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SCC CGRs of Alloys 690 and 152 Weld in PWR Water

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Program Objectives and Presentation Topics

ANL NRC Program Objectives

- SCC CGRs of Alloys 690/52/152
- SCC CGRs of service Alloys 600/82/182 (previous work included materials from Davis-Besse and V.C. Summer plants)

Presentation Topics

- CGR testing in simulated primary water
  - experimental approach
- Crack Growth Rates for Alloy 690
  - cold-worked and as-received conditions
- Crack Growth Rates for Alloy 152 Weld

Stress Corrosion Cracking Testing Facilities

- Four (of eight) hydraulic testing frames:
  - upgraded with Instron digital controls
  - 1-6L autoclaves rated to 320-350°C
  - instrumented for CGR measurements
  - independent water loops

- Crack initiation facility:
  - two 8-L autoclaves rated to 350°C
  - independent water loops
  - accommodate reverse U-bend and tubular specimens

Experiment

- Temperature: 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 sequence to facilitate the transitioning from transgranular fatigue cracking to intergranular SCC cracking

Transitioning to SCC

- ANL approach very similar to the widely-used method (increasing R and decreasing frequency) but with a few differences:

  - Precracking is always conducted in the environment[1]
  - Use of slow/fast sawtooth with increasing rise times
    - Loading takes into account possible ΔK and ΔK_{th} effects[2]
  - Monitor specimen response
    - Calculate cyclic CGRs based on rise time[3]
    - Monitor cyclic rates for environmental enhancement [4]
  - Attempt to transition only from those conditions that show environmental enhancement

[1] Provides (essential) baseline cyclic data

[2] $\Delta K/\Delta K_{th}$ effects have been observed/formulated for Alloy 690

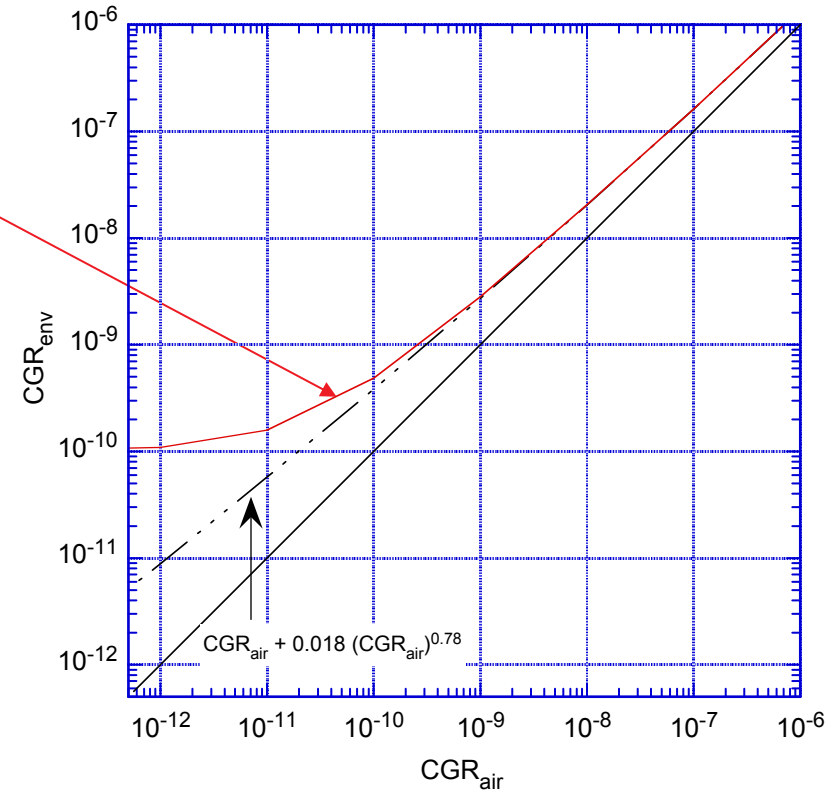
[3] Well-characterized cyclic CGR also enables the calculation of the SCC component for periods with hold times or constant load with periodic unloading

[4] Accomplished by plotting the measured in the environment vs. the rates that would be expected in air under the same loading conditions

*The Analysis of Cyclic CGR Data**

- Superposition model (Kassner & Shack)

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



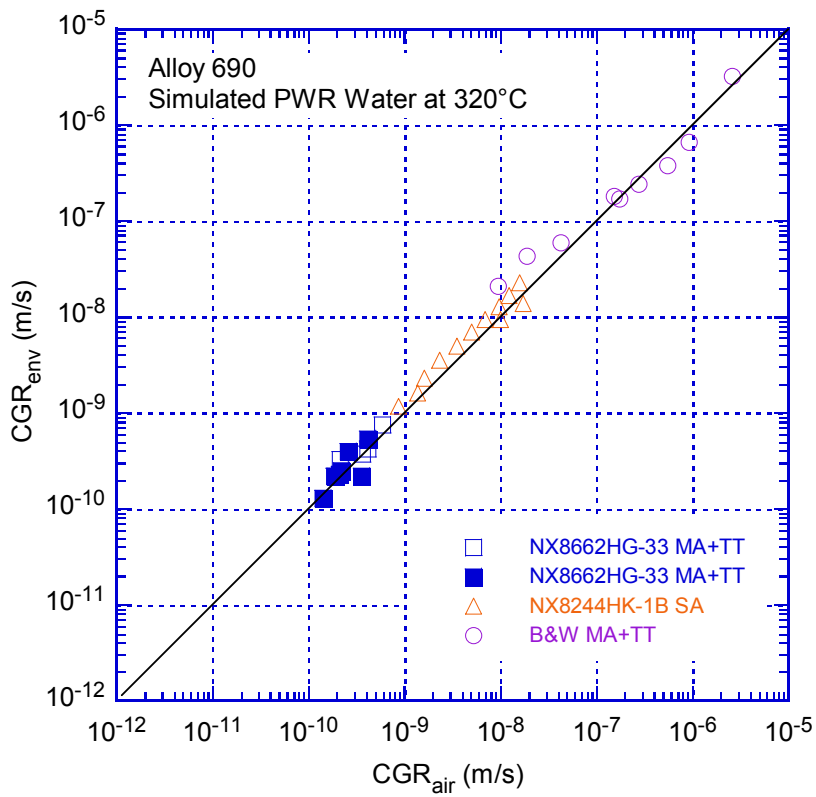
- For Ni-welds:

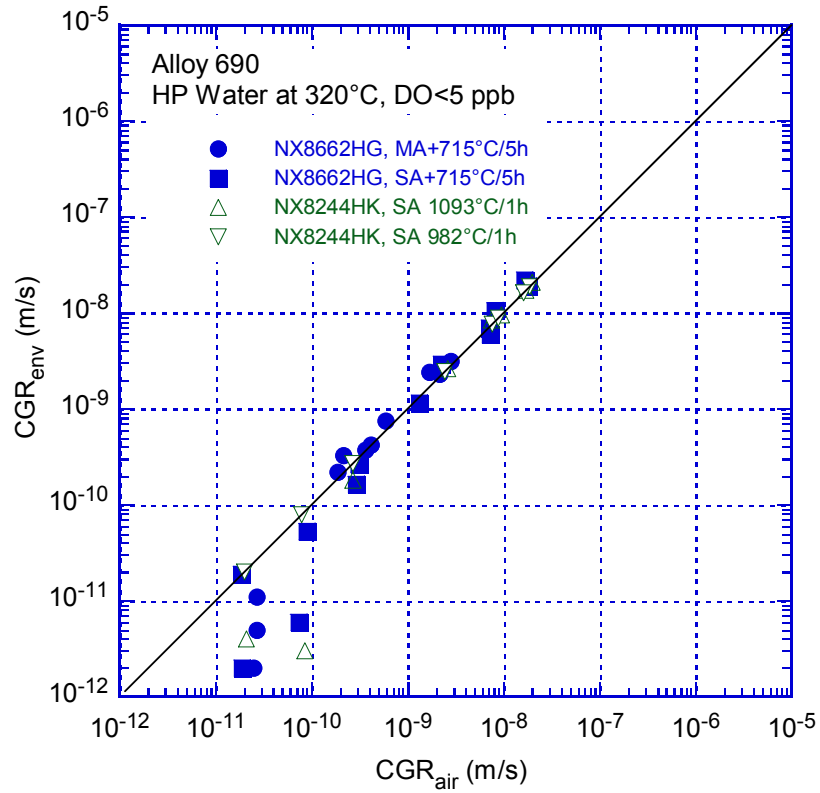
$$\dot{a}_{air} + \dot{a}_{CF} = \dot{a}_{air} + 0.018 \cdot \left(\dot{a}_{air}\right)^{0.78}$$

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

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

Cyclic CGR Data for Alloy 690 in PWR and HP Water at 320°C

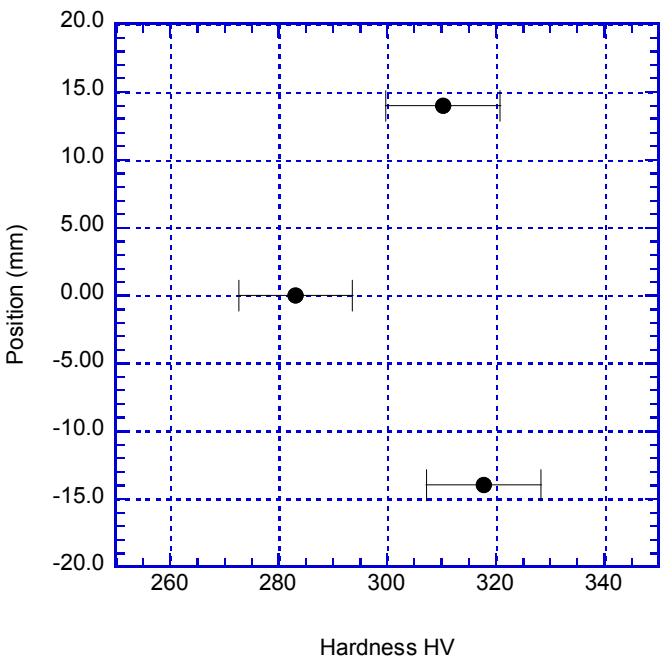


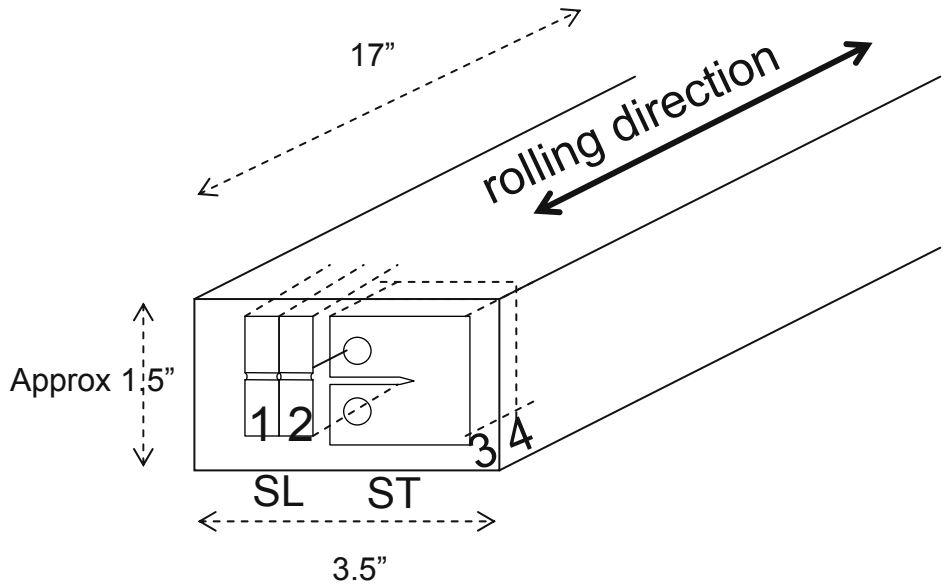


- Earlier ANL and B&W data in good agreement; no environmental enhancement
- $\Delta K/\Delta K_{th}$ was observed/formulated for Alloy 690; the effect is taken into account in current tests

Cold-Rolled Alloy 690 Specimens

- Alloy 690 in plate form (MIL-DTL-24802), Heat NX3297HK12
  - Cold-rolled in three passes to achieve approx. 26% reduction in thickness
  - Deformation is inhomeogeneous: near-surface harder than mid-plane by 12%
  - 1/2T-CT specimens were cut in SL and ST orientations (mid-plane)

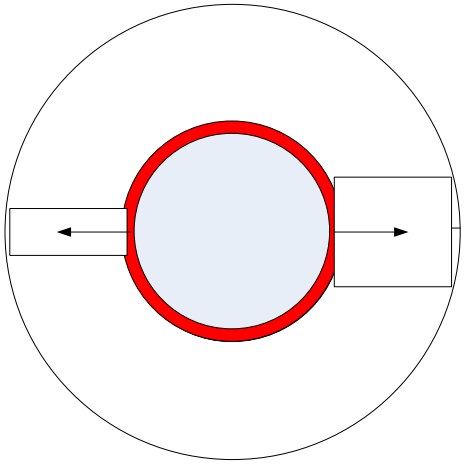


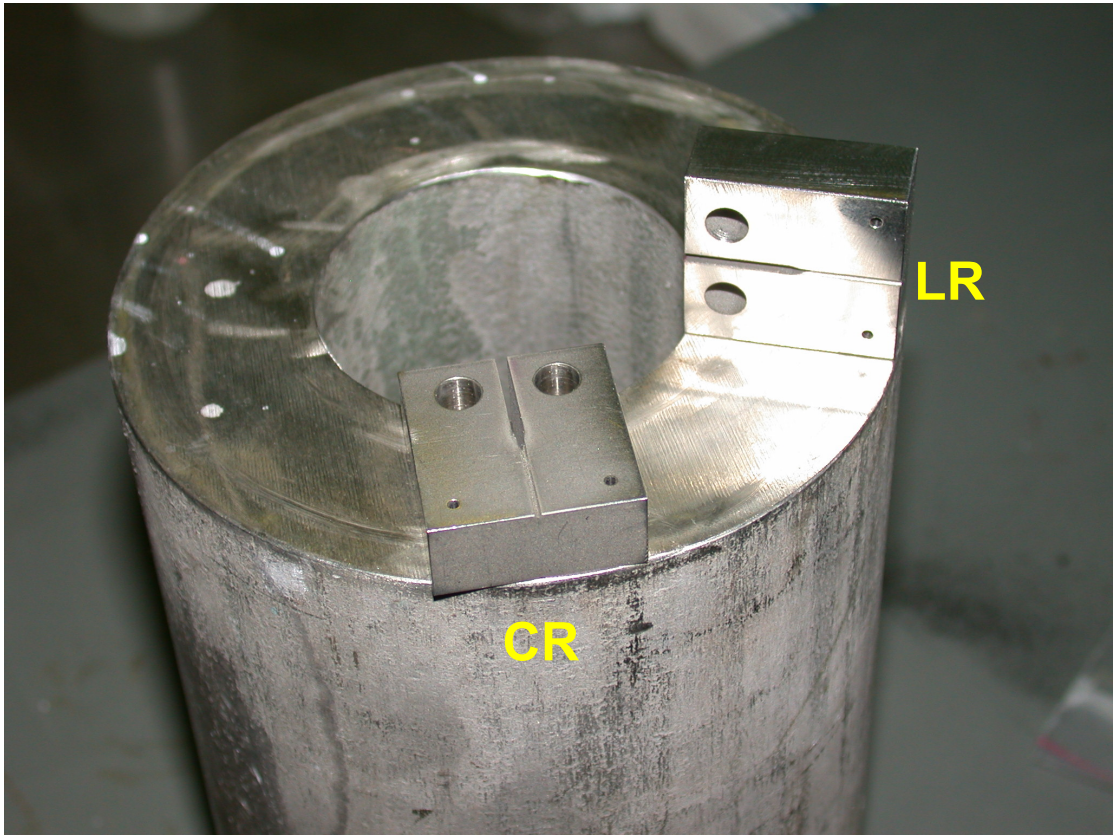


Alloy 690TT Specimens

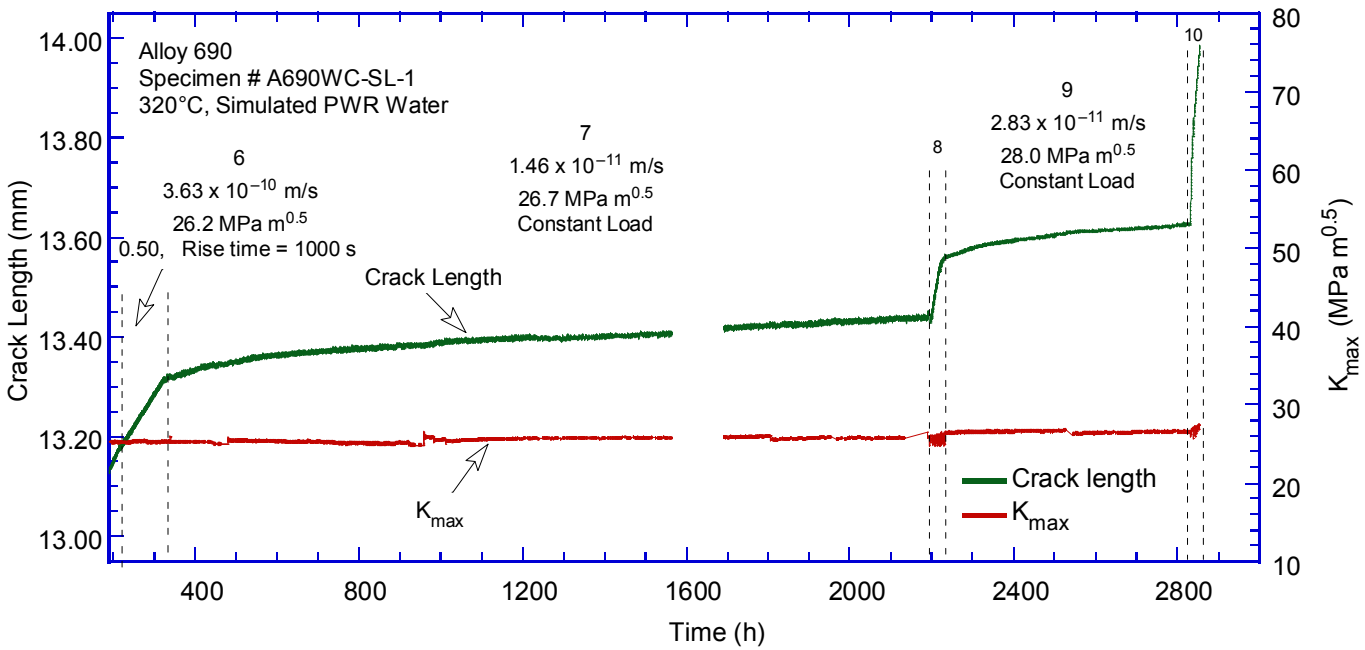
- Alloy 690TT CRDM tubing, 2541 – Heat WP142

  - 1/2T-CT specimens were cut from tubing (in as-received condition) in CR and LR orientations



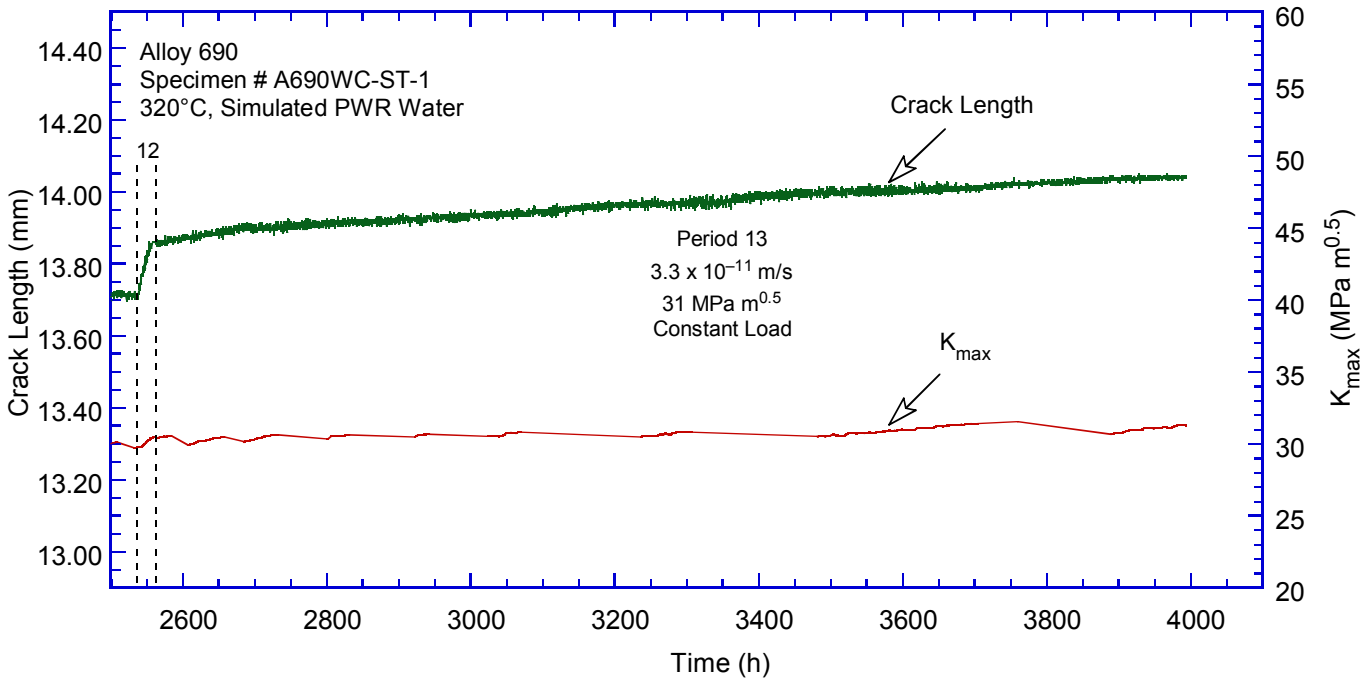


Cold-Rolled Alloy 690 Specimen A690WC-SL-1



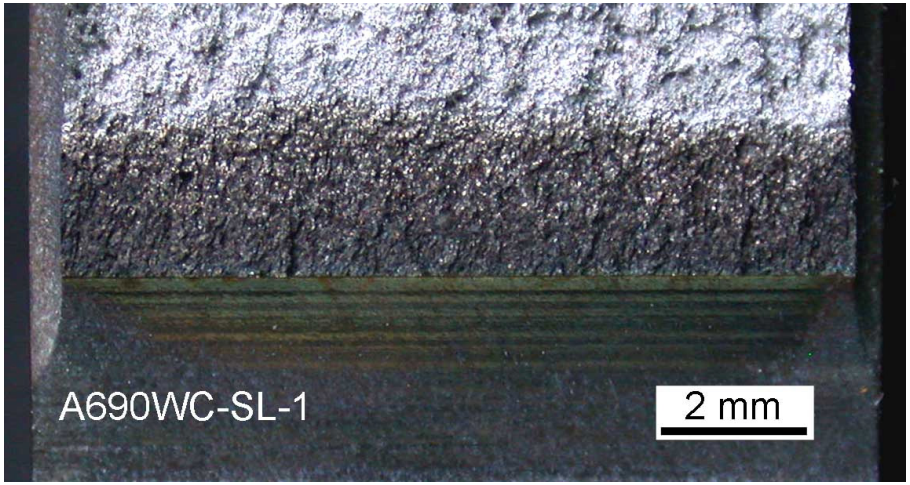
- Well-behaved crack advance under constant load

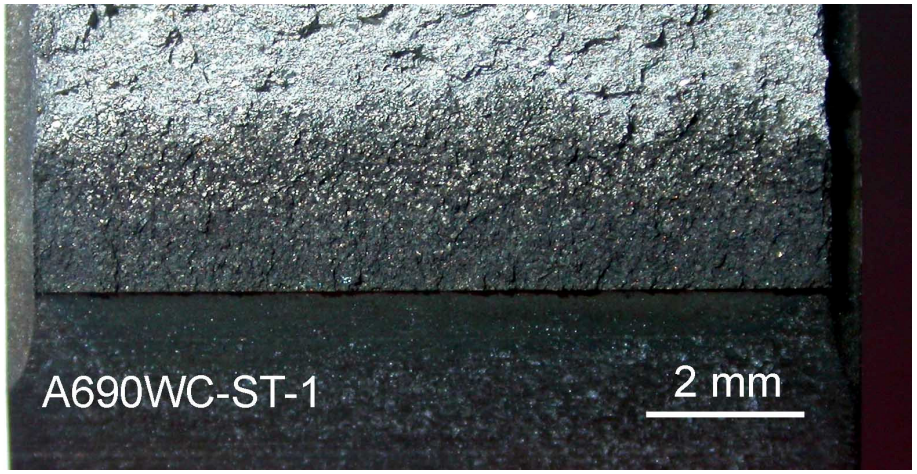
Cold-Rolled Alloy 690 Specimen A690WC-ST-1



- Well-behaved crack advance under constant load

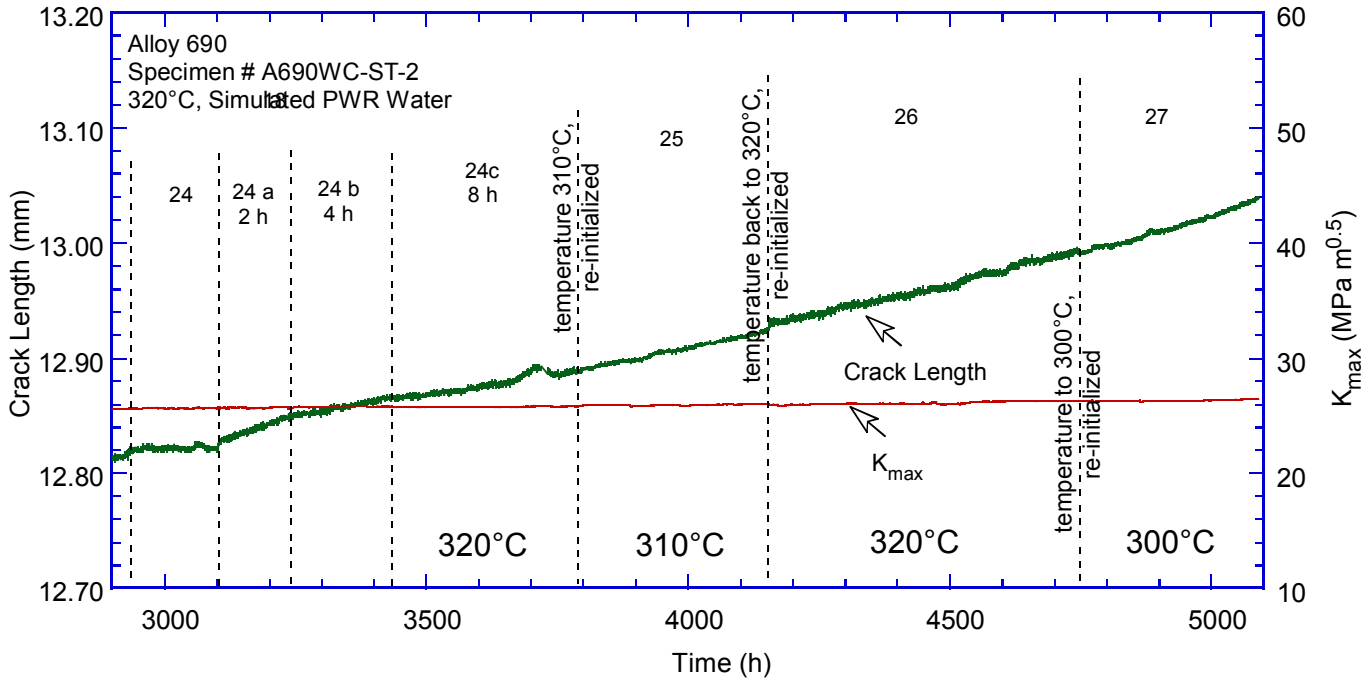
Fracture surfaces of A690WC-SL-1 and A690WC-ST-1





- Straight fracture surfaces, uniform SCC engagement

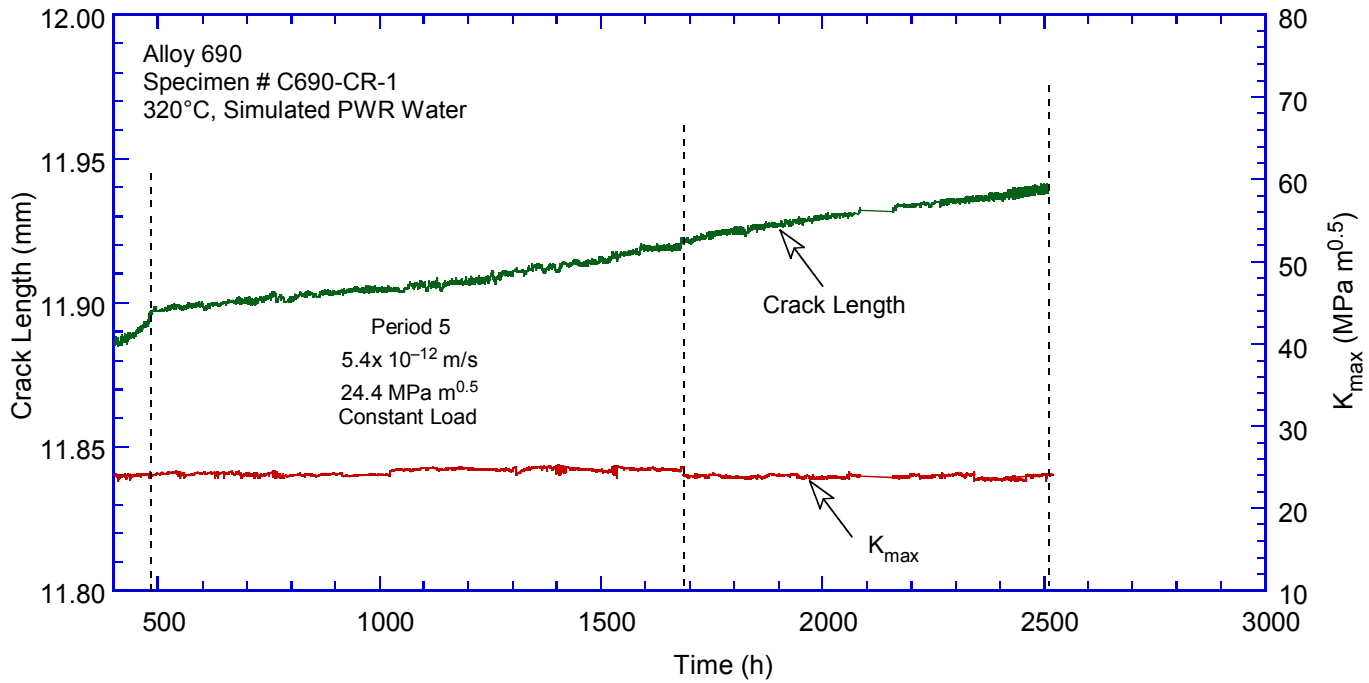
*Cold-Rolled Alloy 690 Specimen A690WC-ST-2**



- No effect of temperature (good agreement with Bettis and GE observations)

* Test in progress

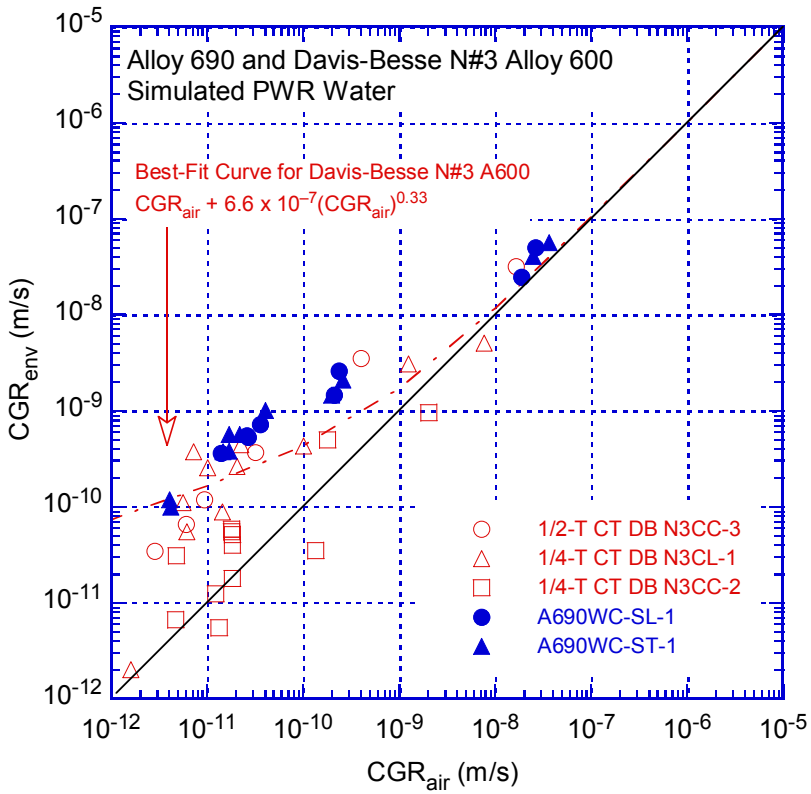
Alloy 690 Specimen C690-CR-1 (as-received condition)*

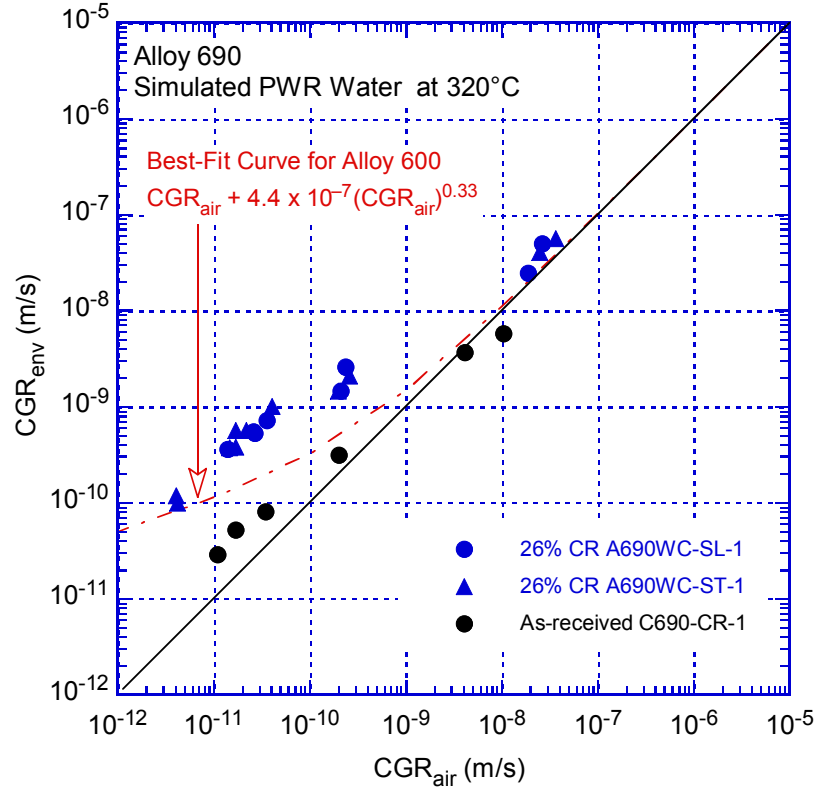


- CGR of 5×10^{-12} m/s maintained for approx. 1100 h under constant load

* Test in progress

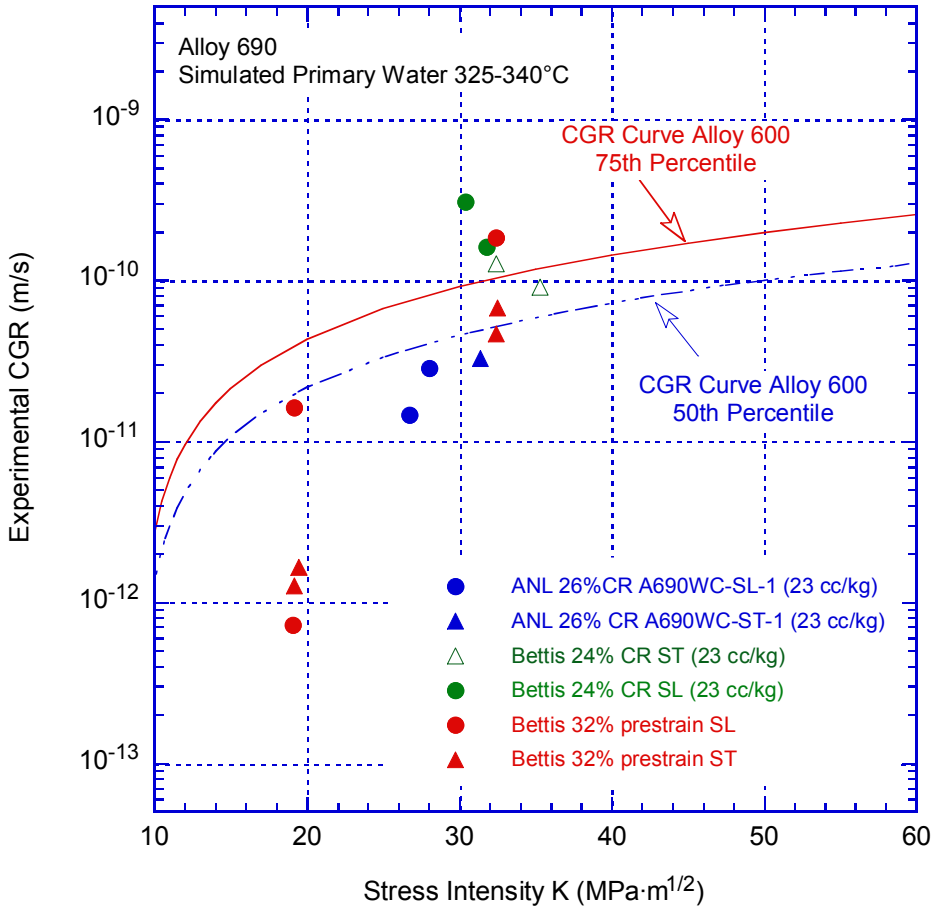
Cyclic CGR data for Alloy 690





- Alloy 690 cold-rolled shows significant environmental enhancement, comparable to Alloy 600 from Davis-Besse (Nozzle #3)
- Cyclic CGR rates for as-received alloy lower than those for cold-rolled alloy

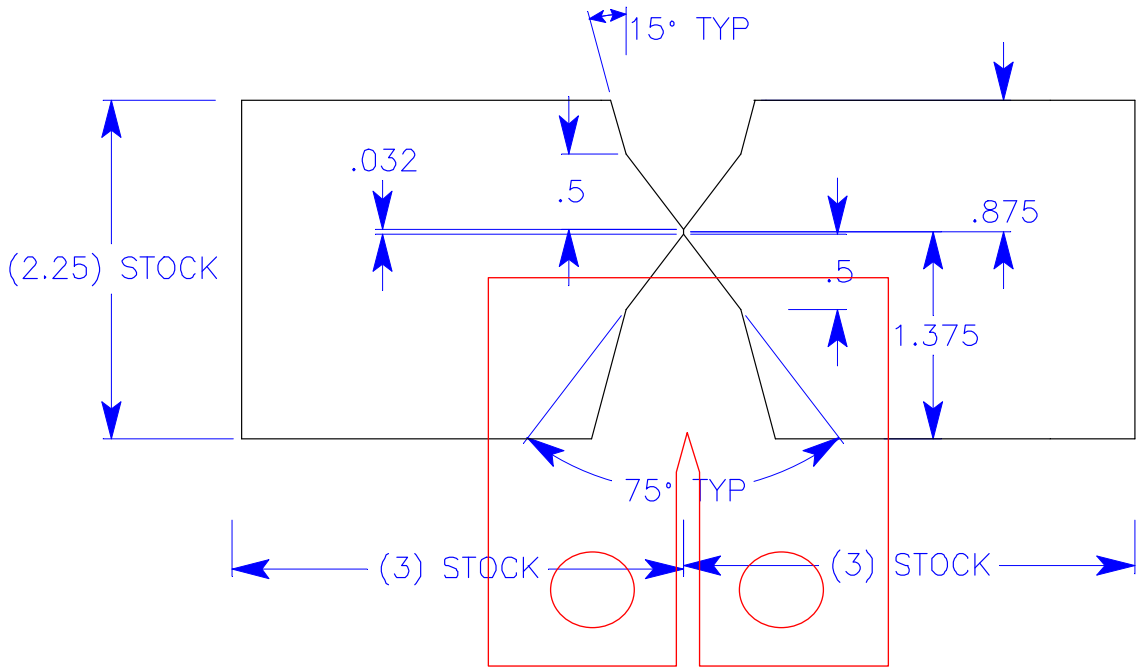
SCC CGRs vs. K for Alloy 690



- Good agreement with Bettis data at the same hydrogen level (23 cc/kg)
- ANL data: CGR rates for as-received* alloy lower than those for cold-rolled alloy

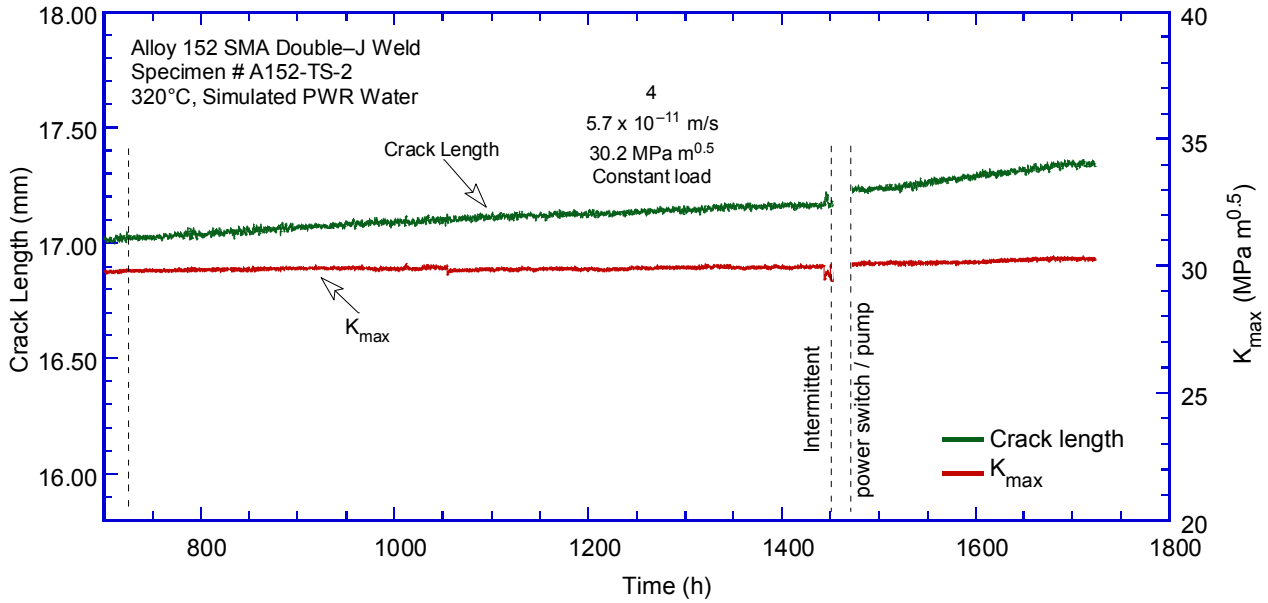
* C690-CR-1 testing in progress

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



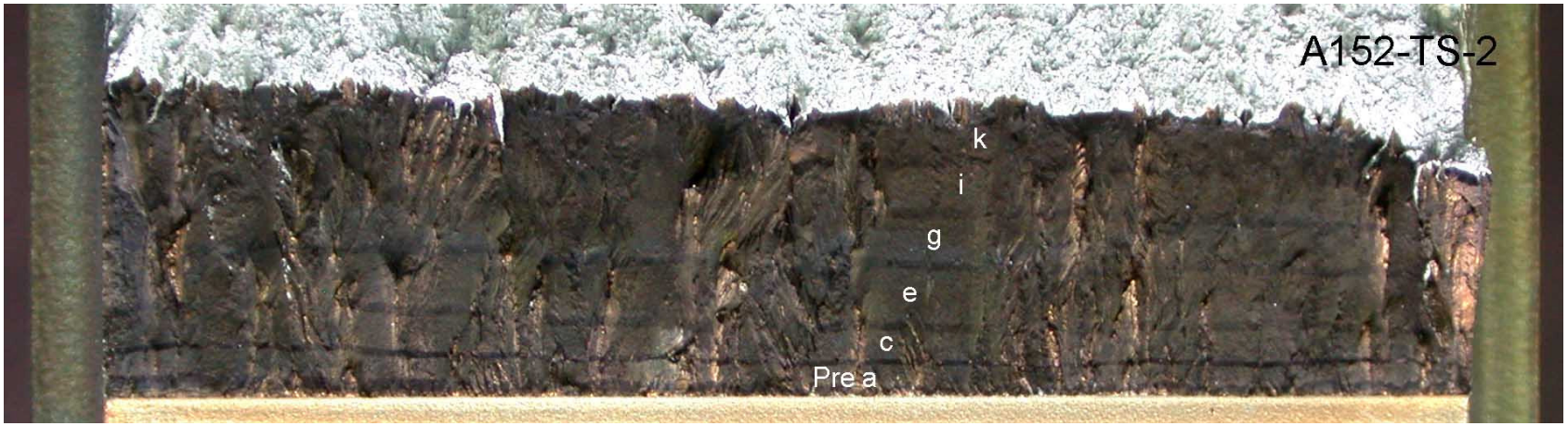
- Electrode heats: NX168IJK (52, 3/32), WC96D8 (152, 1/8), WC43E9 (152, 3/32), WCO4F6 (152, 1/8)
- 1-T CT specimens cut in TS orientation (T= long transverse, S = short transverse). Crack growth is along the direction of dendrites

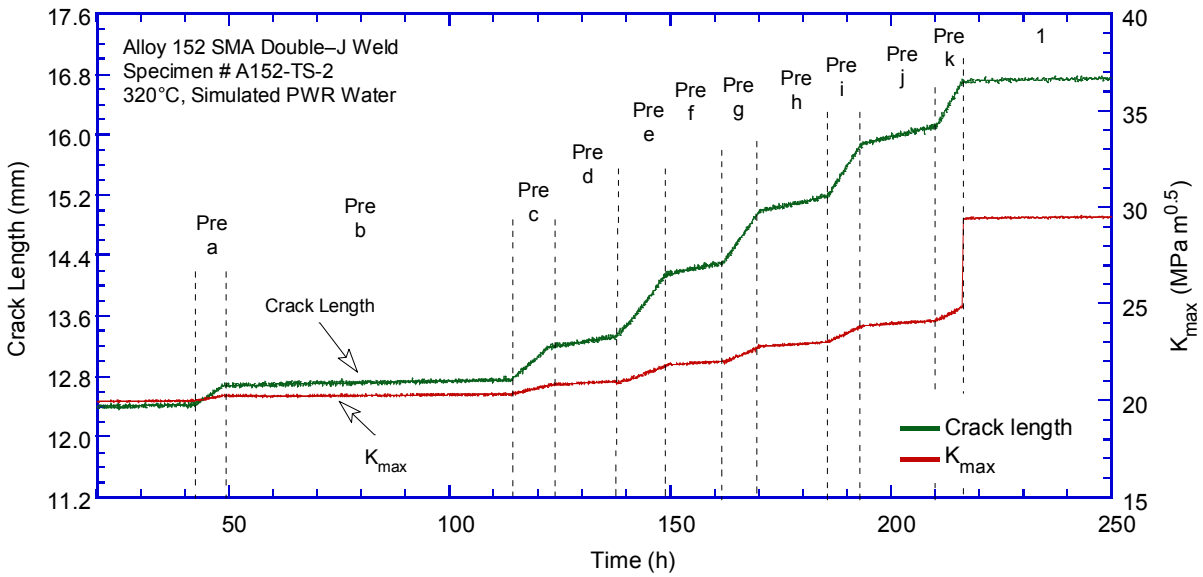
Alloy 152 specimen A152-TS-2



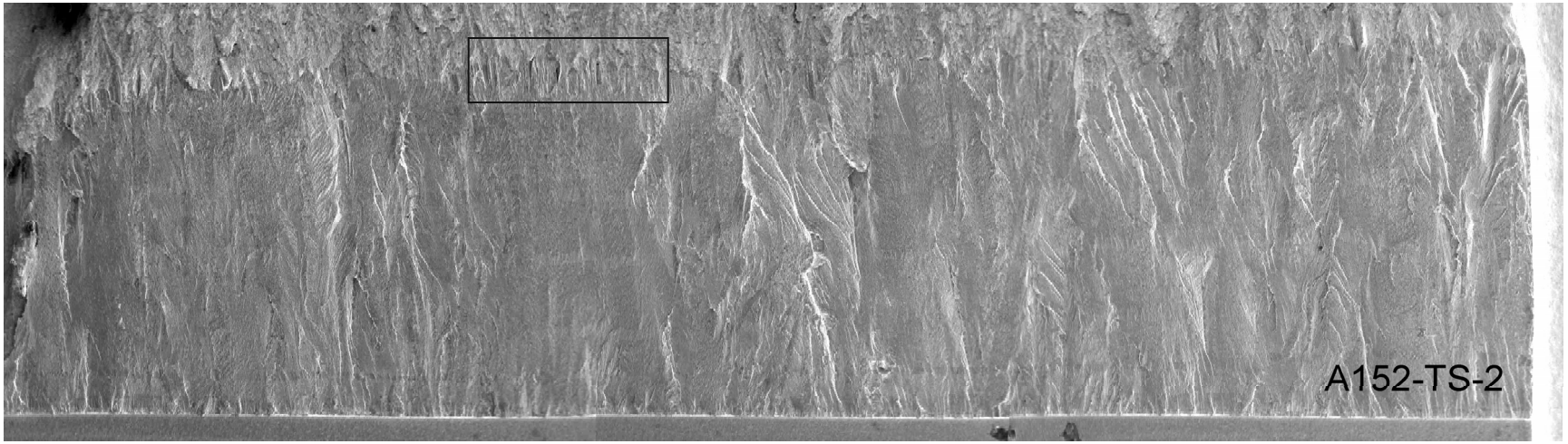
- Well-behaved crack advance under constant load

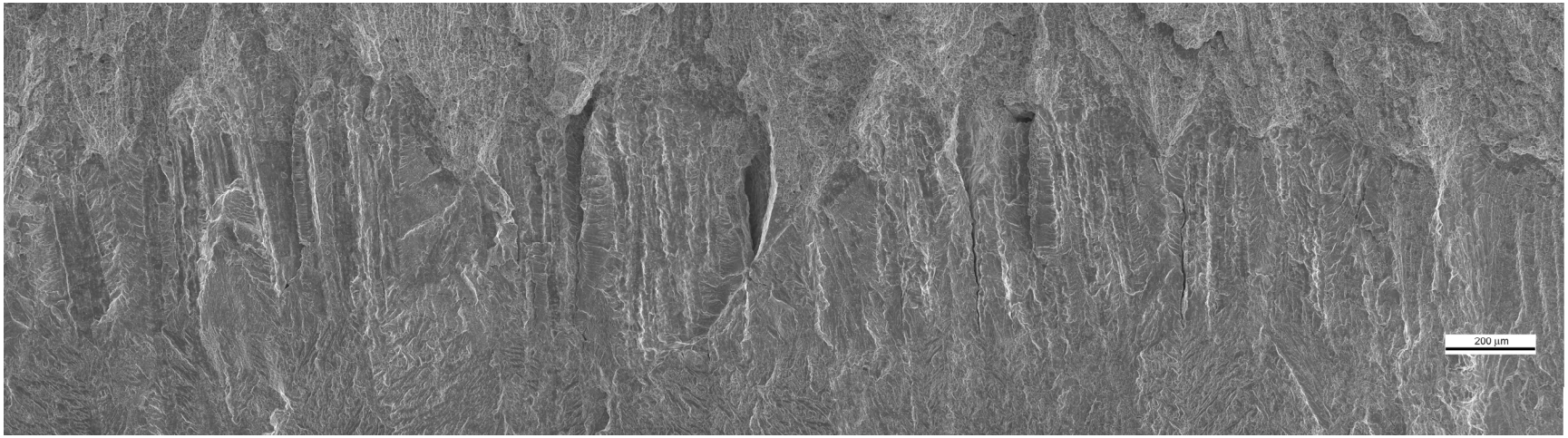
Fracture surface of A152-TS-2



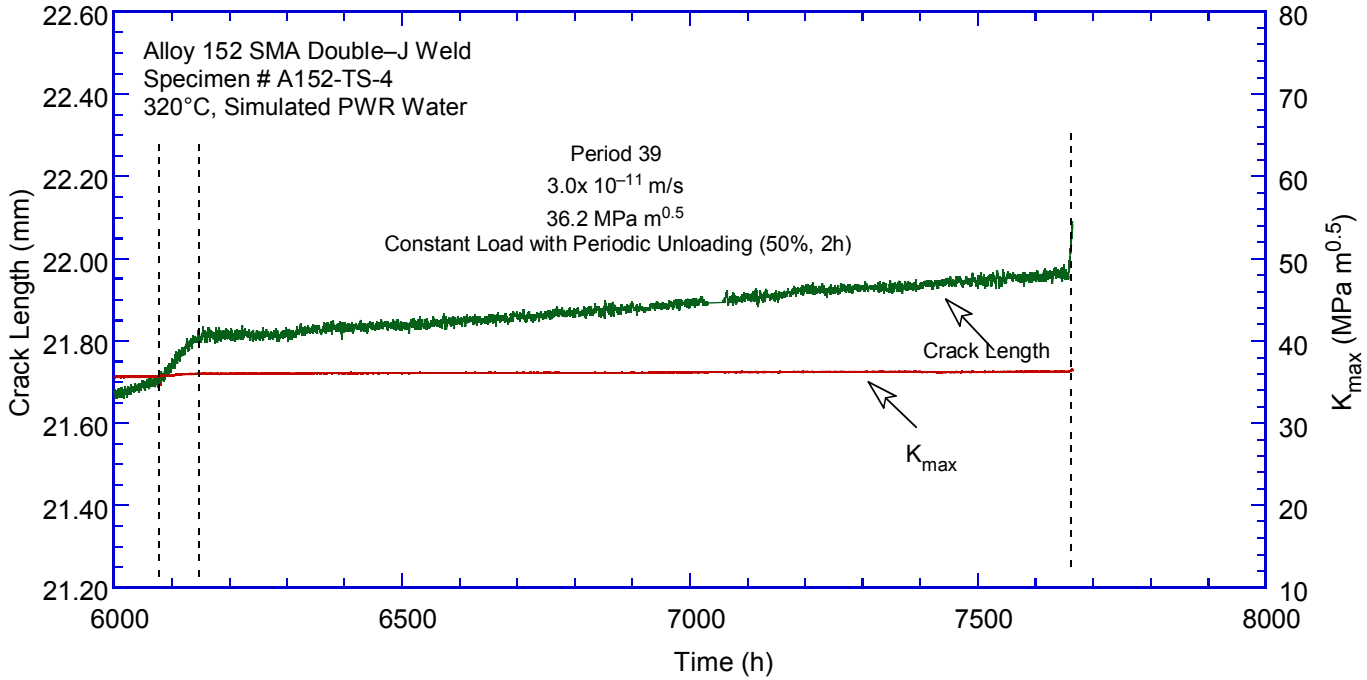


Fracture surface of A152-TS-2



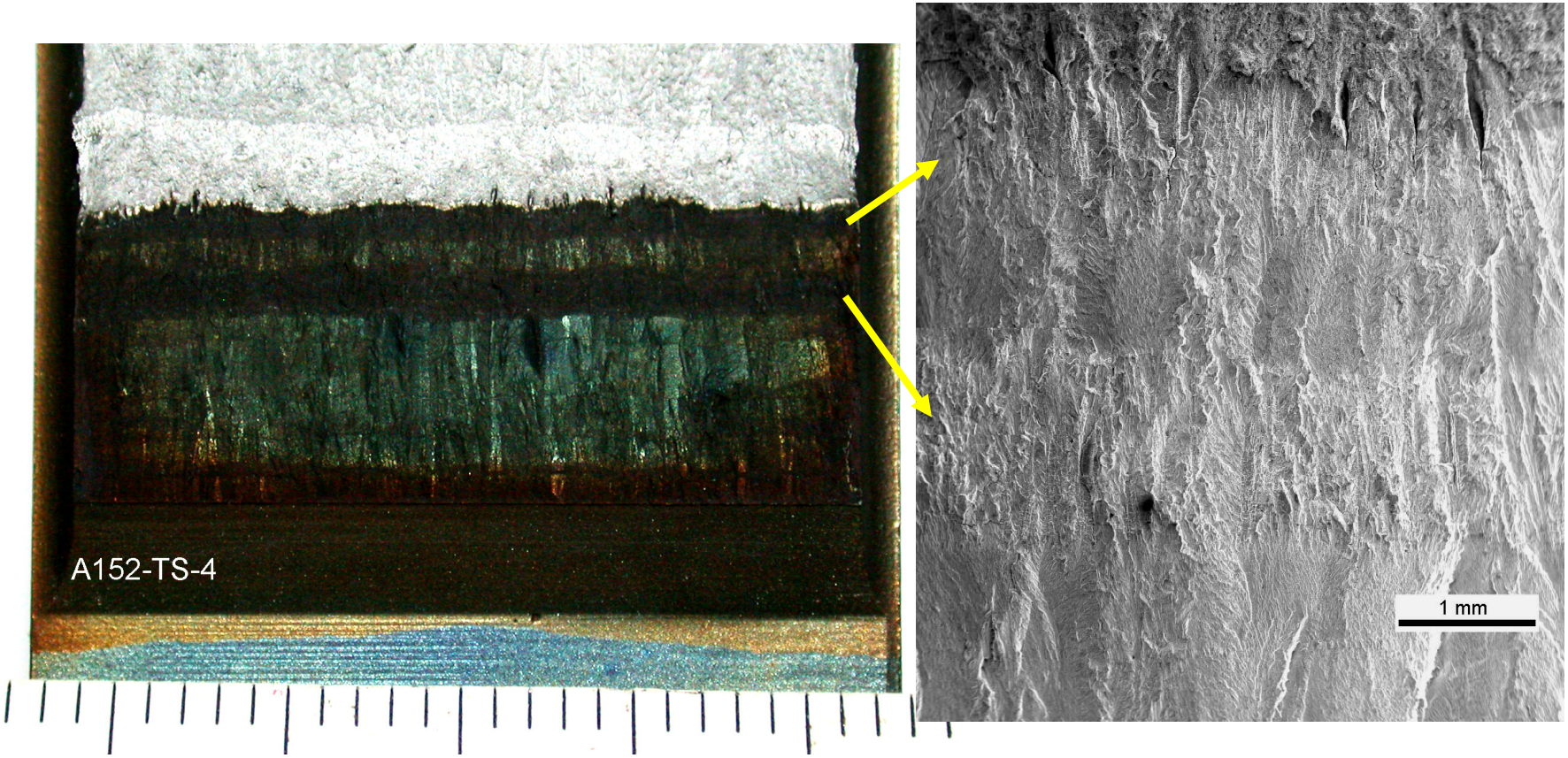


Alloy 152 specimen A152-TS-4



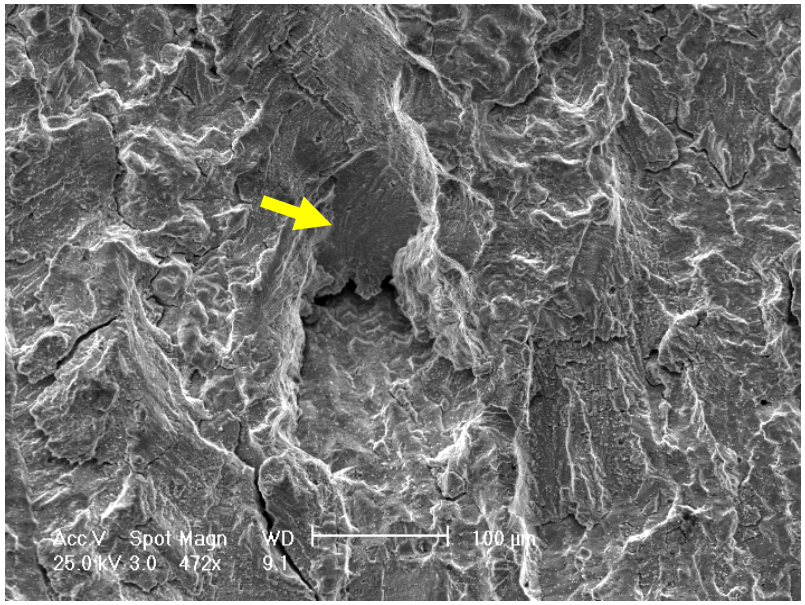
- Well-behaved crack advance under constant load with periodic unloading (this type of loading was necessary to break the ligaments)

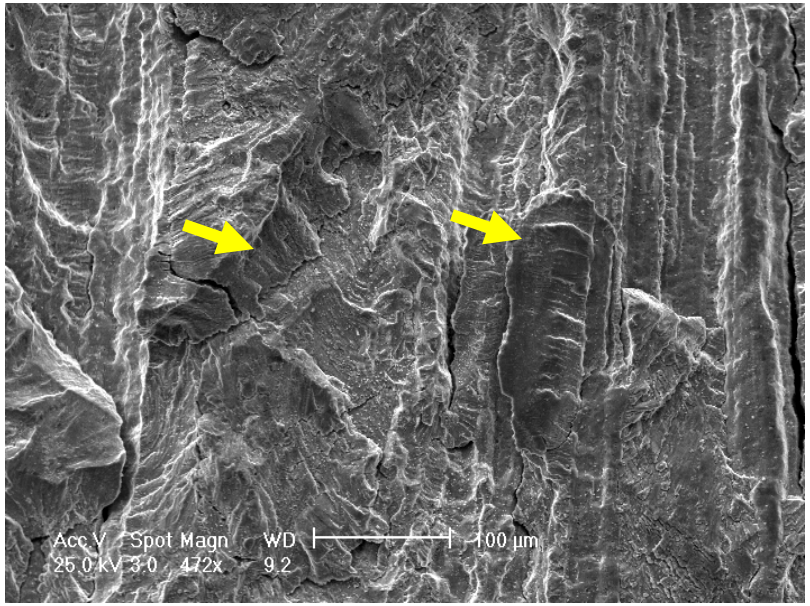
Fracture surface of A152-TS-4

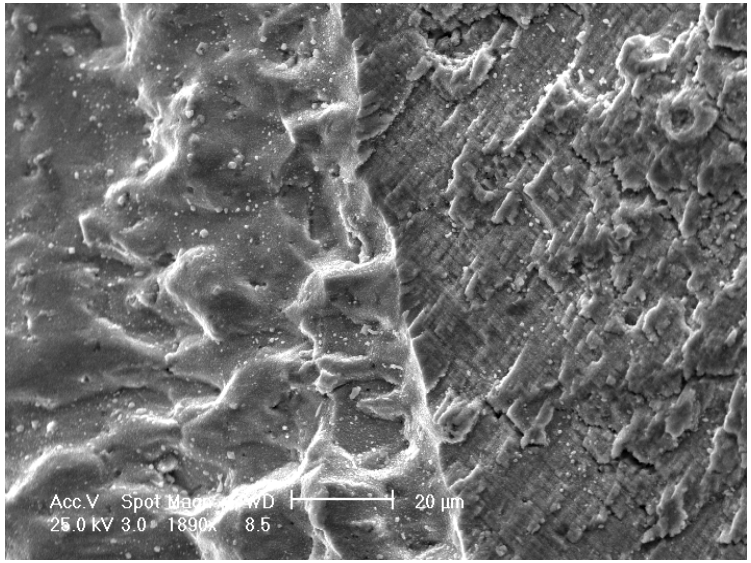


- Specimen was transitioned to SCC twice, maintained growth under constant load conditions only in 2 of 7 attempts
- Observed behavior suggested the formation of ligaments
- SCC CGRs measured during cyclic loading with hold times or at constant load with periodic unloading

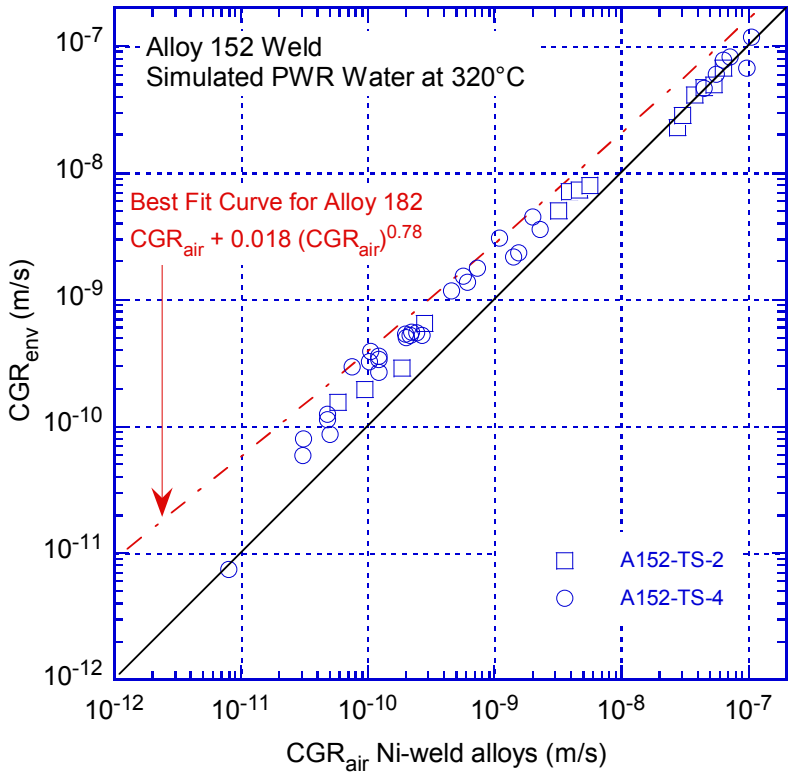
Fracture surface of A152-TS-4 (Examples of Ligaments)





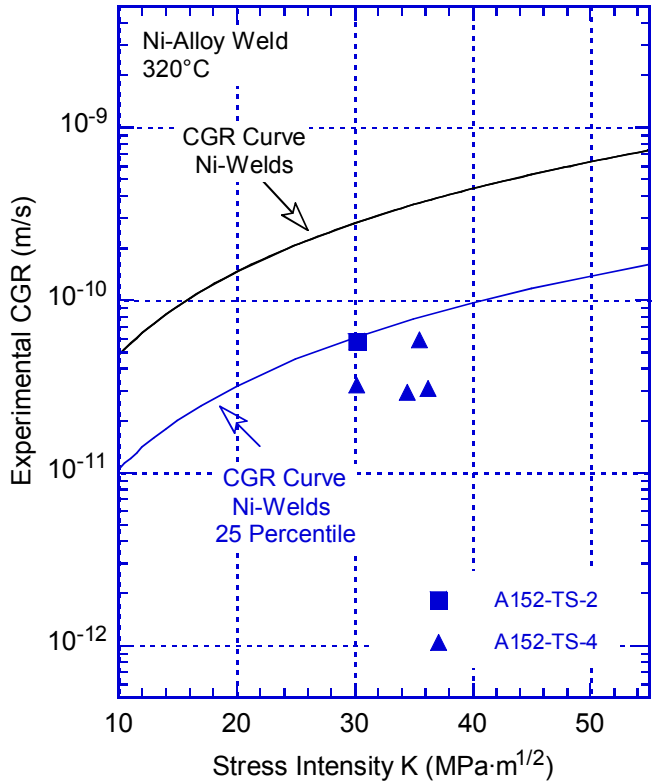


Cyclic CGR Data for Alloy 152 Weld



- Select conditions show environmental enhancement
- R=0.7 and rise 1000s shows no enhancement; the behavior seems to suggest a ΔK effect (and is consistent with other Alloy 690/152 observations)

SCC CGRs vs. K for Alloy 152



- 25th Percentile of Ni-weld Curve bounds the data

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
- As-received Alloy 690 appears to show less environmental enhancement than the cold-rolled alloy
- The environmental enhancement of cyclic CGRs is minimal for Alloy 152
- The SCC CGRs in simulated PWR water at 320°C are in the 10^{-11} m/s range for cold-rolled Alloy 690 and as-welded Alloy 152