Argonne NATIONAL LABORATORY

… for a brighter future

U.S. Department of Energy

UChicago ▶ Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

Update on SCC CGR testing of Alloy 690 (non cold-worked conditions)

Bogdan Alexandreanu, Yiren Chen, Ken Natesan and Bill Shack

Argonne National Laboratory

NRC Project Manager: Greg Oberson

Alloy 690 Expert Panel Meeting

Tampa, FL

December 2-5, 2014

Work sponsored by the US Nuclear Regulatory Commission

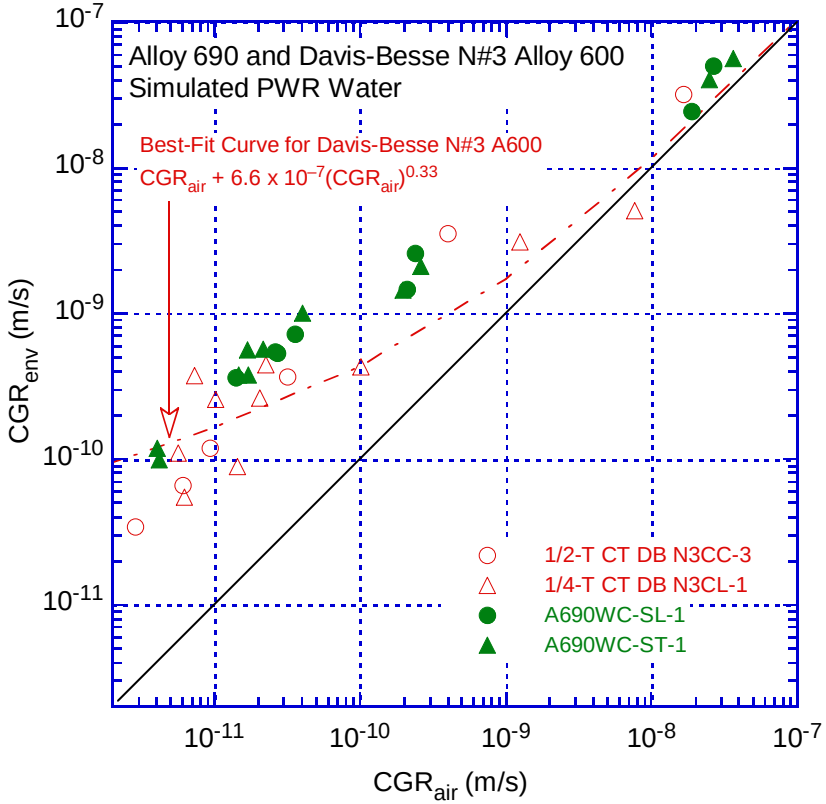
Presentation Outline

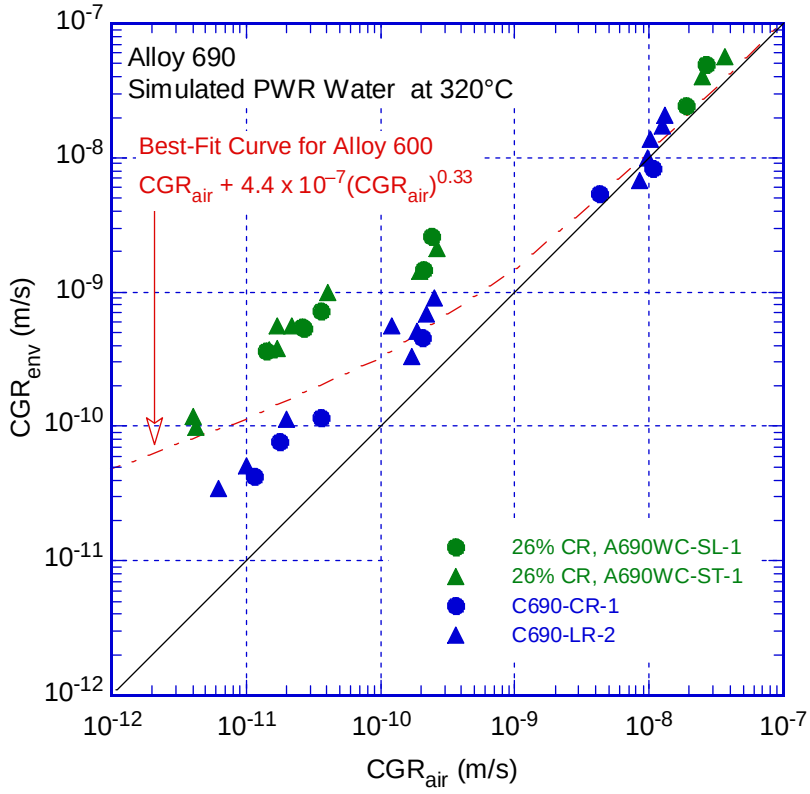
- Background and experimental approach

- Results:
  - Alloy 690 MA in plate form
  - Alloy 690 TT CRDM (Valinox, Sumitomo)

- Summary

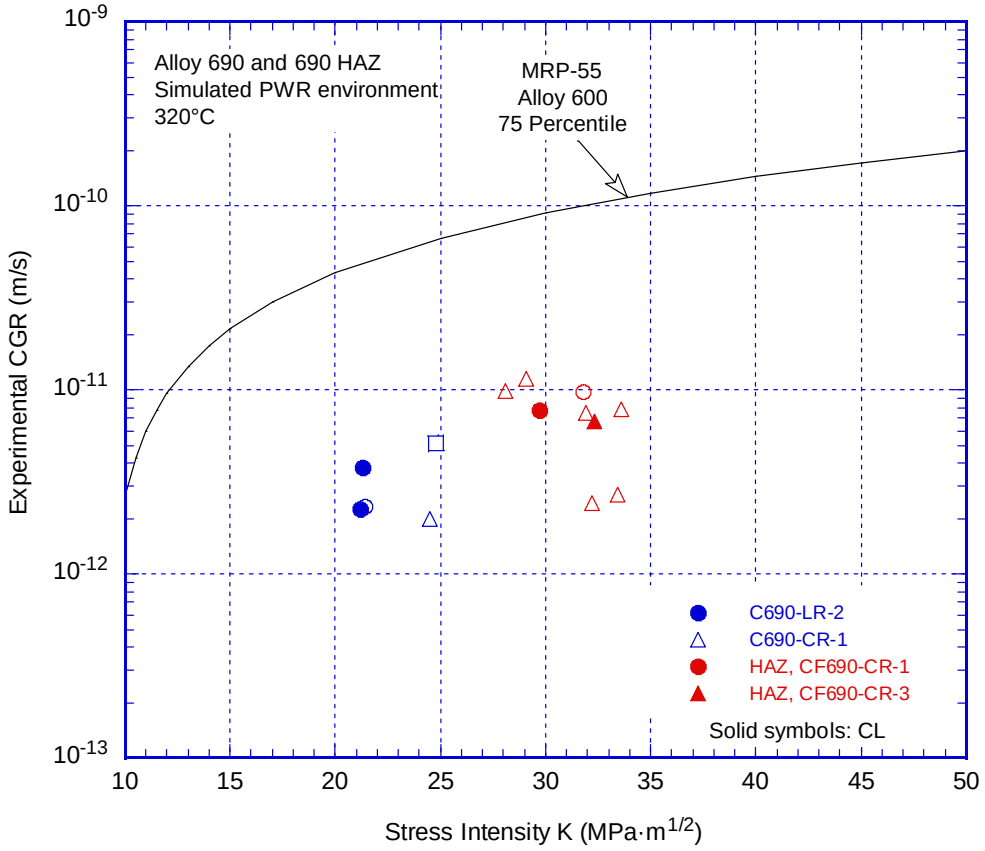
Cyclic response – Alloy 690 in the CW and the as-received conditions





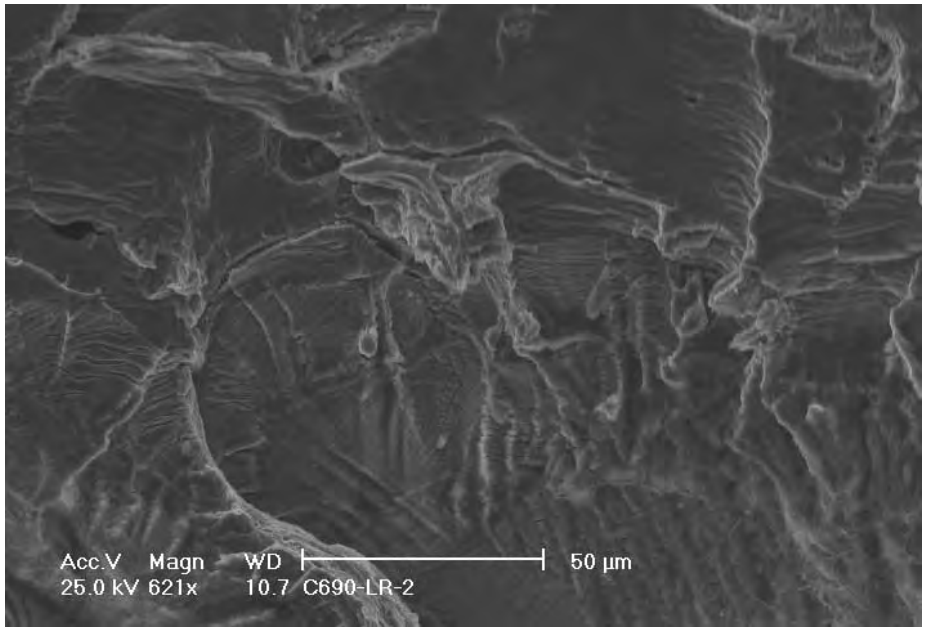
- Alloy 690 26% cold work: environmental enhancement as high as D-B nozzle #3
- Alloy 690 26% cold work: environmental enhancement much higher than as-received condition

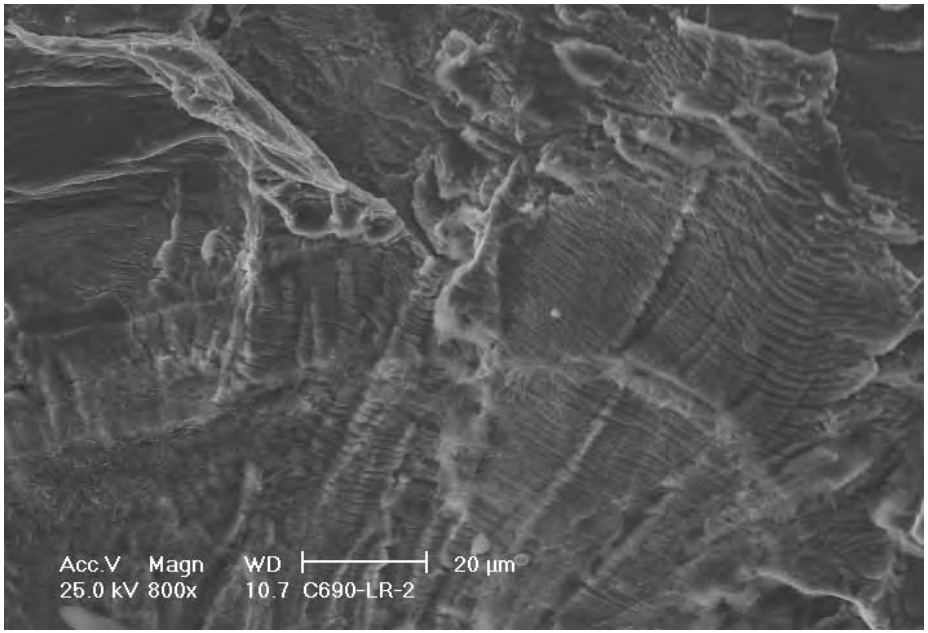
SCC response of non cold-worked Alloy 690 and 690HAZ



- Alloy 690 very low SCC CGRs
- Alloy 690HAZ SCC CGRs are perhaps slightly higher

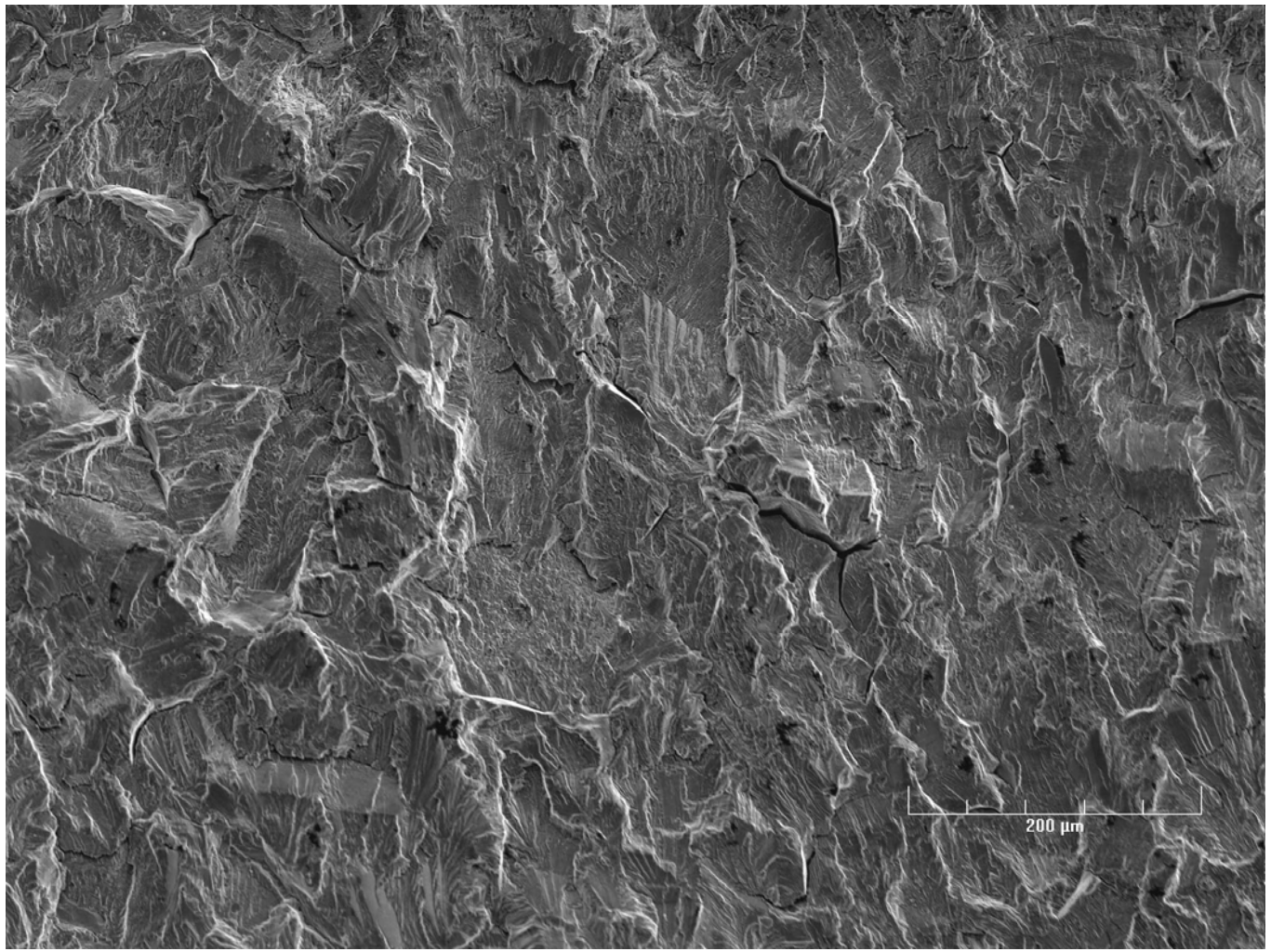
Fracture surface of non cold-worked Alloy 690





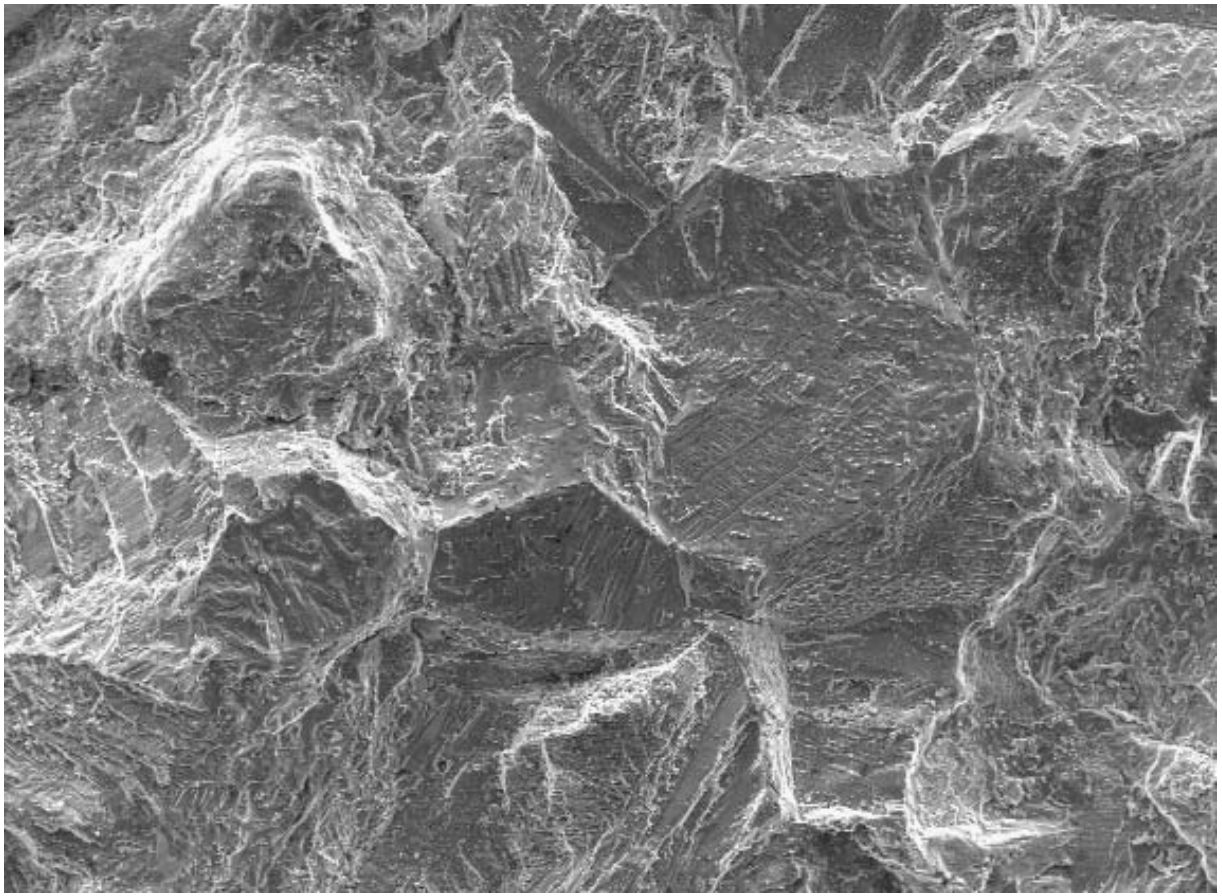
- Facets (TG) and, occasionally, striations (environmental fatigue)

SCC response of non cold-worked Alloy 690



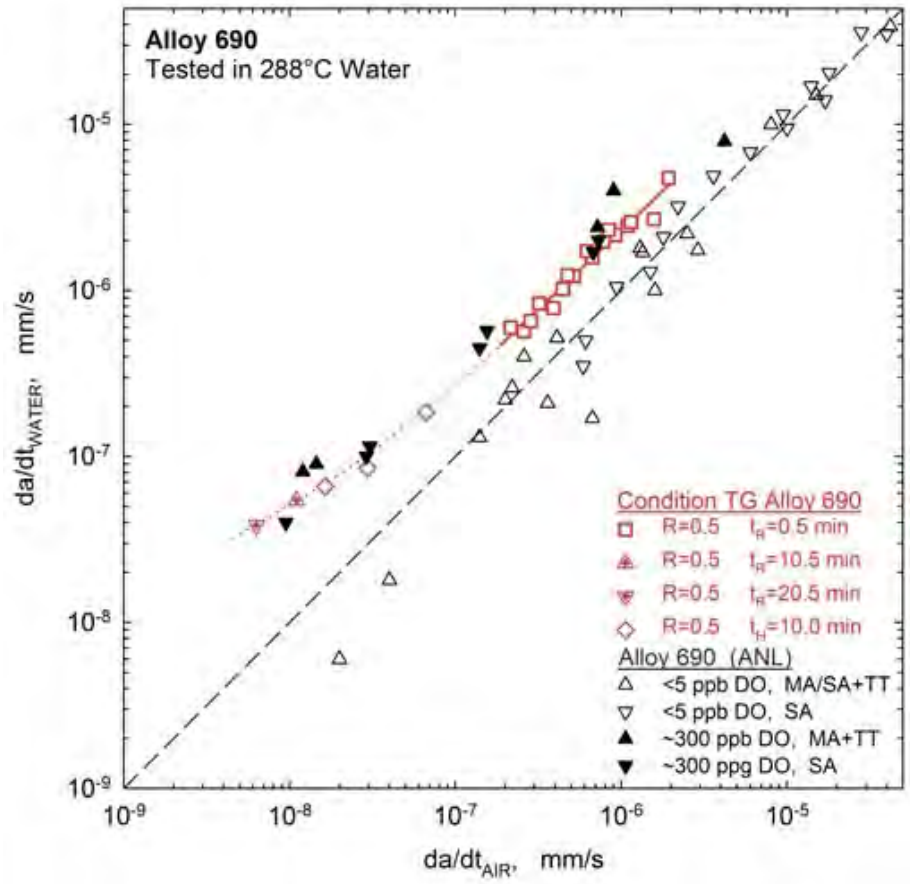
- Unlike the alloy in the as-received condition, the HAZ shows some IG

Bill Mills et al (Env Deg 2009)



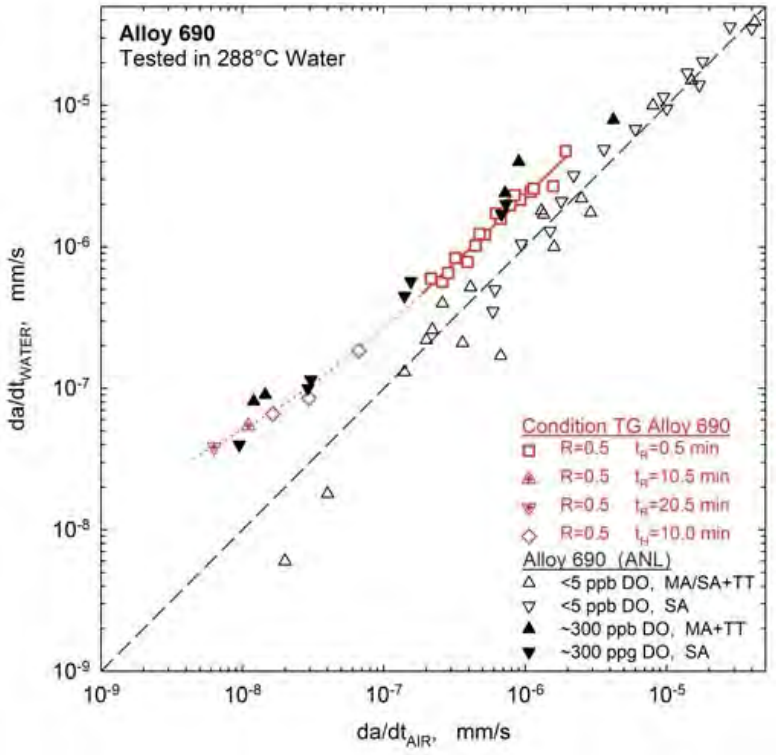
- Bill Mills reports “substantial” IG engagement: 9% for t_R= 30s, and 20% for t_R= 600s under continuous cyclic at ΔK = 12 MPa $m^{1/2}$ in DPW at 288ºC
- No IG engagement for ΔK > 16 MPa $m^{1/2}$

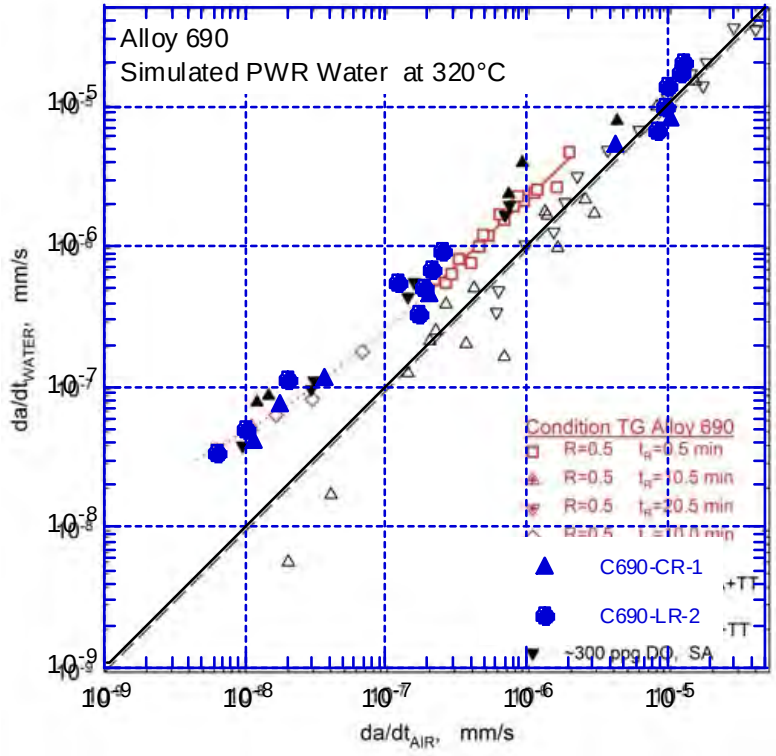
Corrosion fatigue work by Bill Mills et al (Env Deg 2009)



- Bettis data show higher enhancement than ANL DPW (<5 ppb)
- ANL DPW (<5 ppb data) were all obtained with short rise times, t_R = 12 seconds

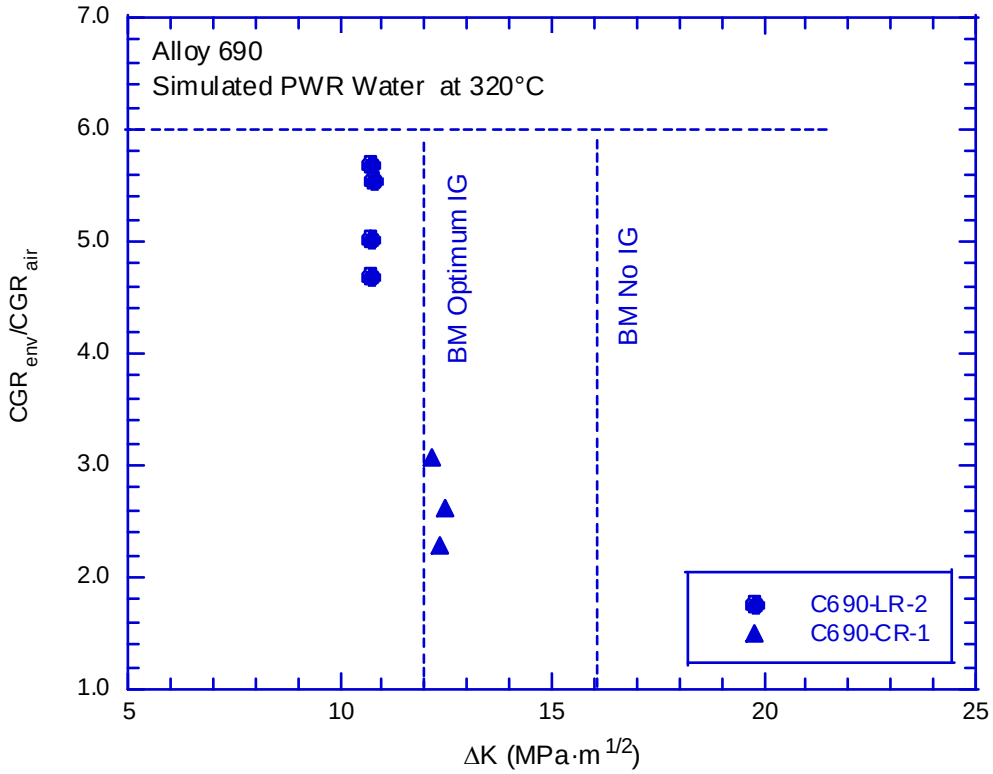
Corrosion fatigue work by Bill Mills et al (Env Deg 2009)





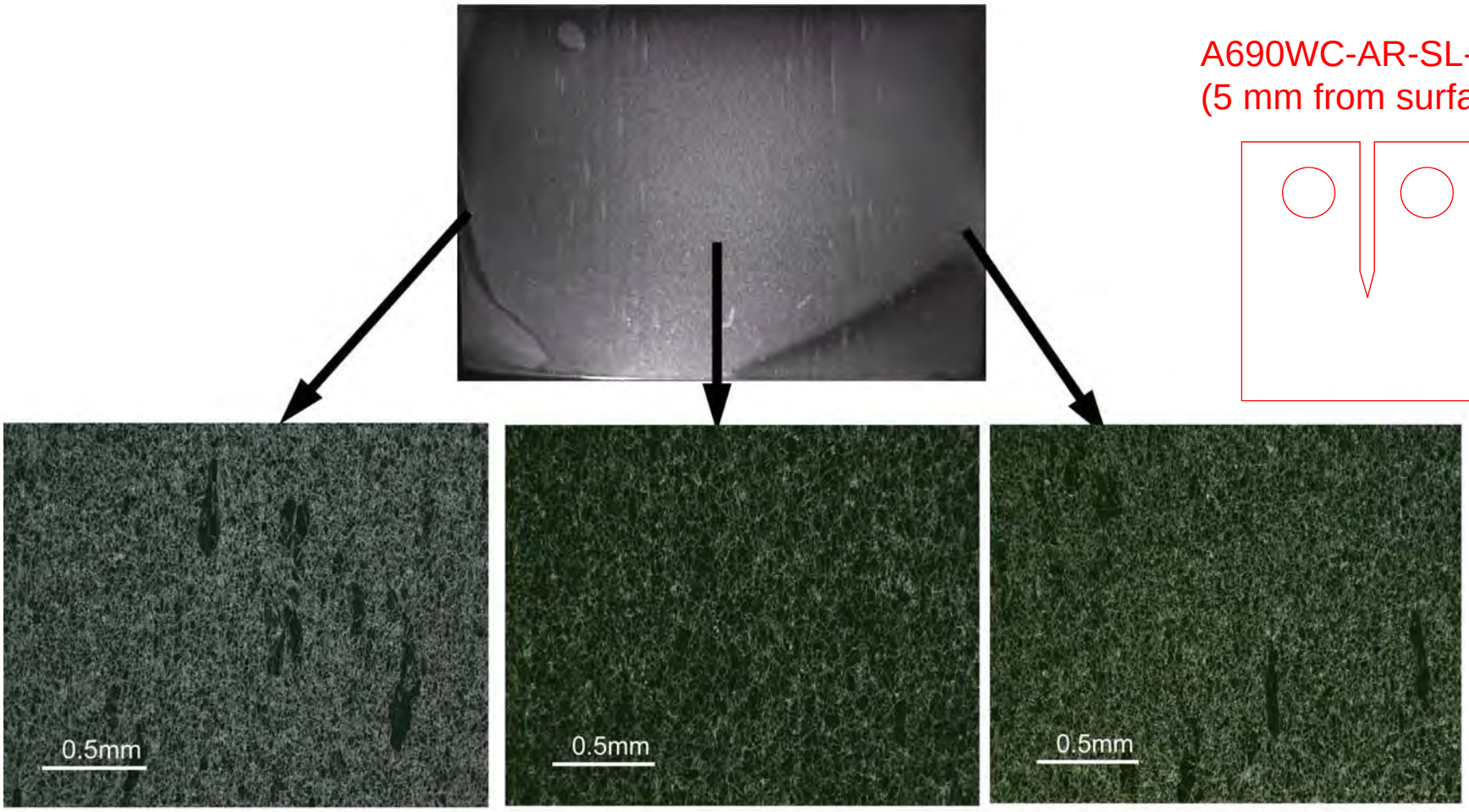
- Excellent agreement between current ANL data (solid blue) and Bettis data (red) on time domain plots (left plot)

Experimental Approach

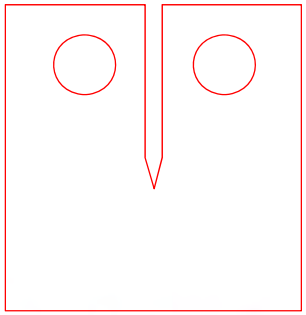


- Bill Mills "optimum": $\Delta K = 12$ MPa $m^{1/2}$, $t_R = 600s$ (da/dN = 5E-8 m/s), $GGR_{env}/CGR_{air} \sim 6$
- No IG engagement for $\Delta K > 16$ MPa $m^{1/2}$
- R=0.5, 600/12 (ΔK = 14-15 MPa $m^{1/2}$) was used extensively at ANL for transitioning; for welds at 320ºC, da/dN = 3.8E-8 m/s

Alloy 690 Plate (Heat NX3297HK12)

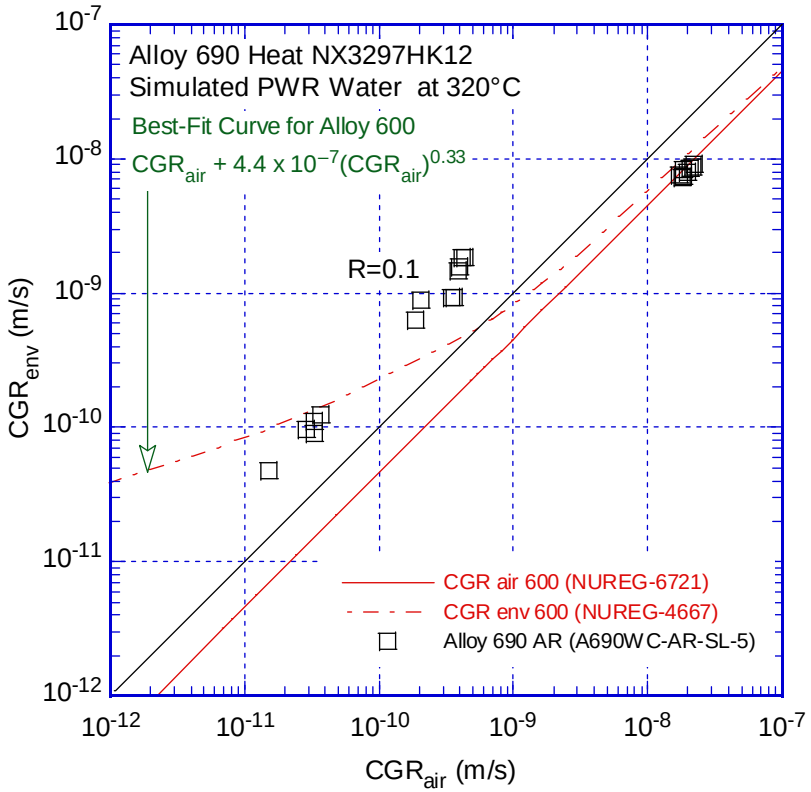


A690WC-AR-SL-5
(5 mm from surface)



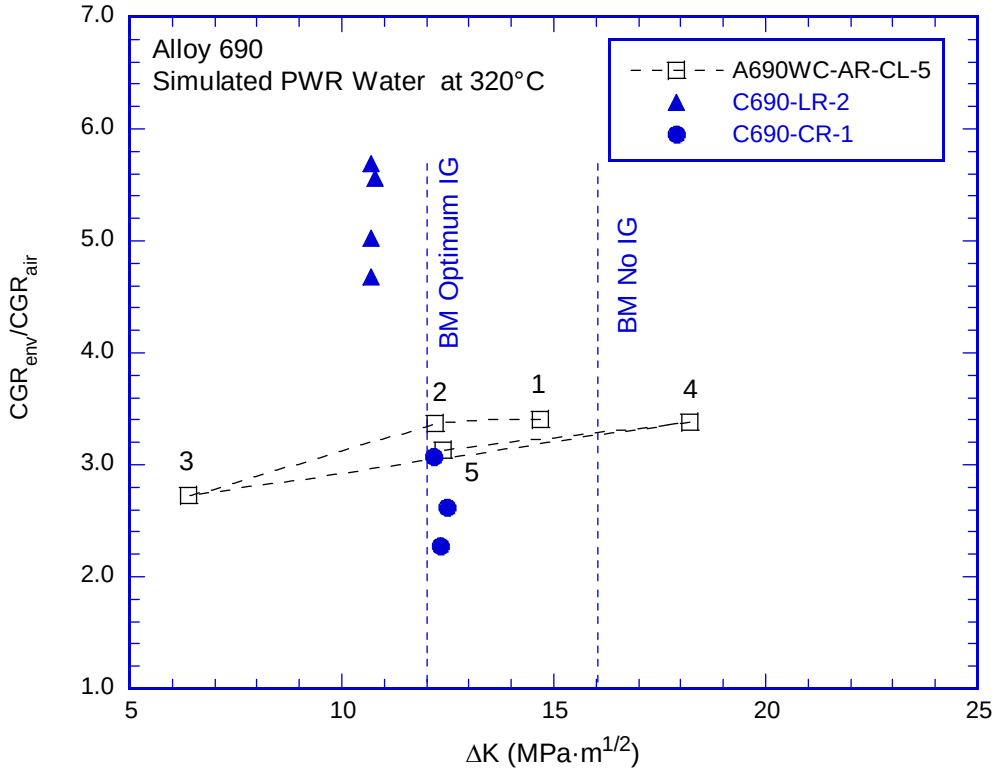
- Tested and cracked at ANL in 2005-2006 in 26% cold-rolled condition
- Subsequently tested worldwide
- Also known as “ANL plate” or “rogue heat” (J. Hickling)

Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5



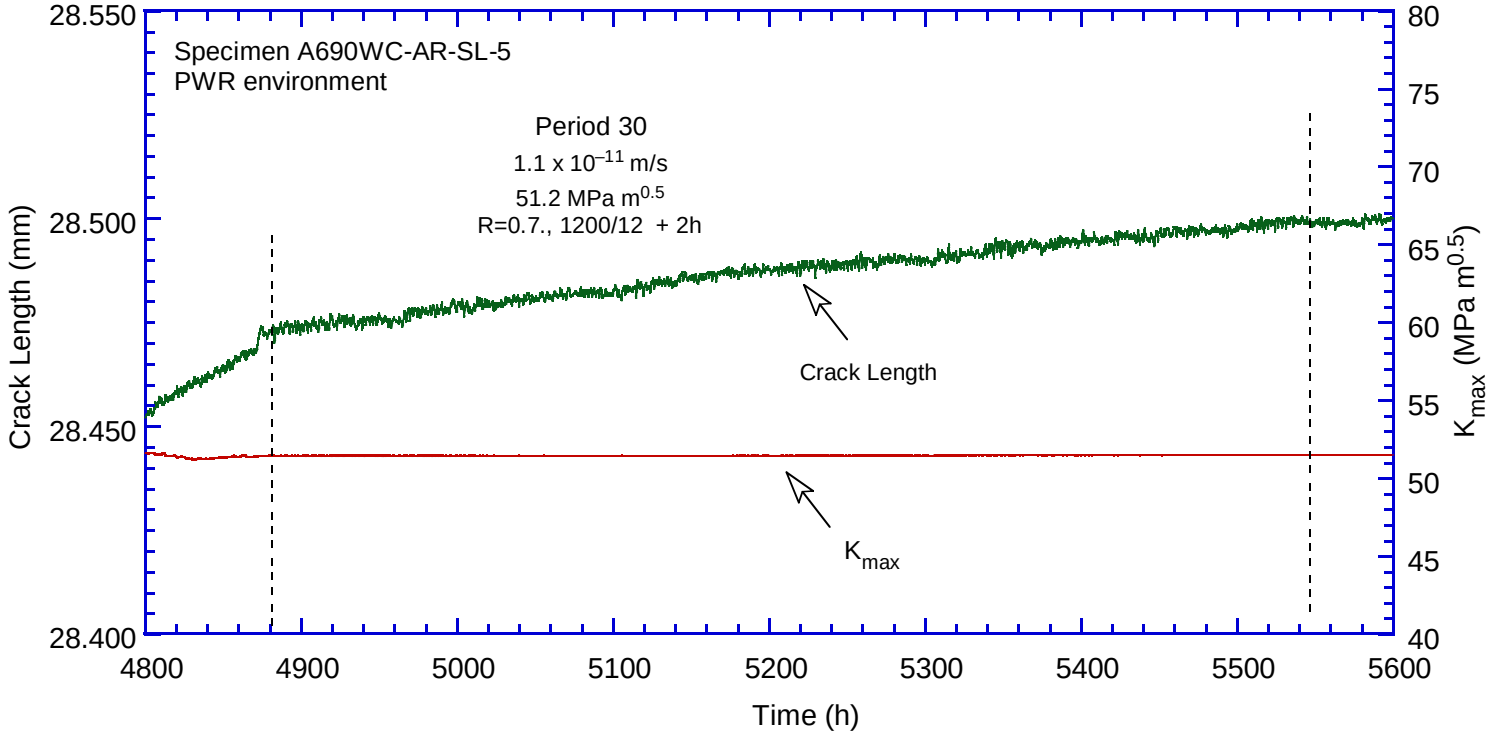
- Heat NX3297HK12 very resistant to fatigue (as resistant as Alloy 600)
- Environmental enhancement is minimal

Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5



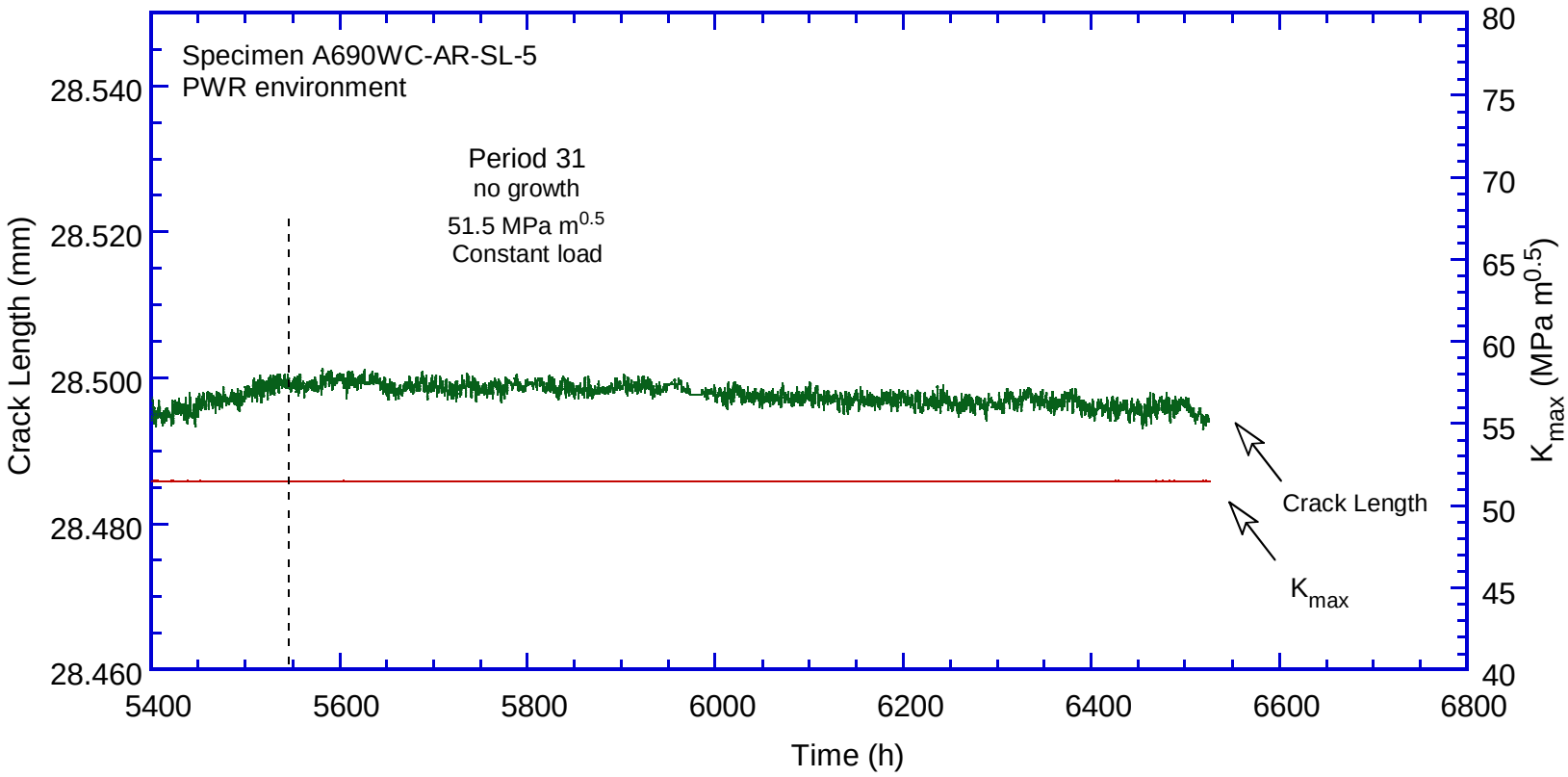
- CGR$_{air}$ = ct. (3E-11 m/s)
- da/dN < 2E-8 m/cycle (BM = 5E-8 m/cycle)
- Environmental enhancement is minimal (less than the Valinox CRDM in LR orientation) and flat (does not seem to show the ΔK dependence)

Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5



- P30: Response from cycle + hold is at the air line (1.04E-11), SCC CGR component is “zero”.

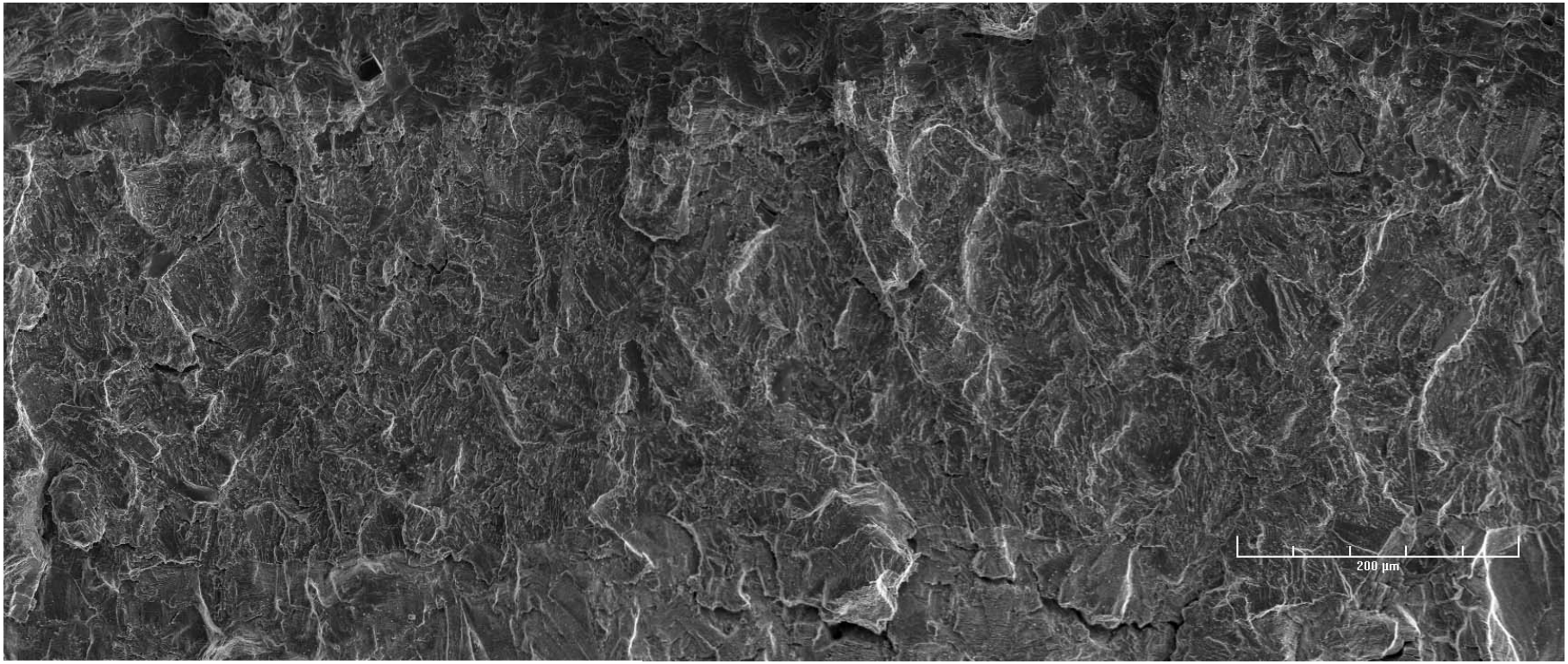
Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5



- P31: “No growth” condition confirmed at constant load
- The “rogue heat” did not live up to its reputations or SCC in a cold-worked condition is not a good predictor for the SCC behavior of the as-received alloy

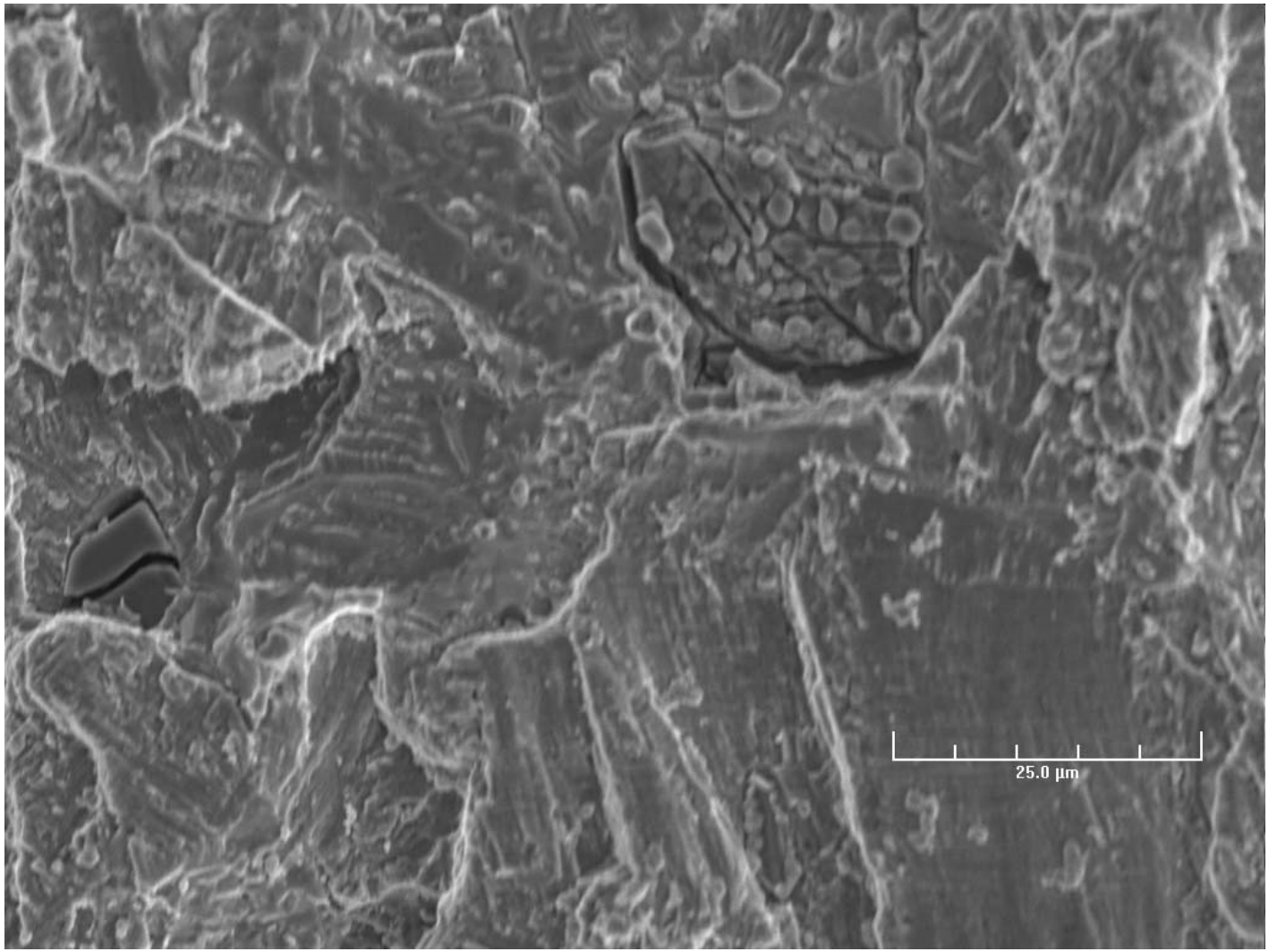
Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5

Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5



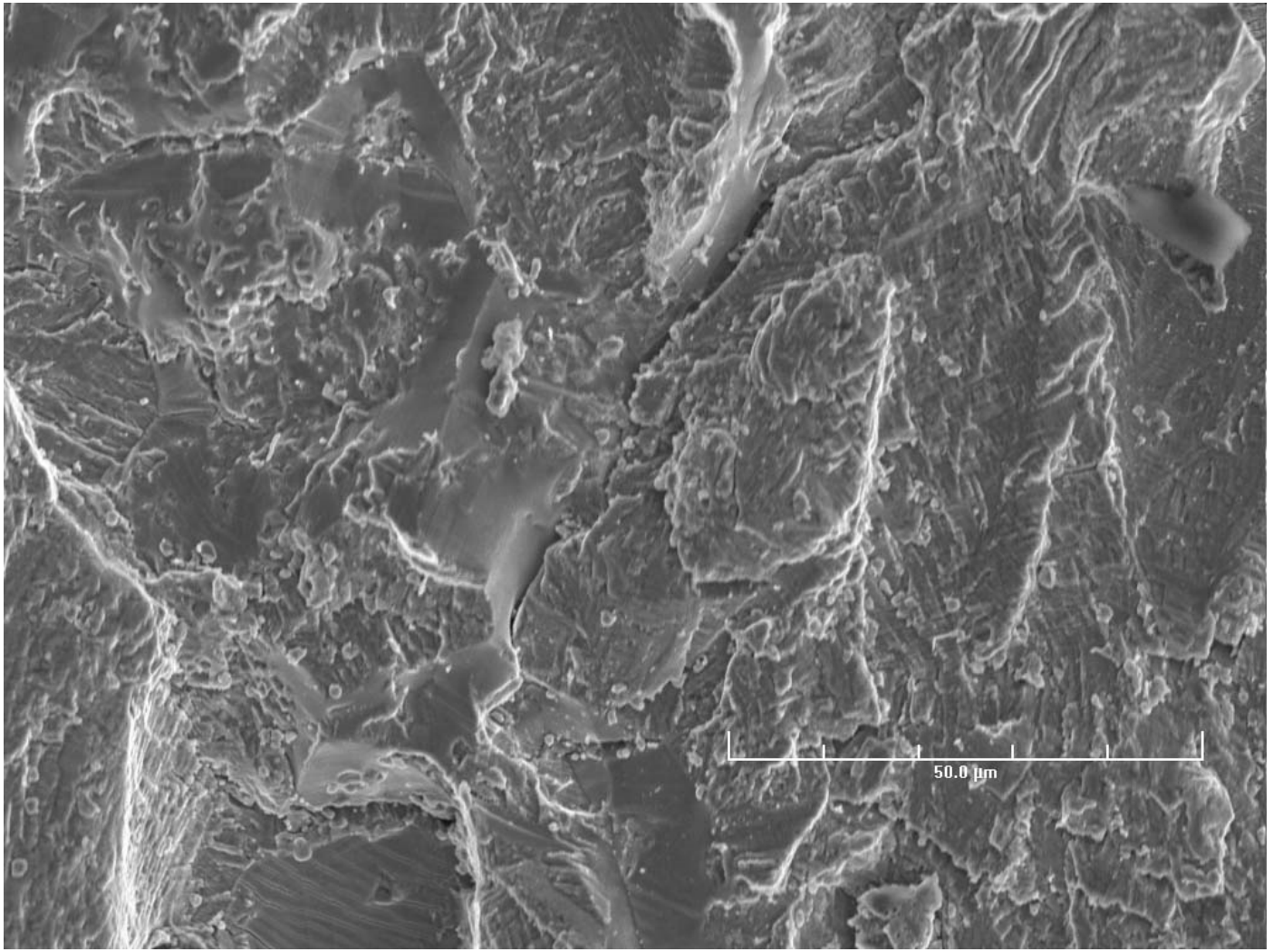
- Last region on the test, TG cracking

Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5



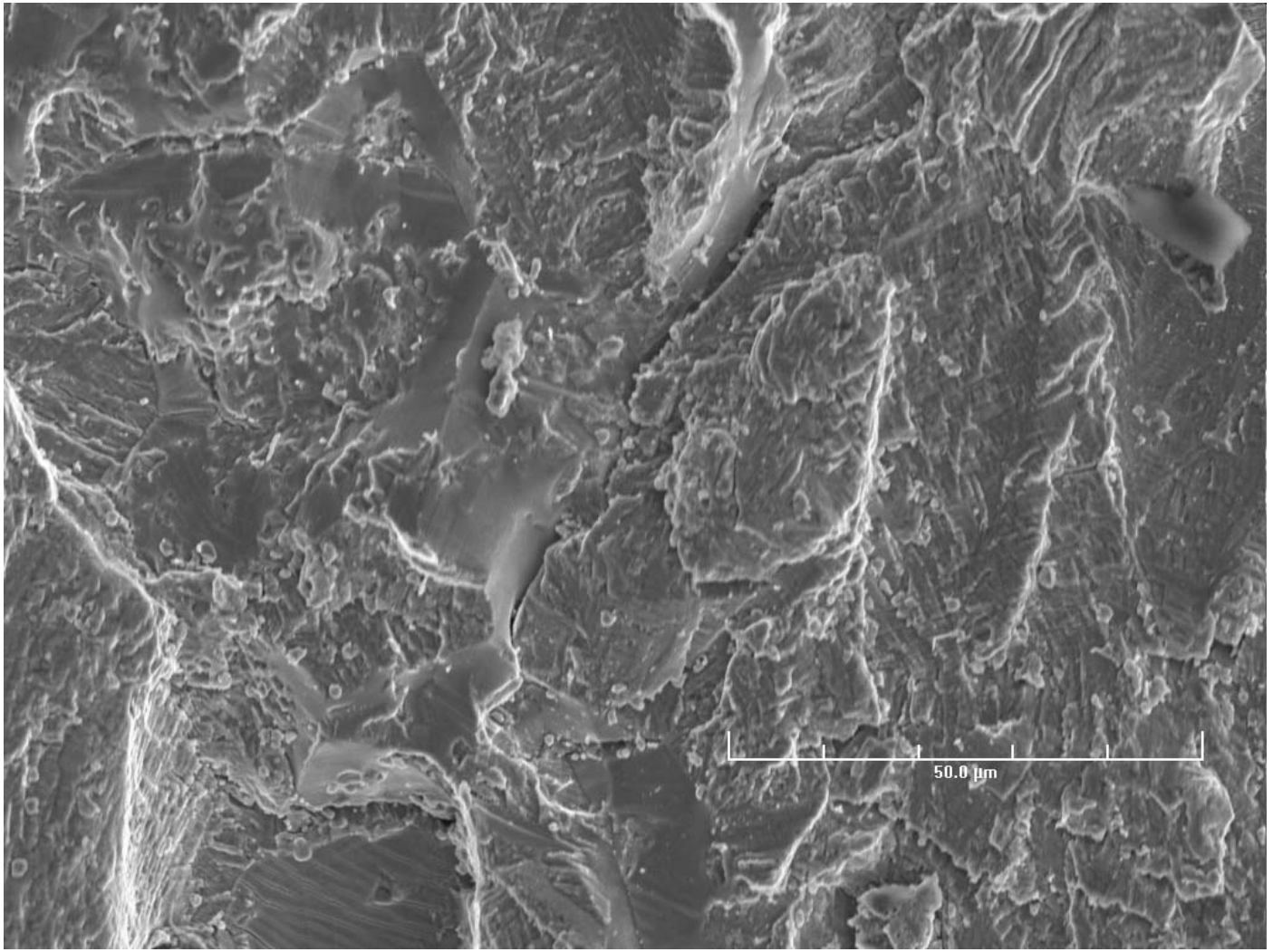
- TG cracking, cracked inclusions

Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5



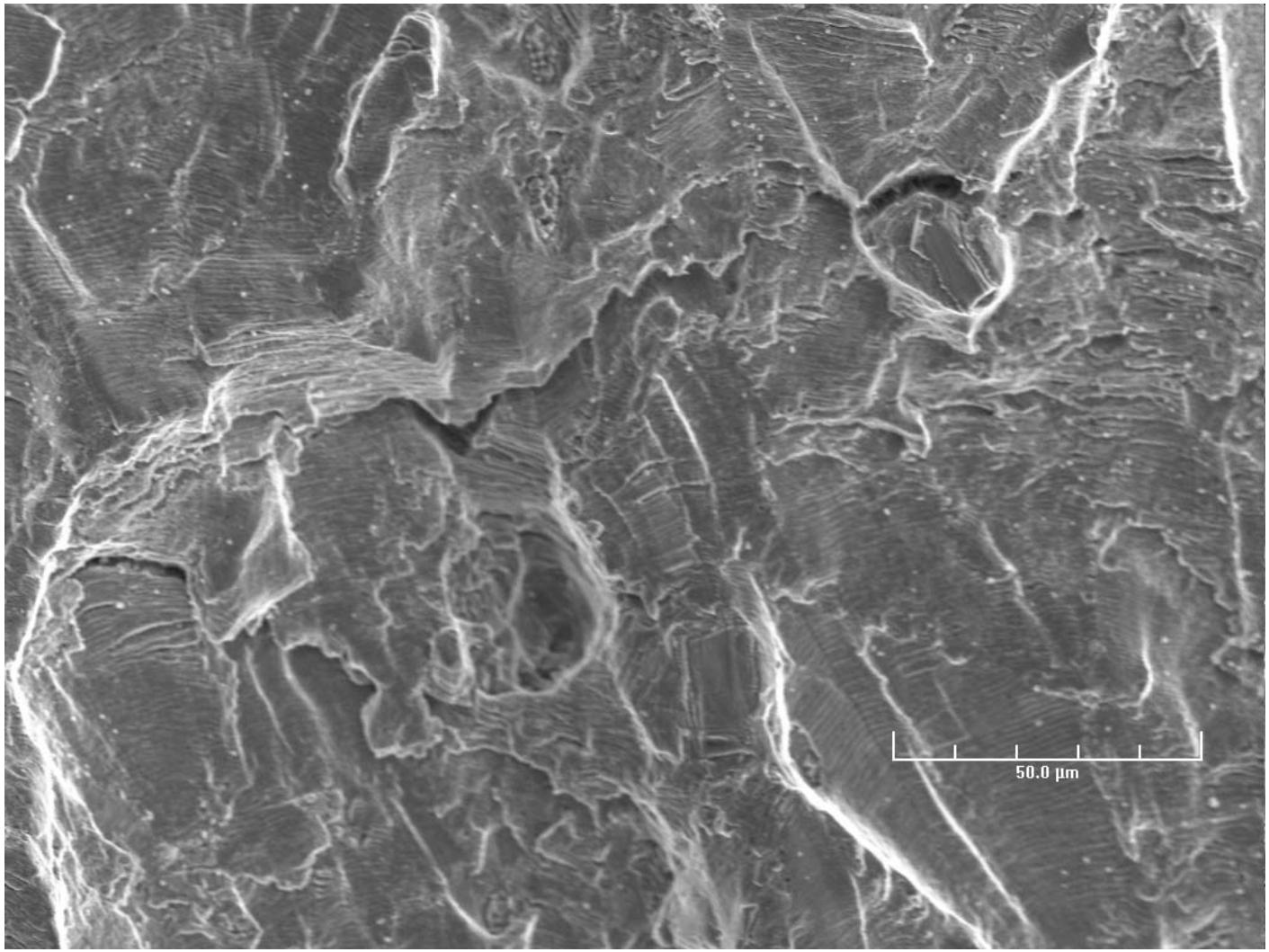
- Some smooth facets, perhaps some IG (not unambiguous)

Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5



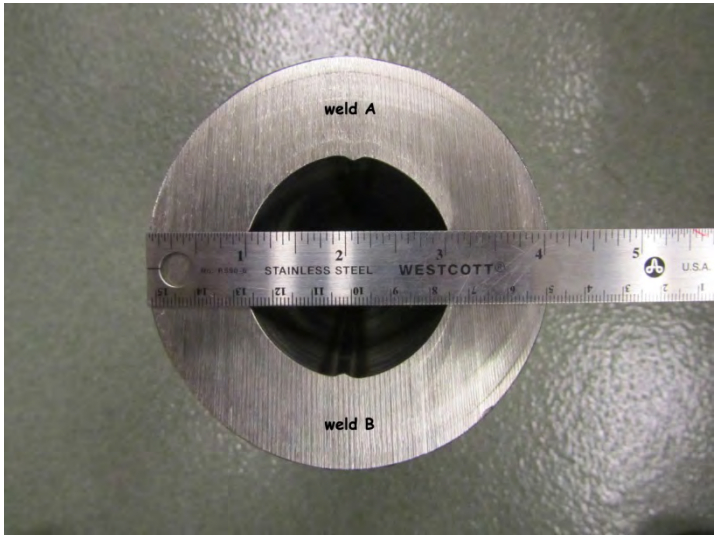
- Some smooth facets, perhaps some IG (not unambiguous)

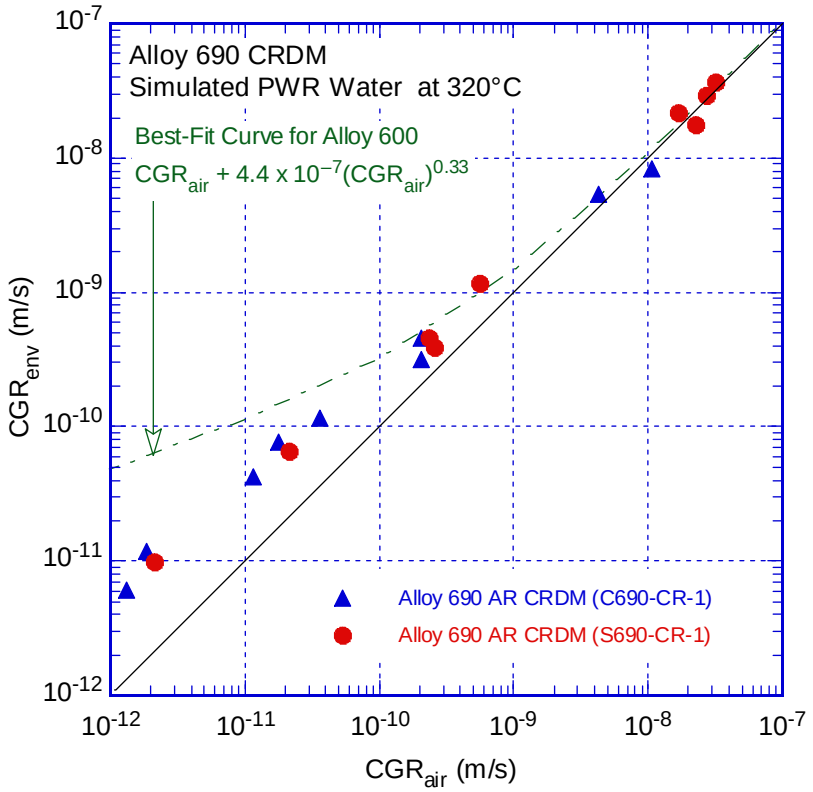
Alloy 690 Plate (Heat NX3297HK12): Specimen A690WC-AR-SL-5



- Striations (environmental fatigue), perhaps some IG (not unambiguous)

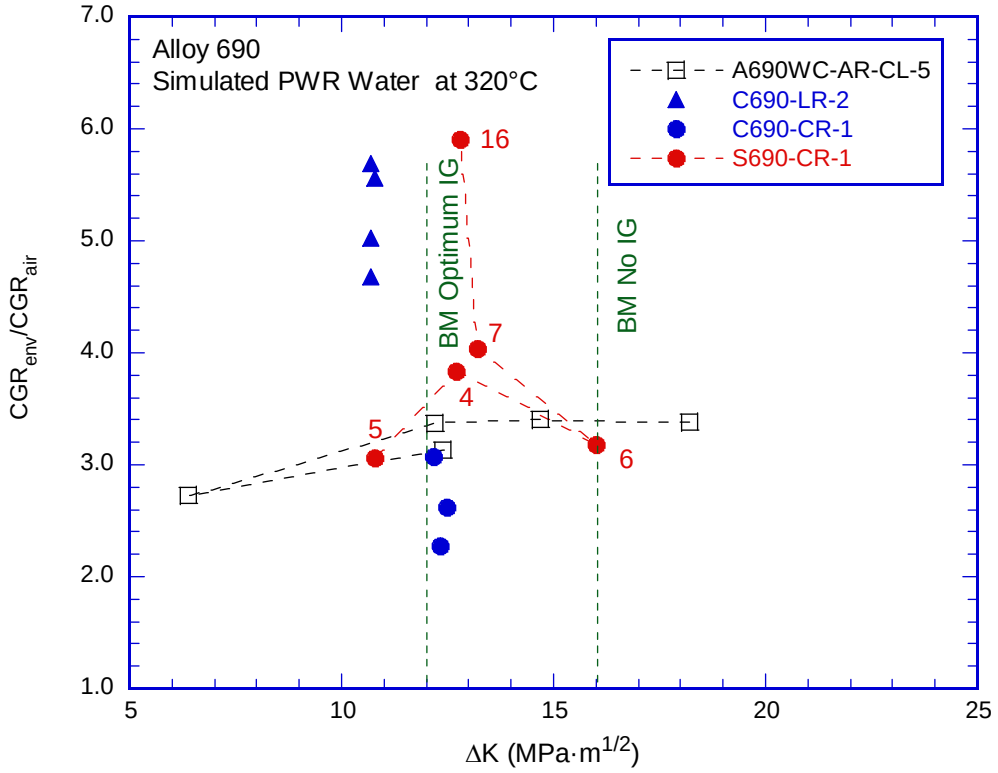
Alloy 690 CRDM (Sumitomo): Specimen S690-CR-1





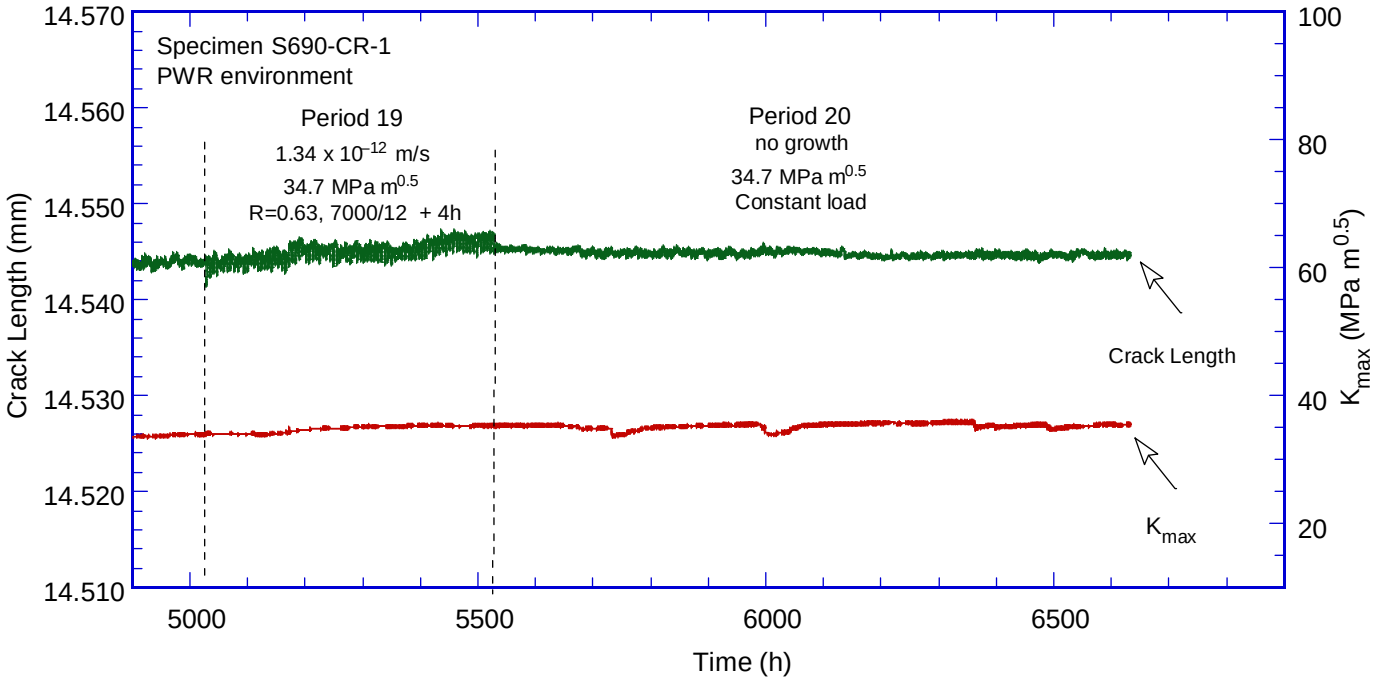
- Identical fatigue and corrosion fatigue response to that of the Valinox CRDM

Alloy 690 CRDM (Sumitomo): Specimen S690-CR-1



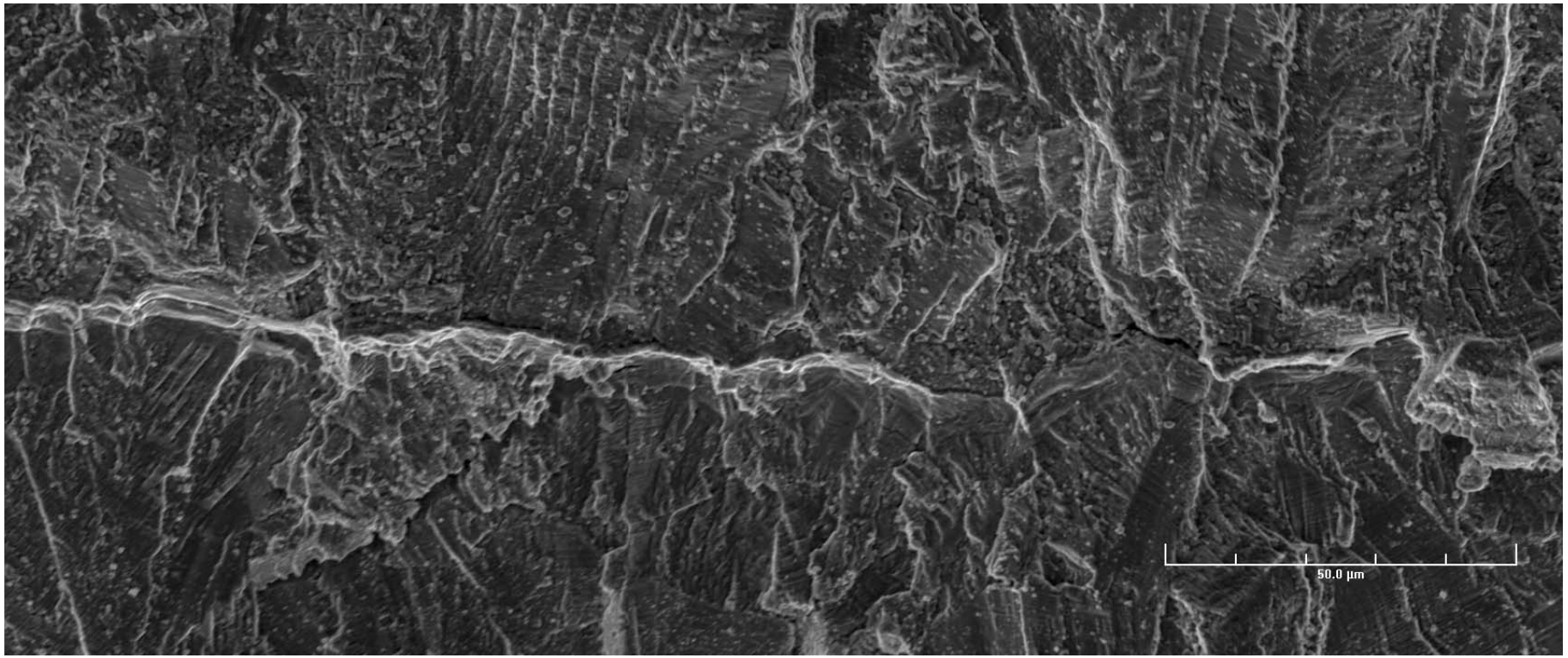
- CGR_{air} = ct. (3E-12 m/s)
- da/dN < 2E-8 m/cycle (BM = 5E-8 m/cycle)
- Environmental enhancement shows max at ΔK = 12 MPa $m^{1/2}$

Alloy 690 CRDM (Sumitomo): Specimen S690-CR-1



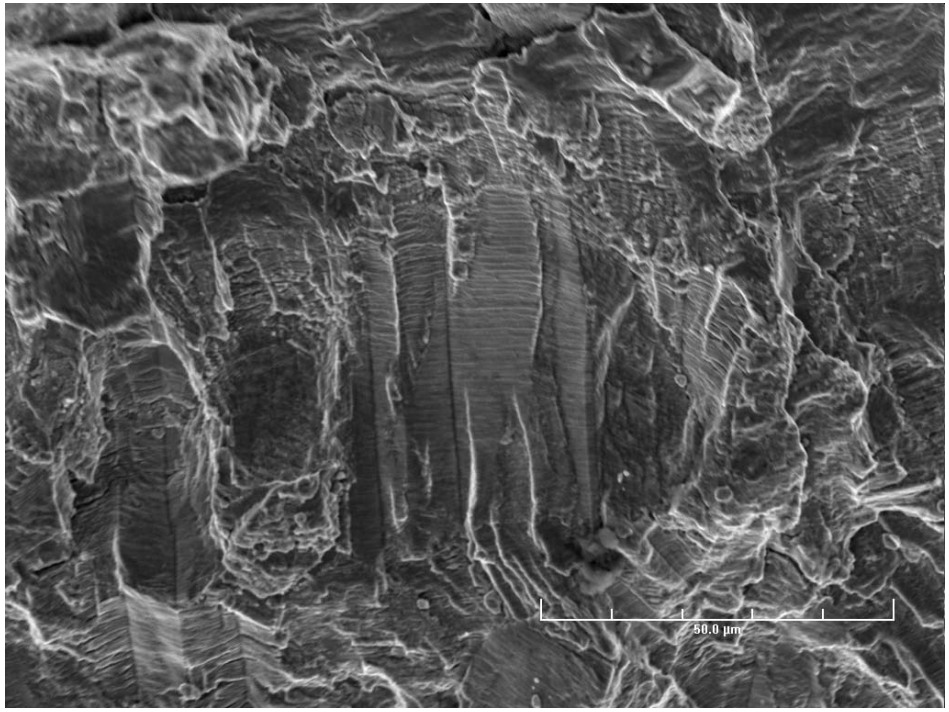
- P19: Environmental enhancement was not maintained when the 4h hold was introduced
- P19: Response from cycle + hold is at the air line (1.04E-11), SCC CGR component is “zero”
- P20: Confirmed at constant load

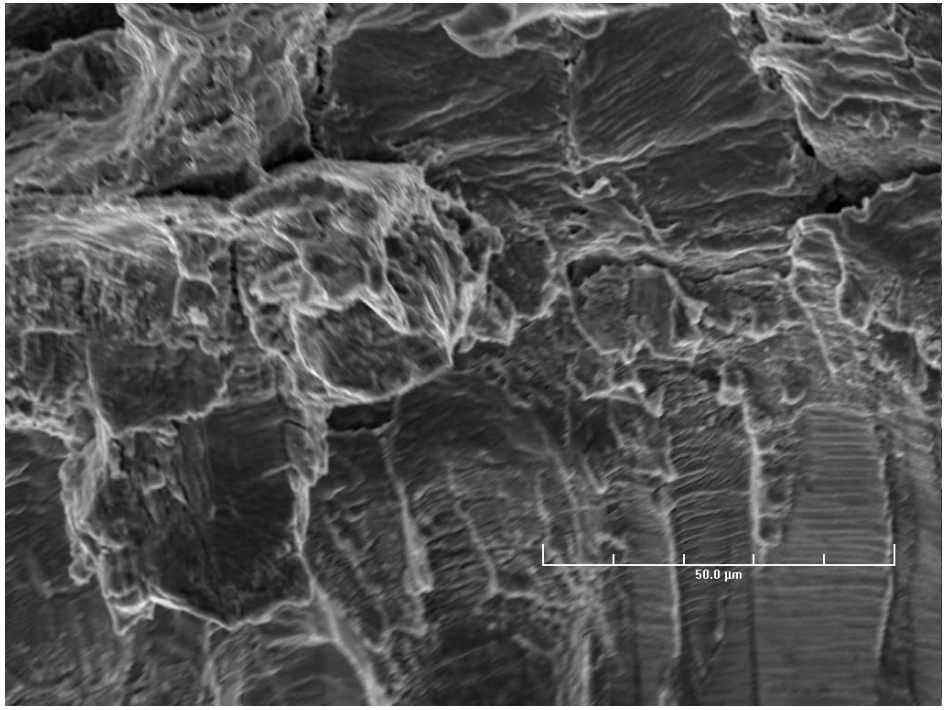
Alloy 690 CRDM (Sumitomo): Specimen S690-CR-1



- Initial CF testing, low enhancement
- No IG cracking, some off-plane growth

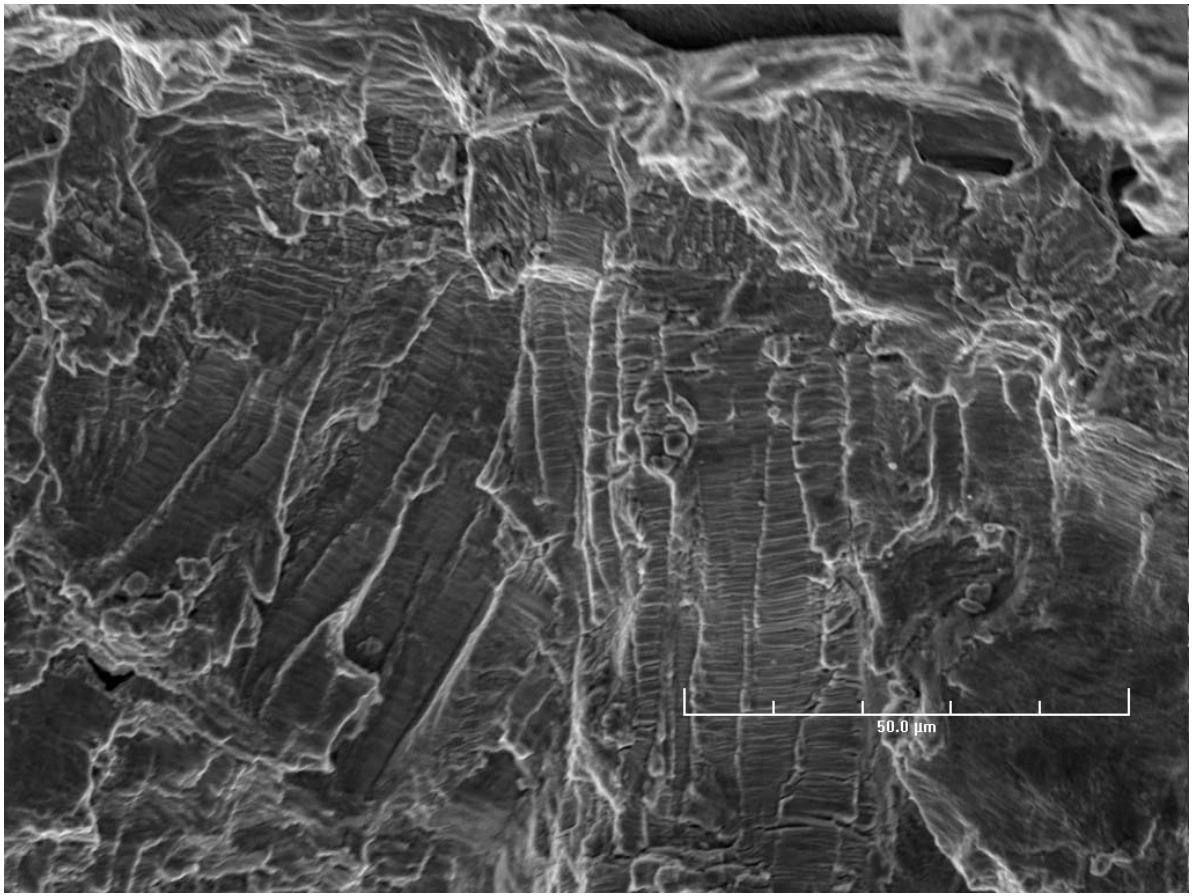
Alloy 690 CRDM (Sumitomo): Specimen S690-CR-1





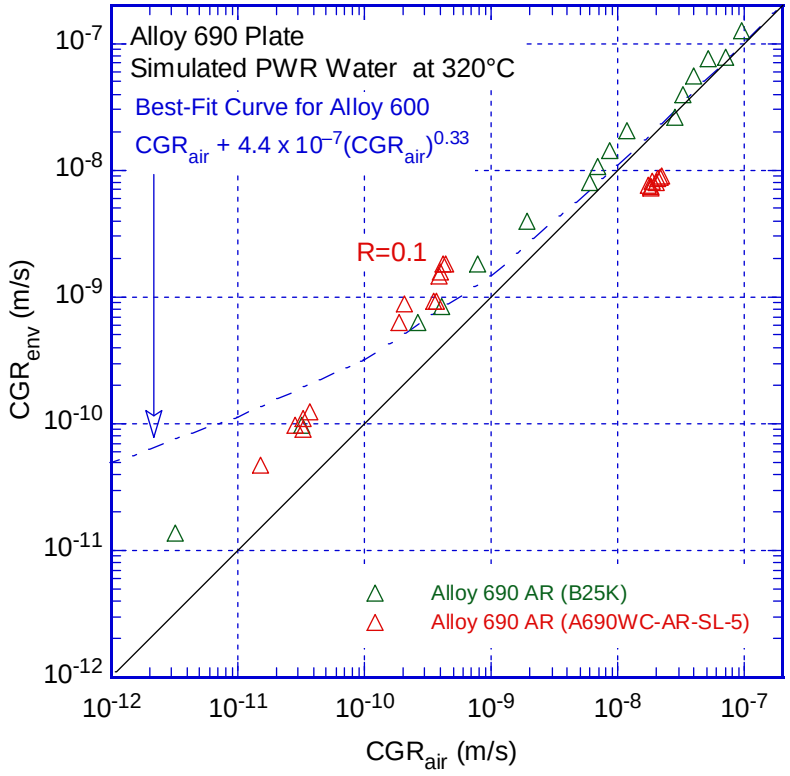
- Final CF testing, high enhancement
- Striations
- No (unambiguous) IG cracking

Alloy 690 CRDM (Sumitomo): Specimen S690-CR-1



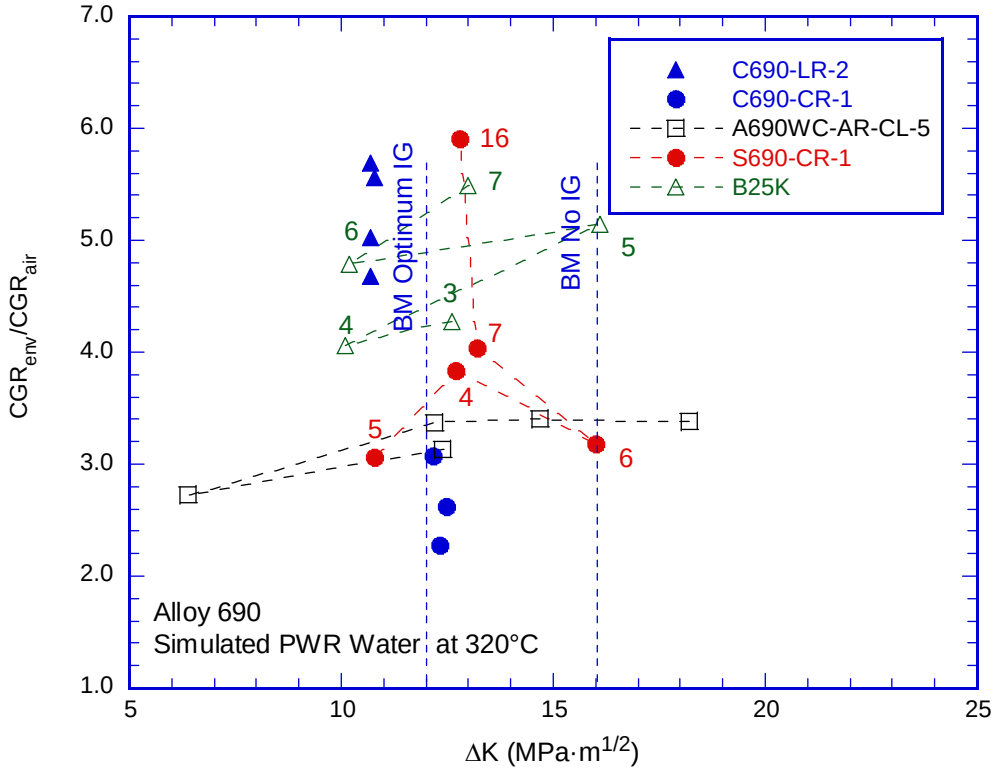
- Final CF testing, high enhancement
- Striations
- No IG cracking

Alloy 690 MA plate (Allvac): Specimen B25K



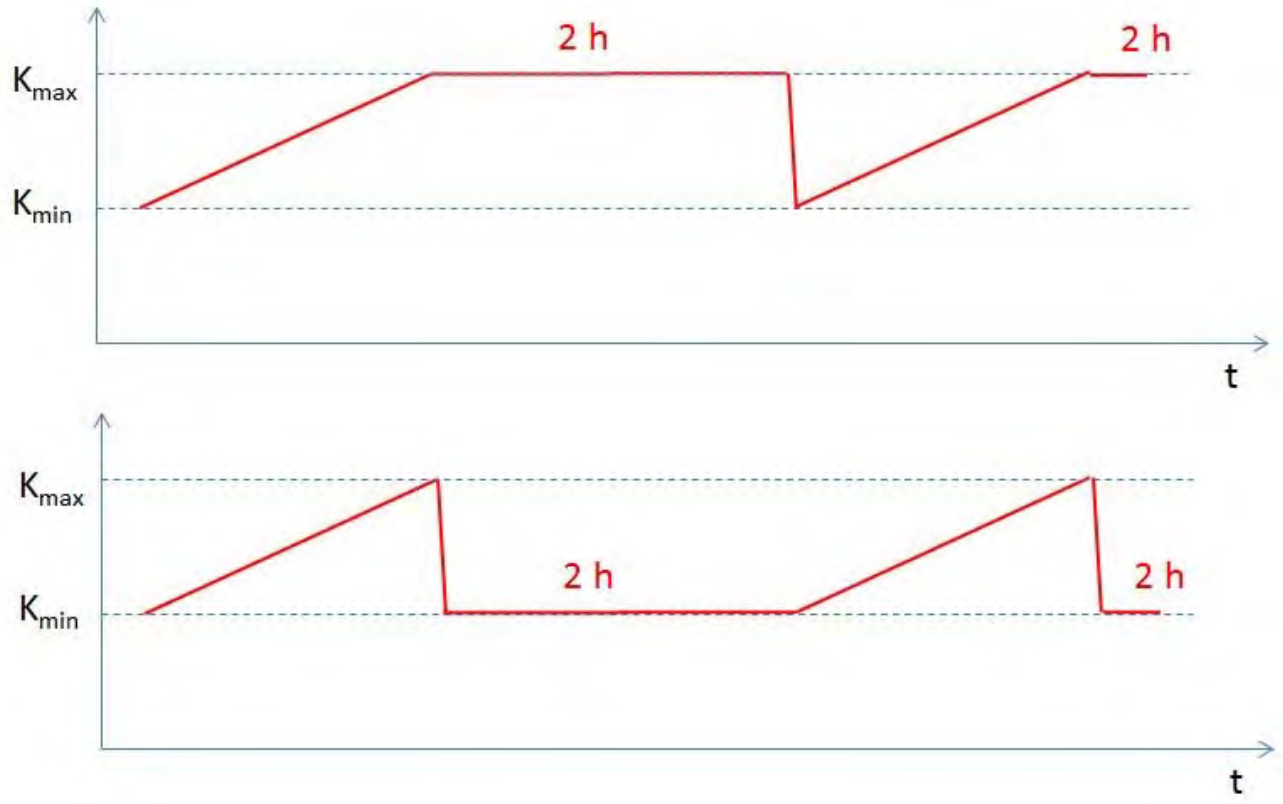
- CGR$_{air}$ = ct. (3E-12 m/s)
- da/dN < 3E-8 m/cycle (BM = 5E-8 m/cycle)
- Environmental enhancement shows max at ΔK = 12 MPa m$^{1/2}$

Alloy 690 MA plate (Allvac): Specimen B25K



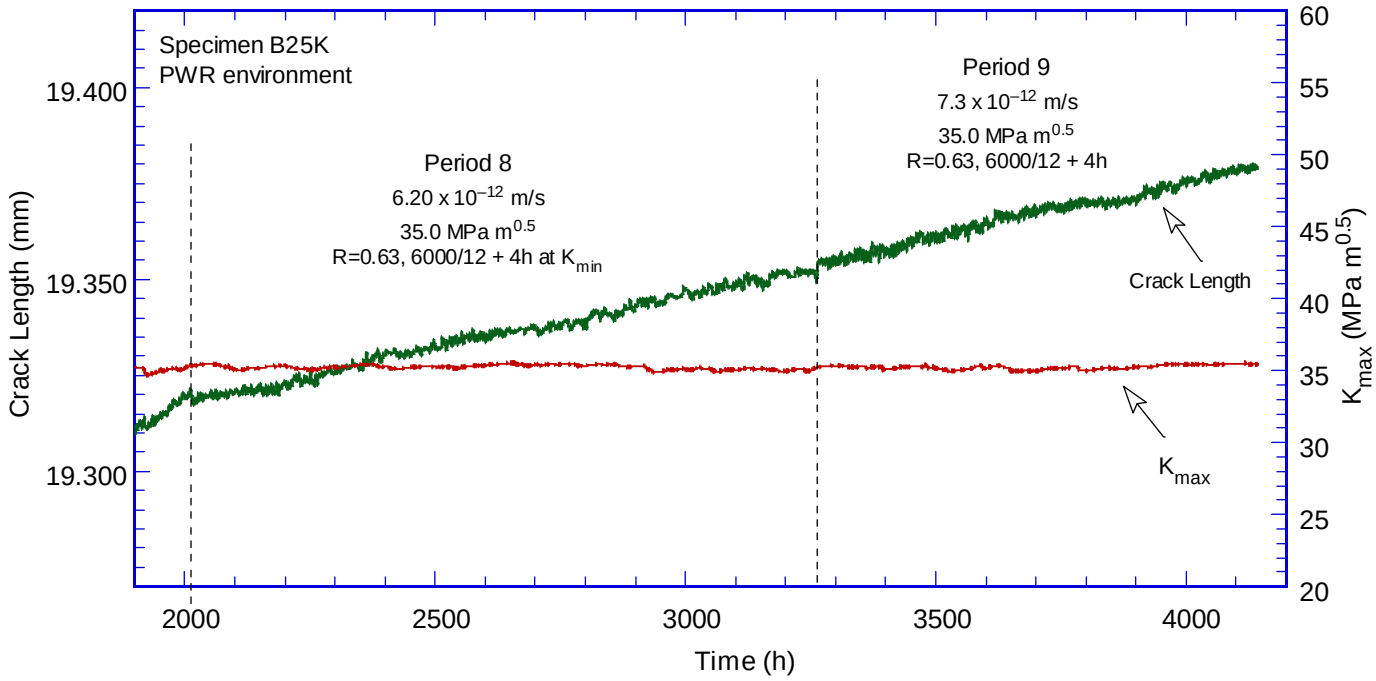
- CGR_{air} = ct. (3E-12 m/s)
- da/dN < 3E-8 m/cycle (BM = 5E-8 m/cycle)
- Environmental enhancement builds-up eventually reaching that observed for CRDM materials (ΔK = 12 MPa $m^{1/2}$)

Experimental approach



- Alternating hold between K_{min} and K_{max} = turns SCC “off” and “on”
- SCC CGR = difference between the two rates
- Maintain cycling longer

Alloy 690 MA plate (Allvac): Specimen B25K



- Maintain cycling for longer periods of time
- Environmental enhancement was maintained (unlike the S690 CRDM)
- SCC CGR = difference between the two rates = 1E-12 m/s

Summary

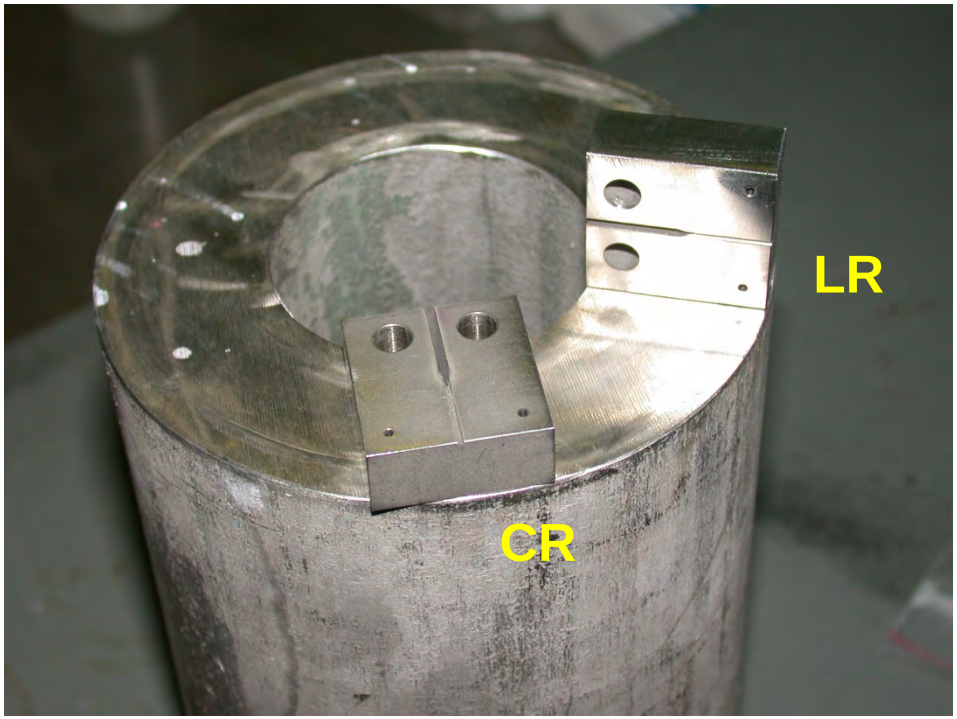
- Tried experimental approach based on Bill Mill's experience
  (very similar to ANL's practice)
- Environmental enhancement depends on ΔK, and has a maximum at $\Delta K = 12$ MPa $m^{1/2}$
- Despite the optimized conditions, the SCC CGRs for as-received Alloy 690 are extremely low or "zero"

Alloy 690TT Specimens (as received condition)

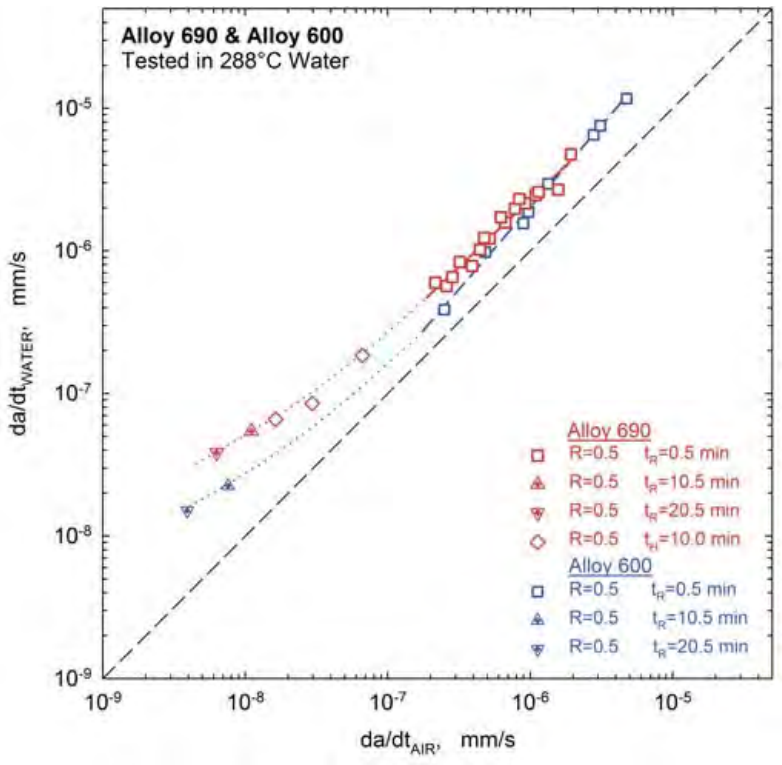
- Alloy 690TT CRDM tubing, 2541 – Heat WP142

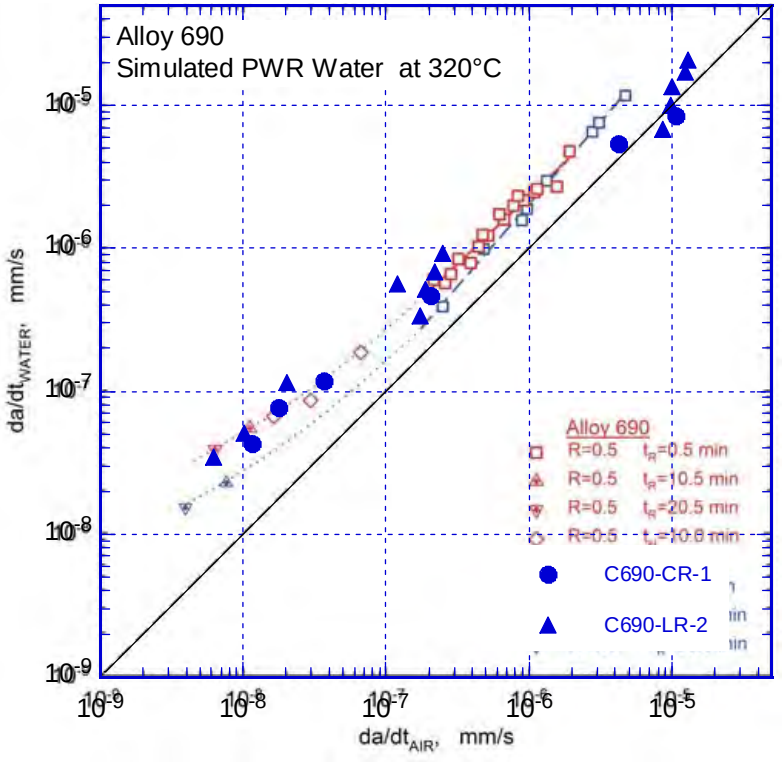
  - specimen designation: C690

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



Corrosion fatigue work by Bill Mills et al (Env Deg 2009)





- Excellent agreement between current ANL data (solid blue) and Bettis data (red) on time domain plots (left plot)