and Alloy 152. Provide a final NUREG/CR report describing the results of the crack growth rate testing of Alloy 690 and Alloy 152. (09/11)

Possible Discussion Point: Transitioning to SCC

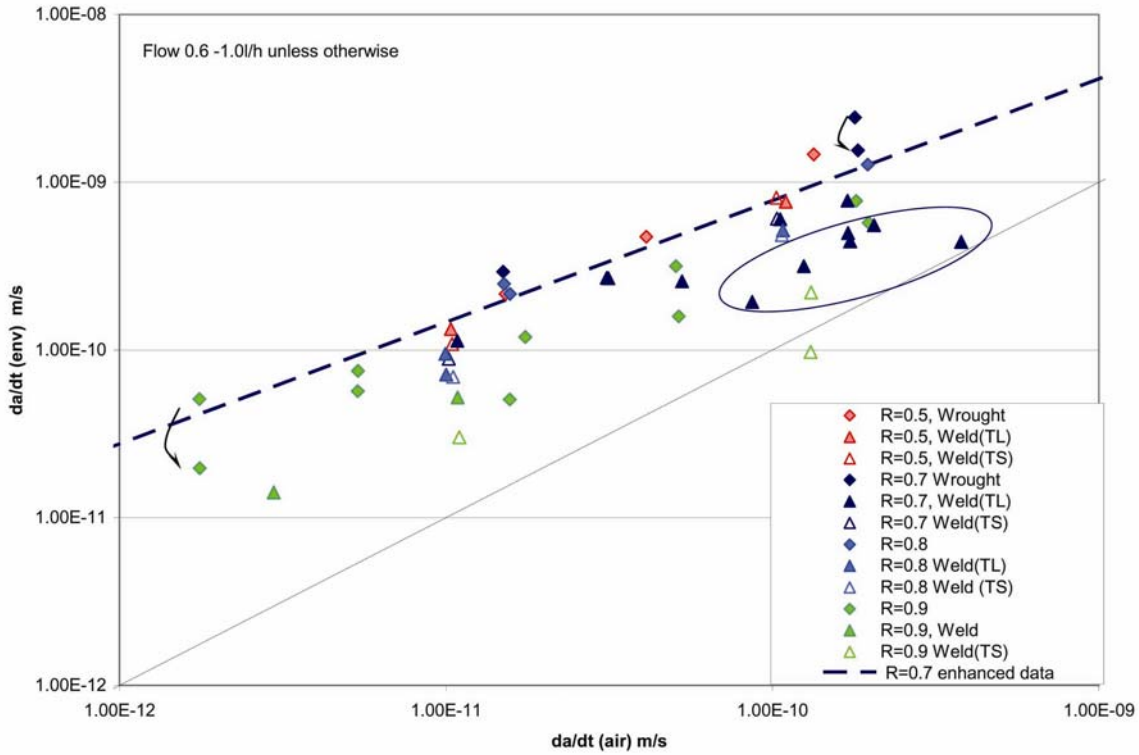
- Transitioning to SCC
  - Widely-used method: increasing R and decreasing frequency
  - ANL approach very similar, but with a few differences:
    - precracking in the environment
    - use of slow/fast sawtooth with increasing rise times
    - calculate cyclic CGRs based on rise time*
    - monitor cyclic rates for environmental enhancement

* Well-characterized cyclic CGR also enables the calculation of the SCC component for periods with hold times or periodic unloading

- Focus on cyclic CGRs

Effect of Increasing R on Cyclic CGRs

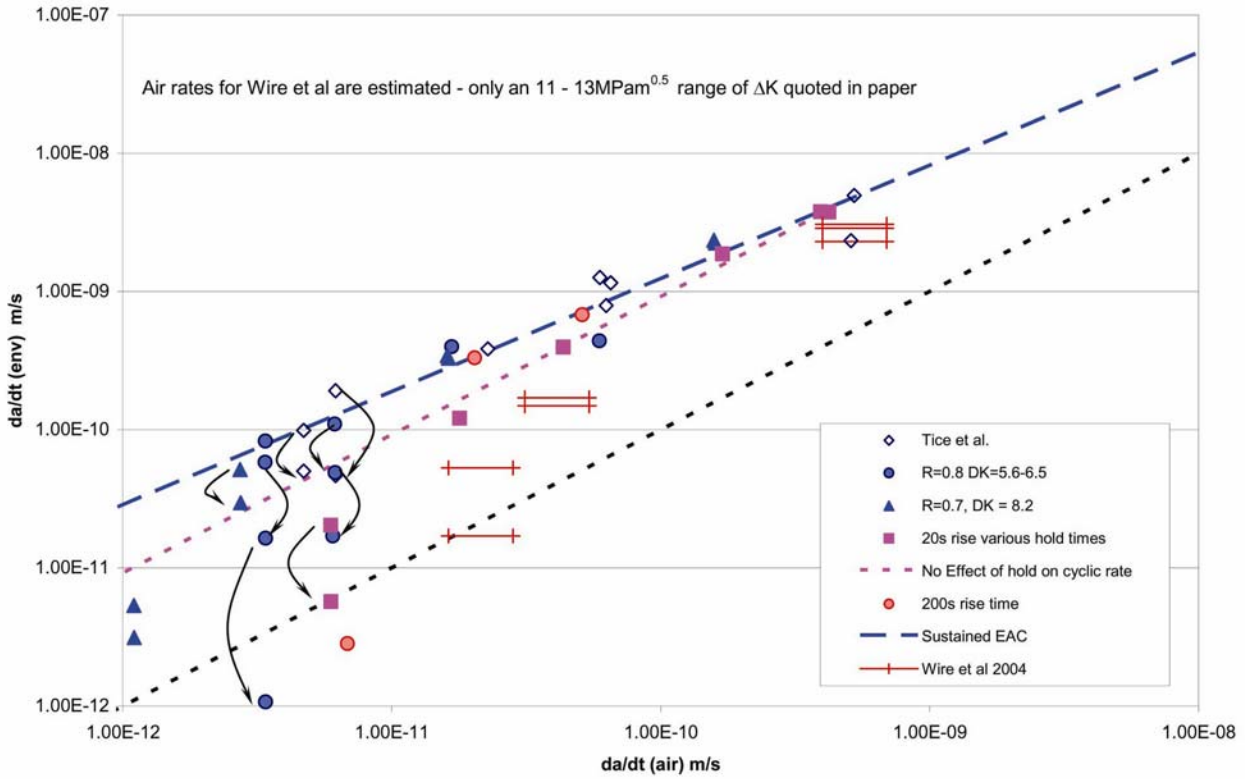
David Tice, 2007 PVP: Wrought 304L and 308L SSs in PWR water at 250°C



- Cyclic CGRs depart from "sustained EAC condition" beyond at R ≥ 0.85

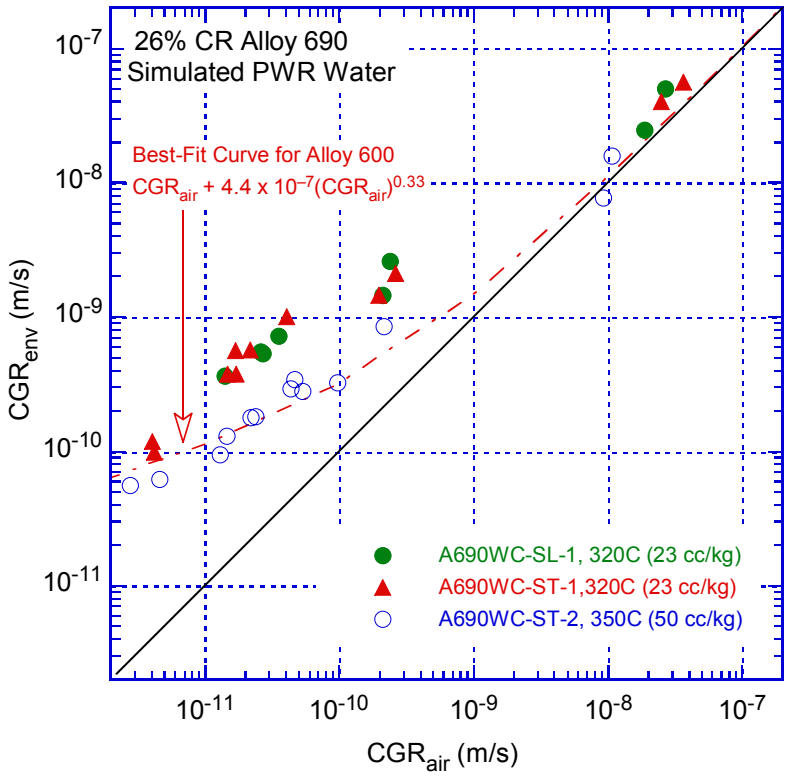
Effect of Hold Time on Cyclic CGRs

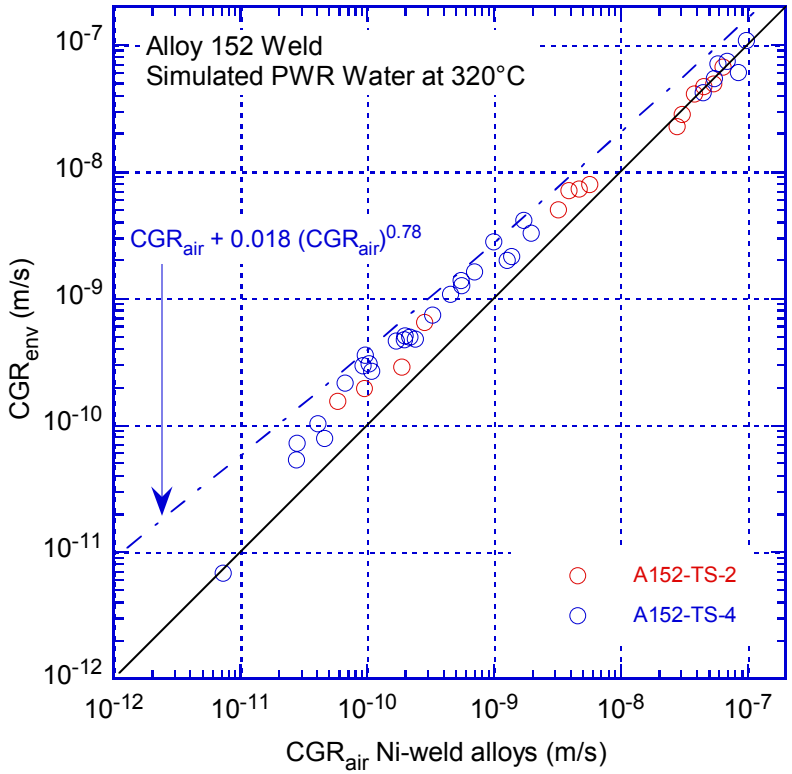
David Tice, 2007 PVP: Wrought 304L SS in PWR water at 300°C



- Cyclic CGRs at R = 0.7-0.8 depart from "sustained EAC condition" when hold times are introduced (especially in the 10^{-11}-10^{-10} m/s range)

Trends for Cyclic CGR data for Alloys 690/152





- Cold-rolled Alloy 690 shows significant enhancement; as-received?
- Alloy 152 shows similar trends to D. Tice's data

Implications for CGR testing of Alloys 690/152

- Environmentally-enhanced cyclic rates enable transitioning to an SCC fracture mode (ANL experience)
- Not all high R – low frequency conditions appear to lead to environmentally enhanced CGRs
  - true for Alloy 152 Weld
  - has to be determined for as-received Alloy 690
- Need to monitor cyclic rates to determine environmentally-enhanced conditions (especially important for alloys difficult to crack)