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CRACKING OF NEUTRON IRRADIATED AUSTENITIC STAINLESS STEELS IN LIGHT WATER REACTOR ENVIRONMENTS

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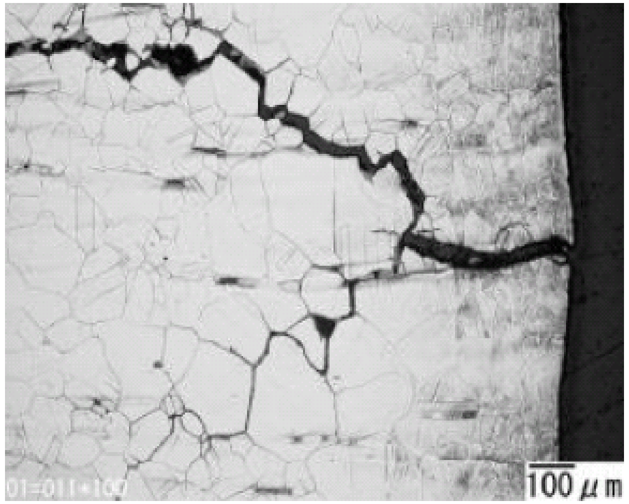
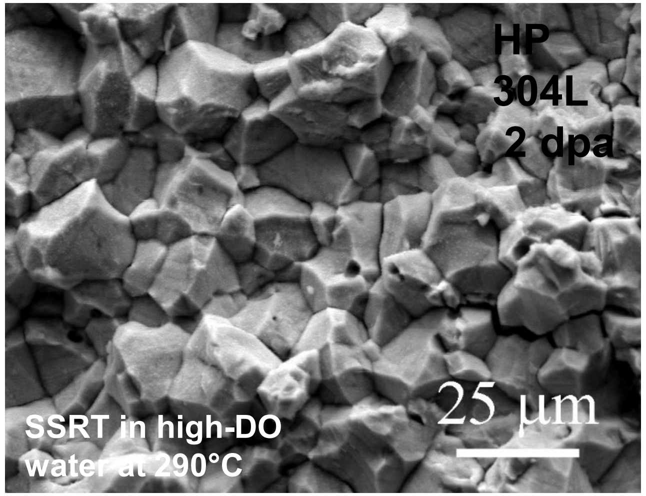
Oct 30th – Nov. 3rd, 2023

Irradiation-assisted stress corrosion cracking

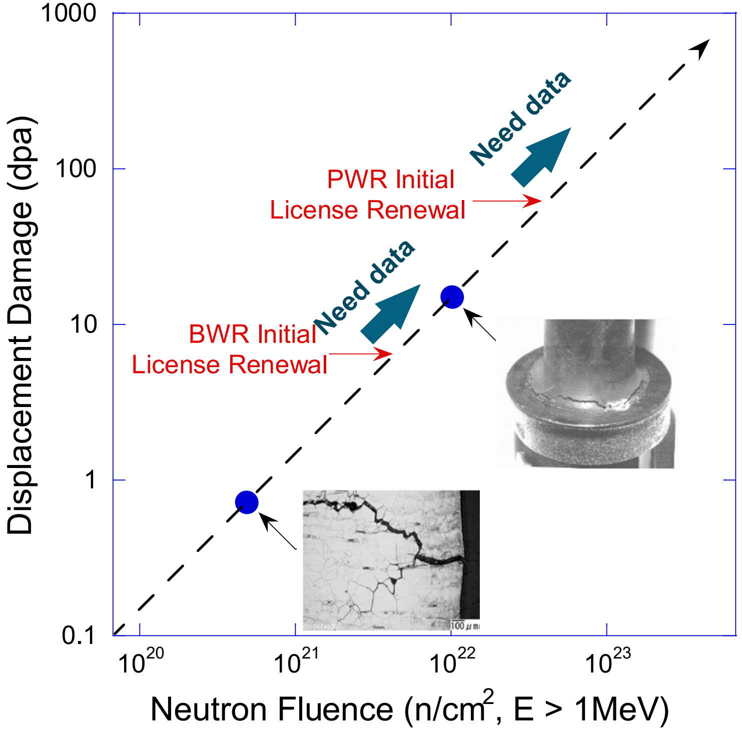
- Stress Corrosion Cracking (SCC) is a wide-spread issue for Light Water Reactors
  - Generic Aging Lessons Learned report (GALL, NUREG-1801, Rev. 1): ~ 40% items identified in the “Reactor Vessel, Internals, and Reactor Coolant System” involve SCC.
- Irradiation damage can elevate SCC susceptibility
  - SCC activated or accelerated by irradiation



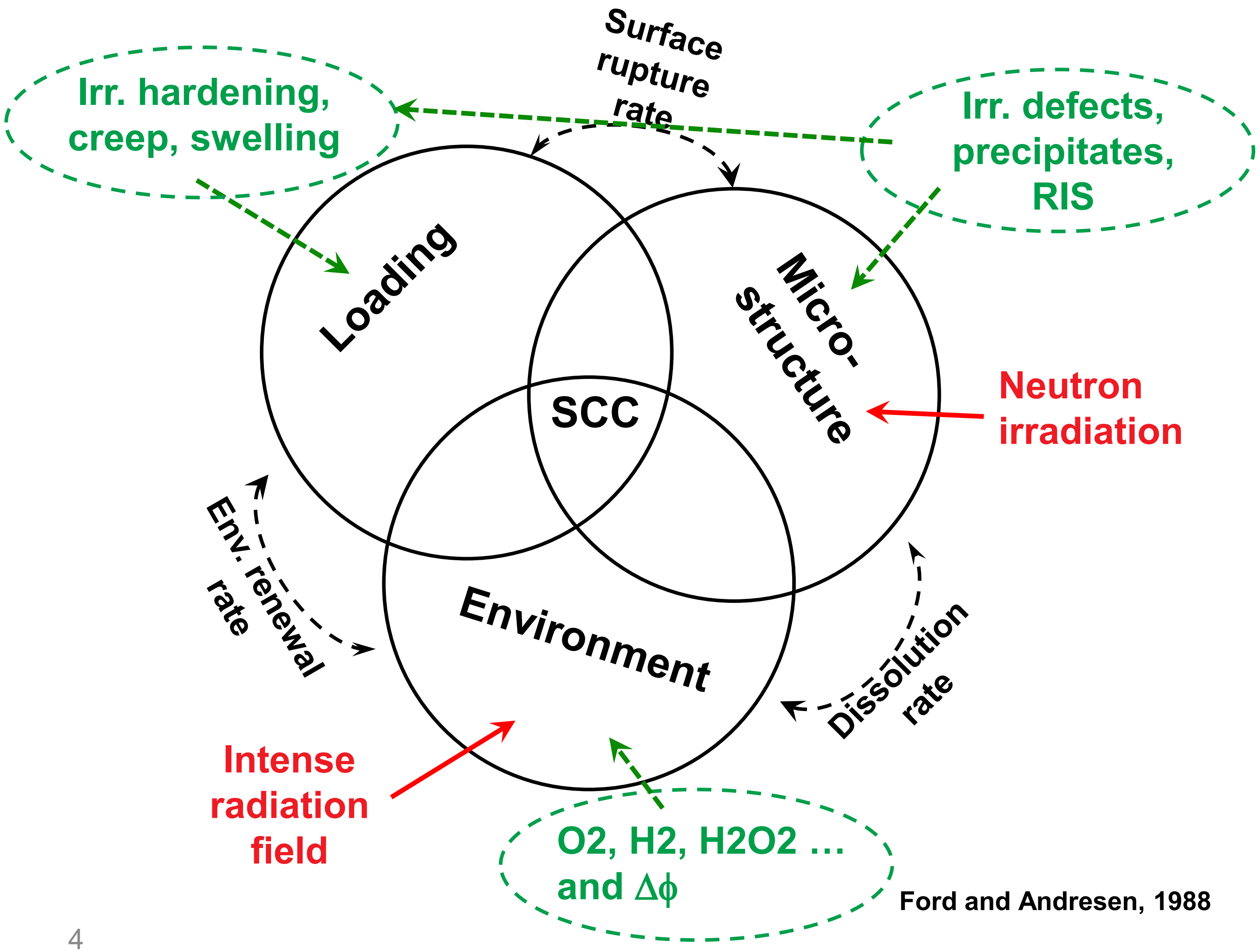
Cracking of core shroud in a BWR,
T. Shoji, 11th Env. Deg. Conf.



Chen et al., NUREG/CR-6965, 2008.



Complexity of IASCC stems from the interdependence of variables



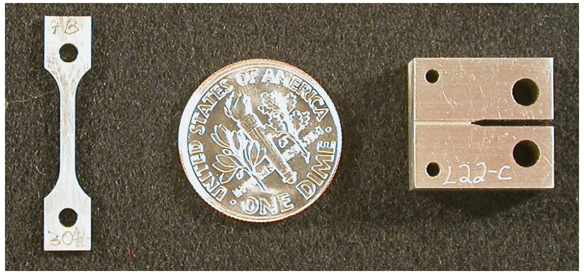
Ford and Andresen, 1988

Variables affecting IASCC

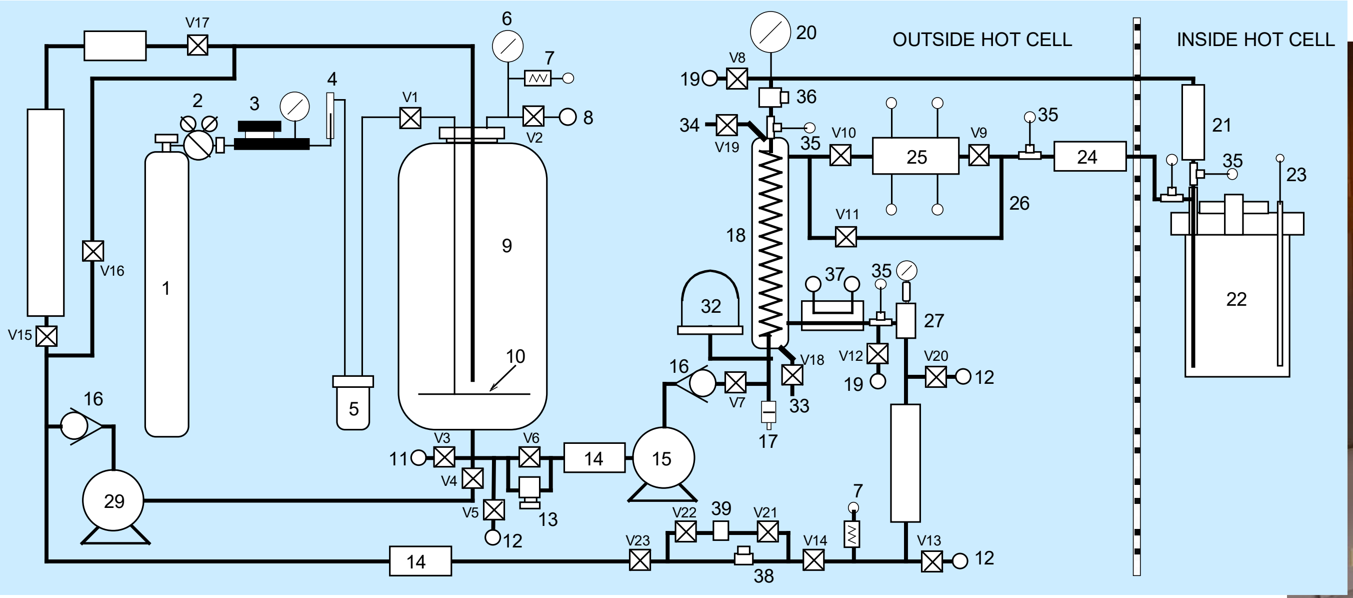
- Loading – K, dK/dt, dK/da …
- Environment – T, ECP, DO, flow rate, conductivity, pH …
- Microstructure – composition, GB characters, SFE, precipitation, heat treatment, YS …
- Irradiation – dose, $T_{irr,,}$ n or γ flux …

Test Facility and Specimens

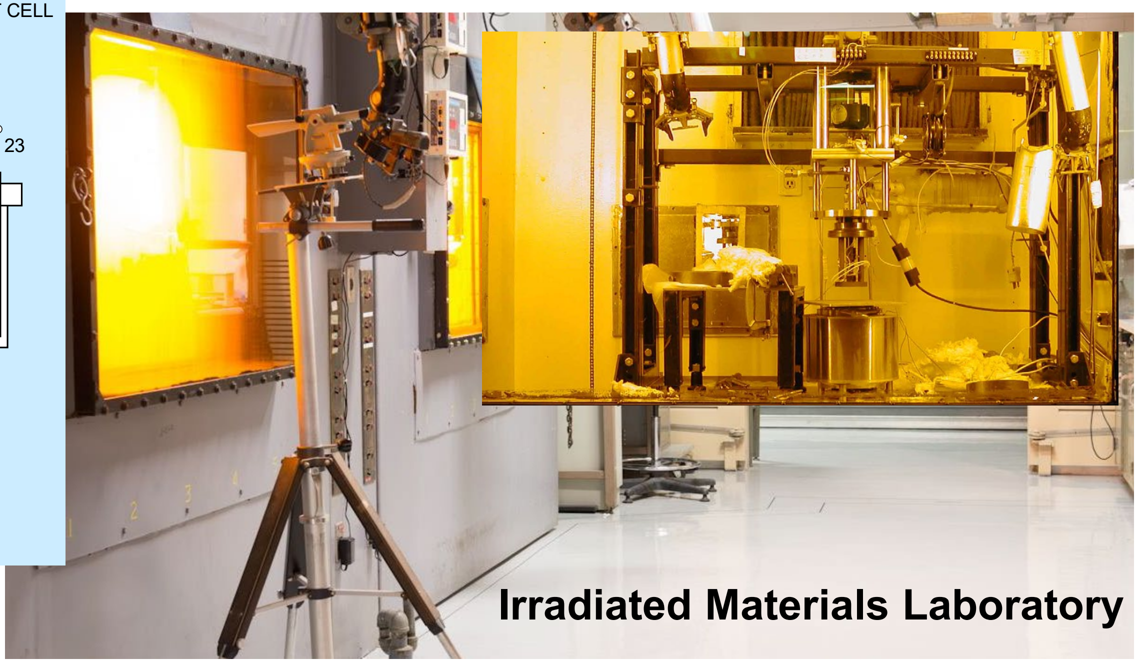
- Highly radioactive neutron-irradiated specimens – dose rates up to 20 R/hr at 30 cm.
- Tested with in-hot-cell servo-hydraulic systems equipped with recirculation loops for simulating BWR and PWR environments



- Materials were various of austenitic stainless steels in SA and CW conditions.
- SSRT samples were irradiated at BOR-60 up to ~40-50 dpa.
- CT samples were irradiated at Halden up to 3 dpa.
- Both irradiations were at LWR-relevant temperatures.

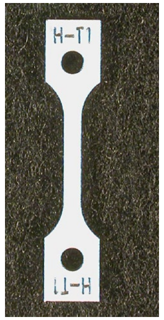


Water loop



Irradiated Materials Laboratory

Slow Strain Rate Tensile tests

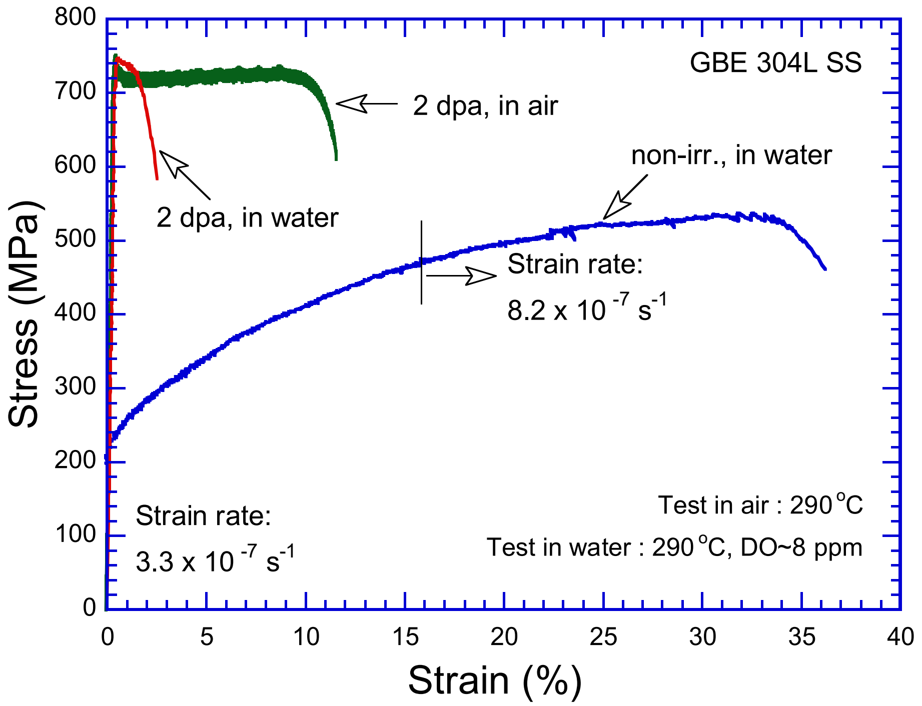


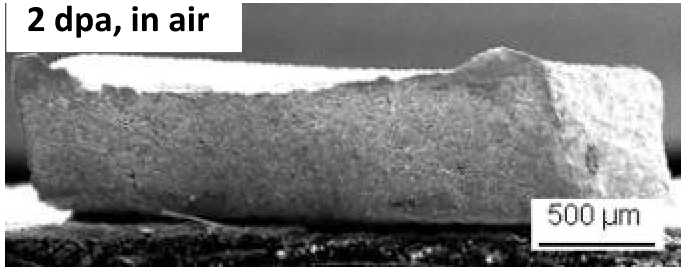
- Strain rate: *7.4 x 10^{-7} s^{-1}*
- Test Conditions:
  - *BWR* water

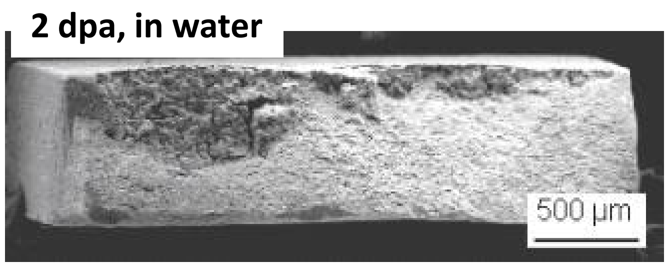
    Temperature: ≈ 290°C | *DO:* 8 ppm
    Pressure: 1400 psig | *Conductivity:* <0.1 μS/cm
    pH: 6.5 - 7 | *ECP:* 200 mV (ss)
    Flow rate: 10-20 ml /min

  - *PWR* water

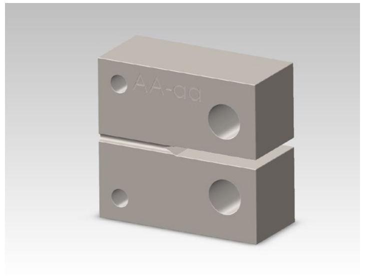
    Temperature: ≈ 315°C | *DO* ~ 10 ppb
    Pressure: 1800 psig | *Conductivity:* 20 μS/cm
    pH: 6.6 | *ECP:* - 650 mV
    Flow rate: 10-20 ml /min







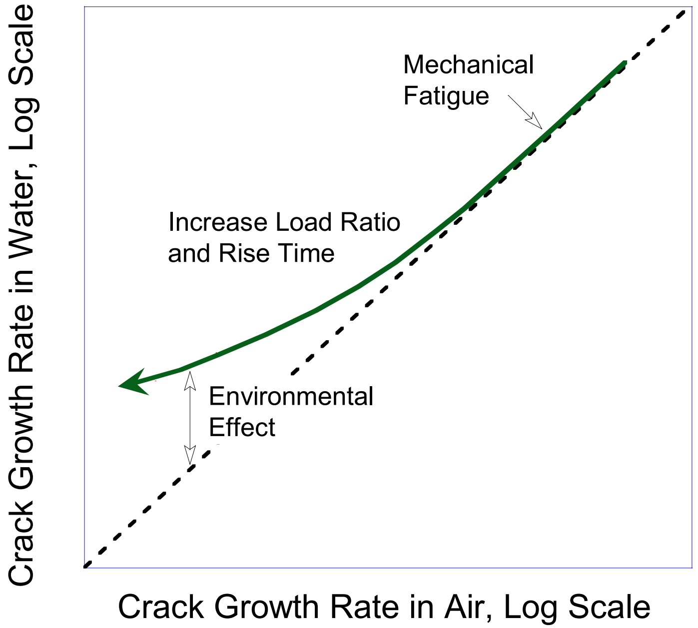
Crack Growth Rate tests



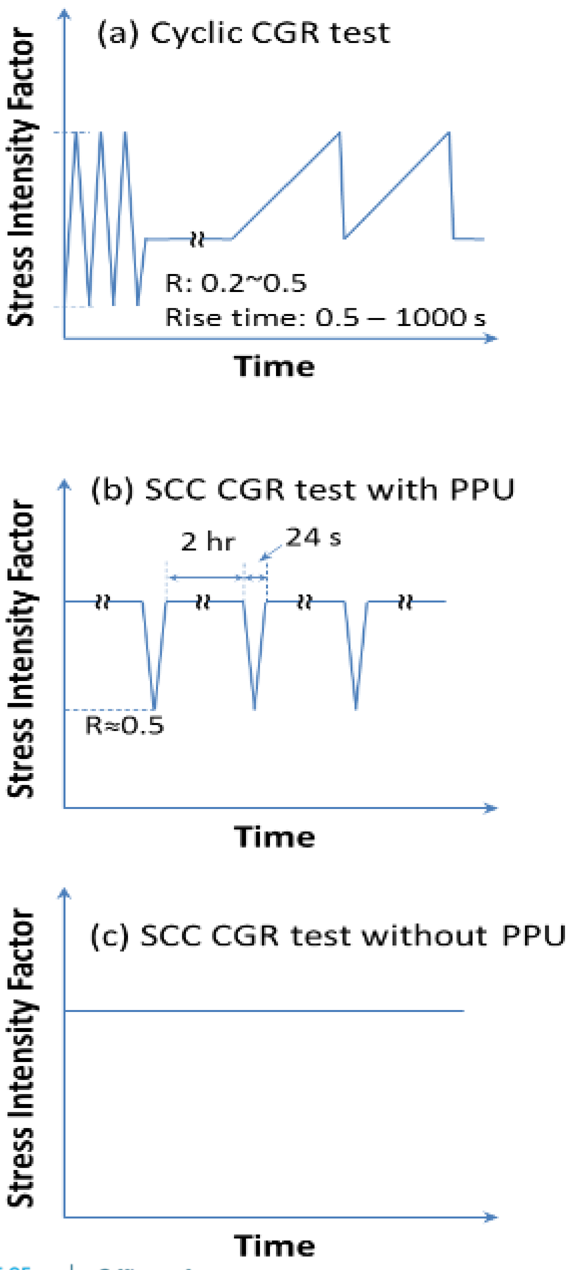
- Apply cyclic or static load while monitoring the crack propagation online with potential drop method.
- Pre-crack in test environments, and transition to a SCC test when environmental enhancement is observed.

$$CGR_{env} = CGR_{air} + CGR_{cf} + CGR_{scc}$$

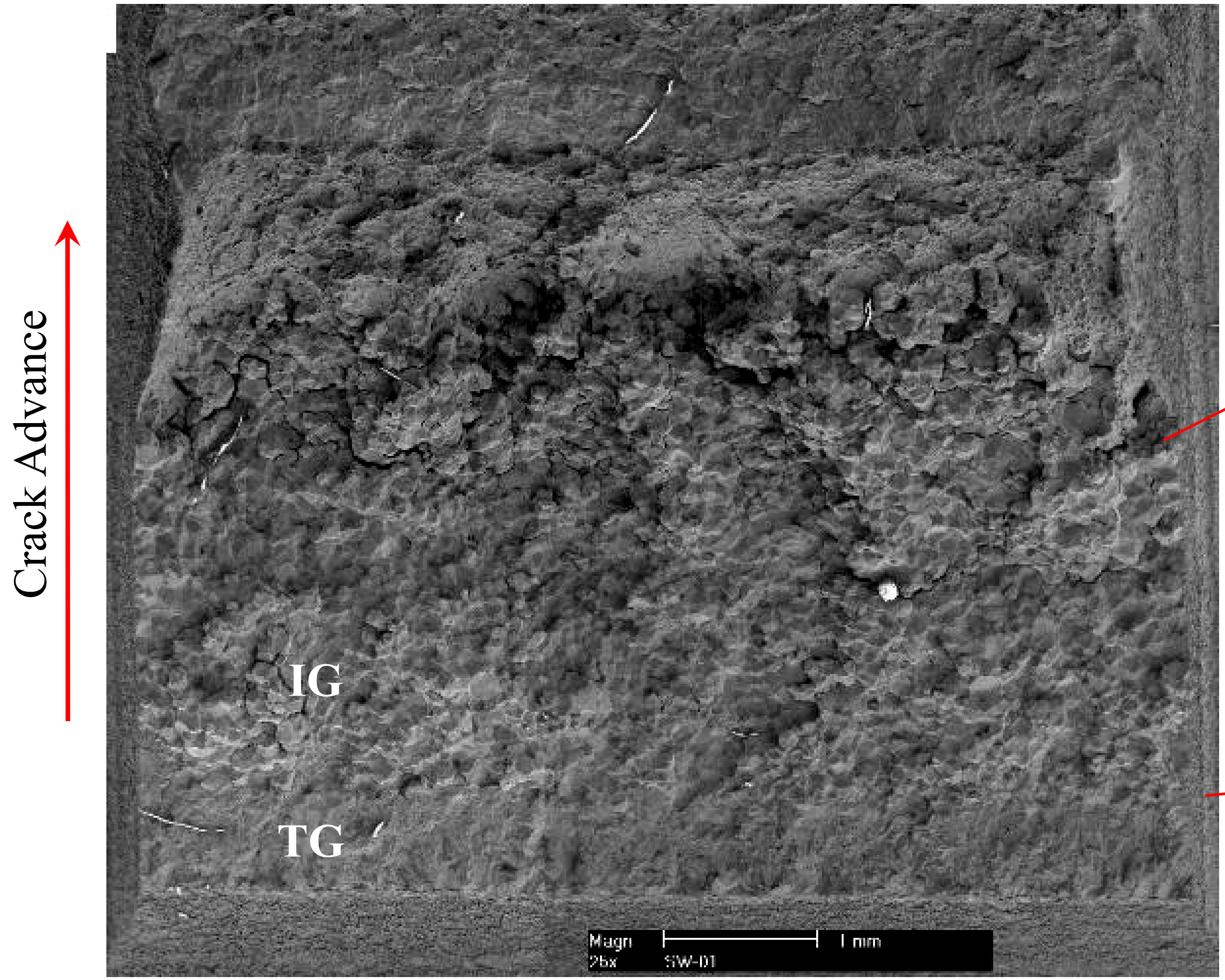
- **Fatigue precrack at R=0.2-0.3 at 1 Hz, K_{max}=10-15 MPa $m^{1/2}$**
- **Gradually increase load ratio up to 0.7**
- **Use slow/fast sawtooth waveform, and gradually increase rise time up to 1000s.**

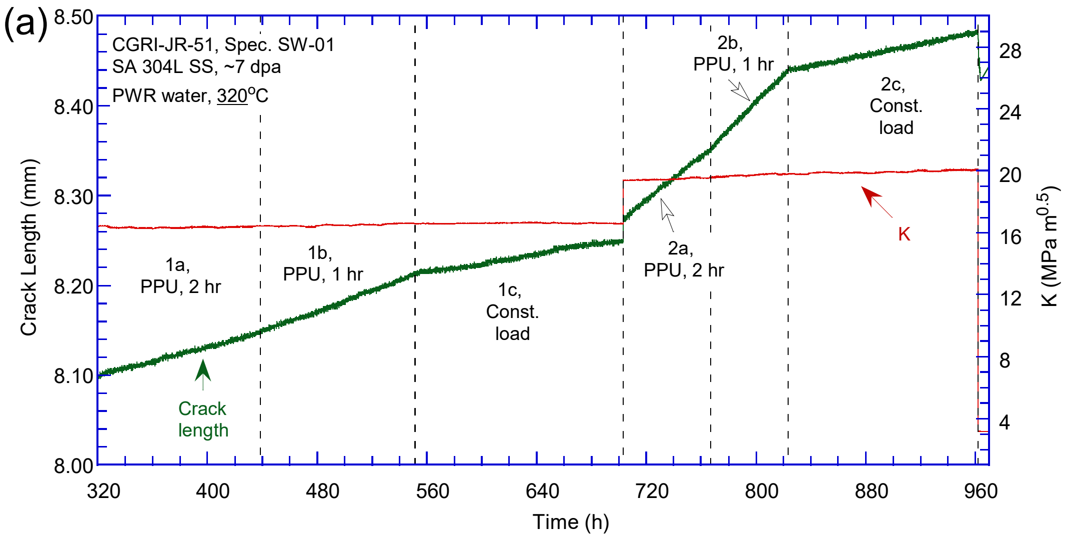


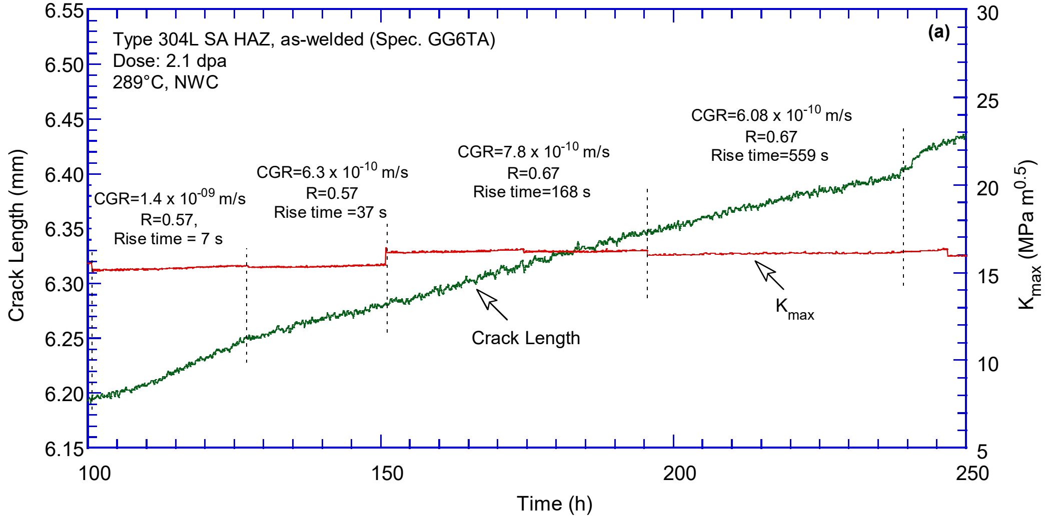
- Constant-K (by load shedding) with and w/o periodic partial unloading (PPU)



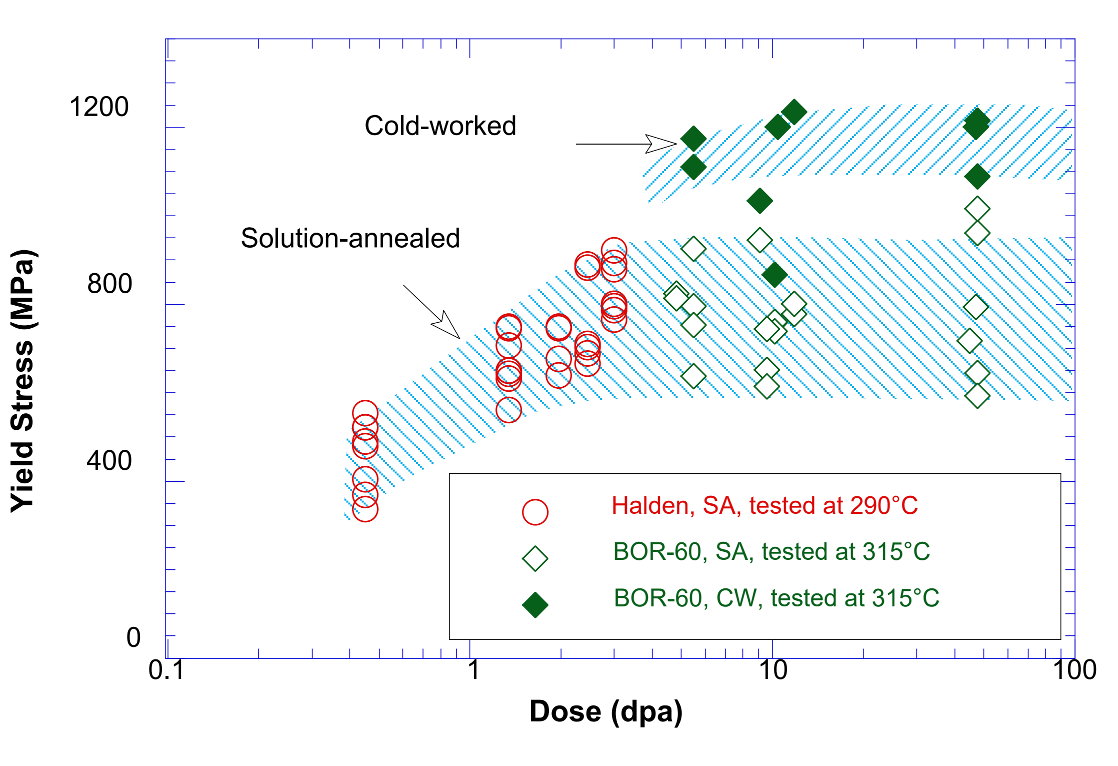
Crack Growth Rate (CGR) tests

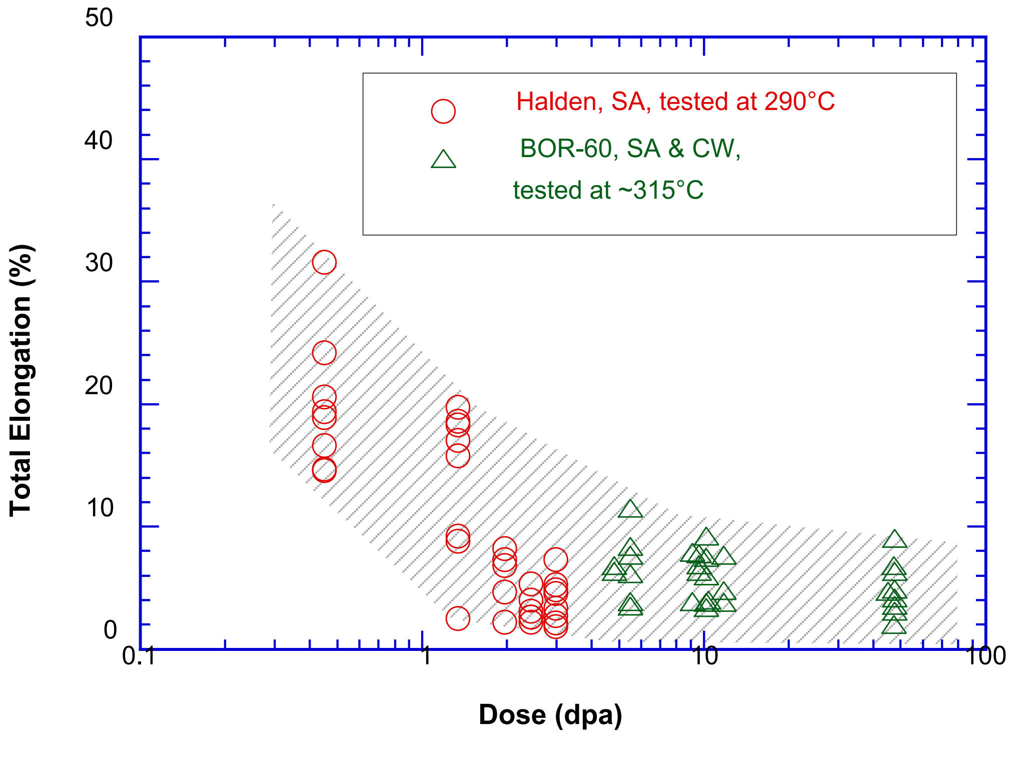






Slow Strain Rate Tensile Results



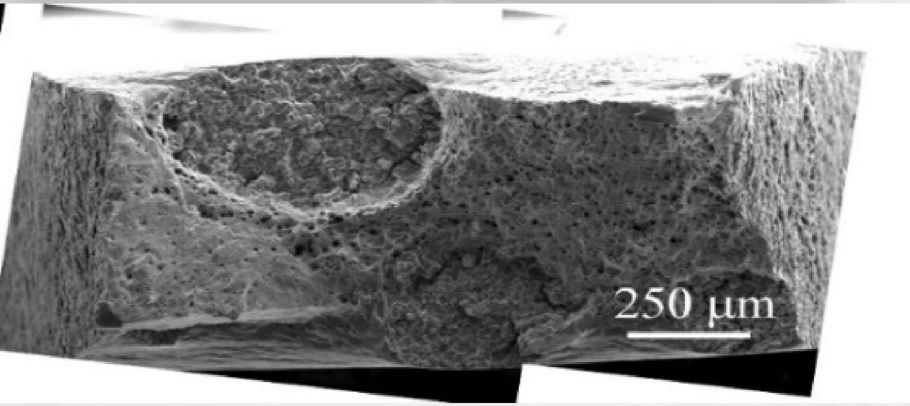


- **Yield strength increases, and total elongation decreases with dose. The saturation is between 3 and 10 dpa.**
- **Cold-worked samples have higher strengths.**

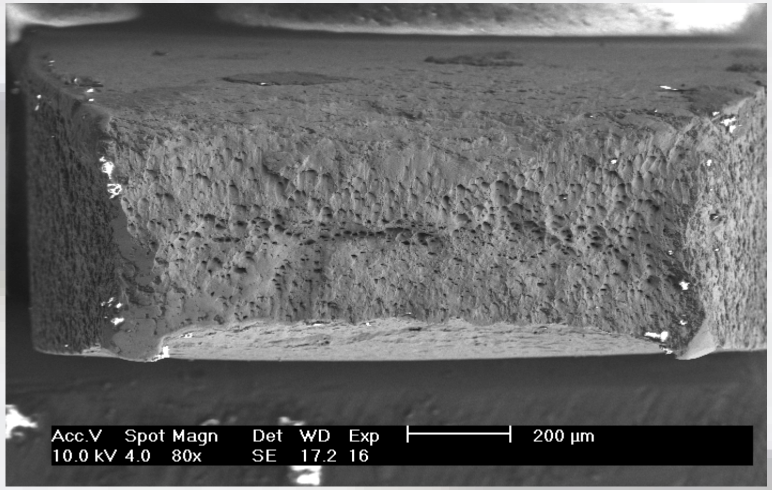
* Note the Halden samples were larger than the BOR-60 samples, making their results not directly comparable.

Slow Strain Rate Tensile Results

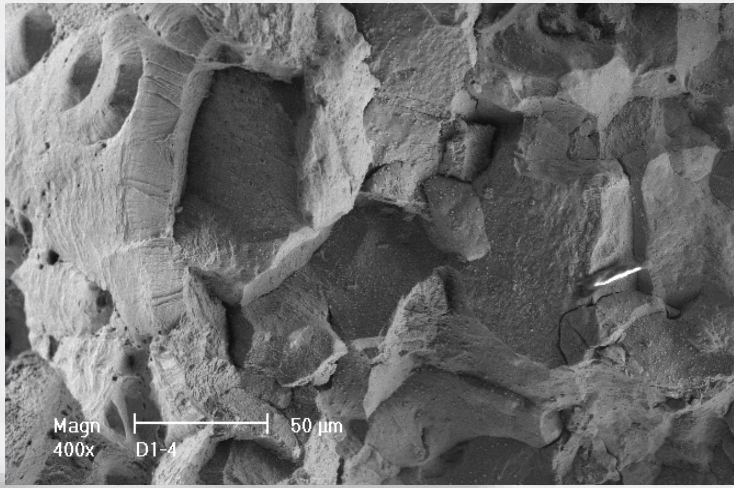
BWR NWC, 5 dpa



PWR, 10 dpa

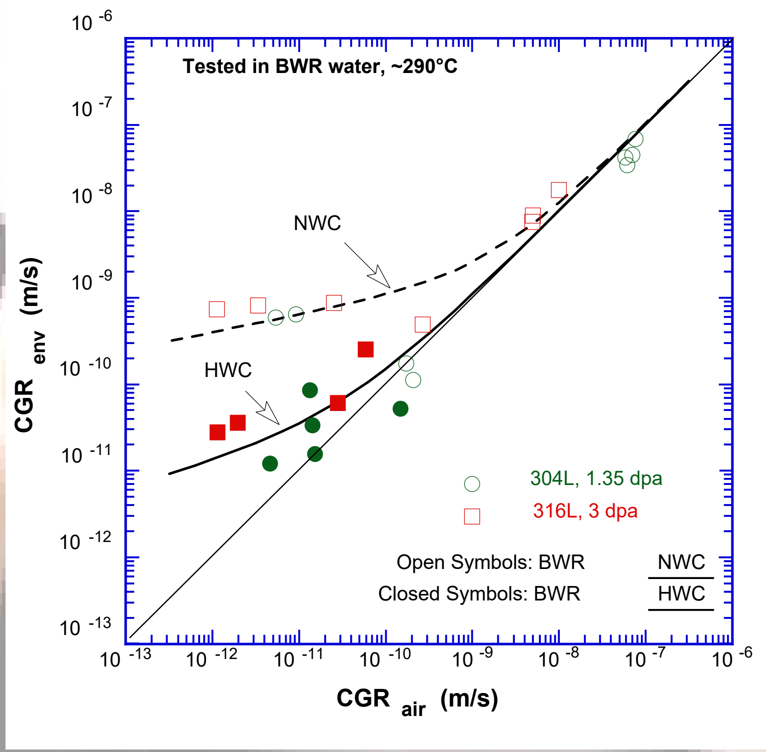


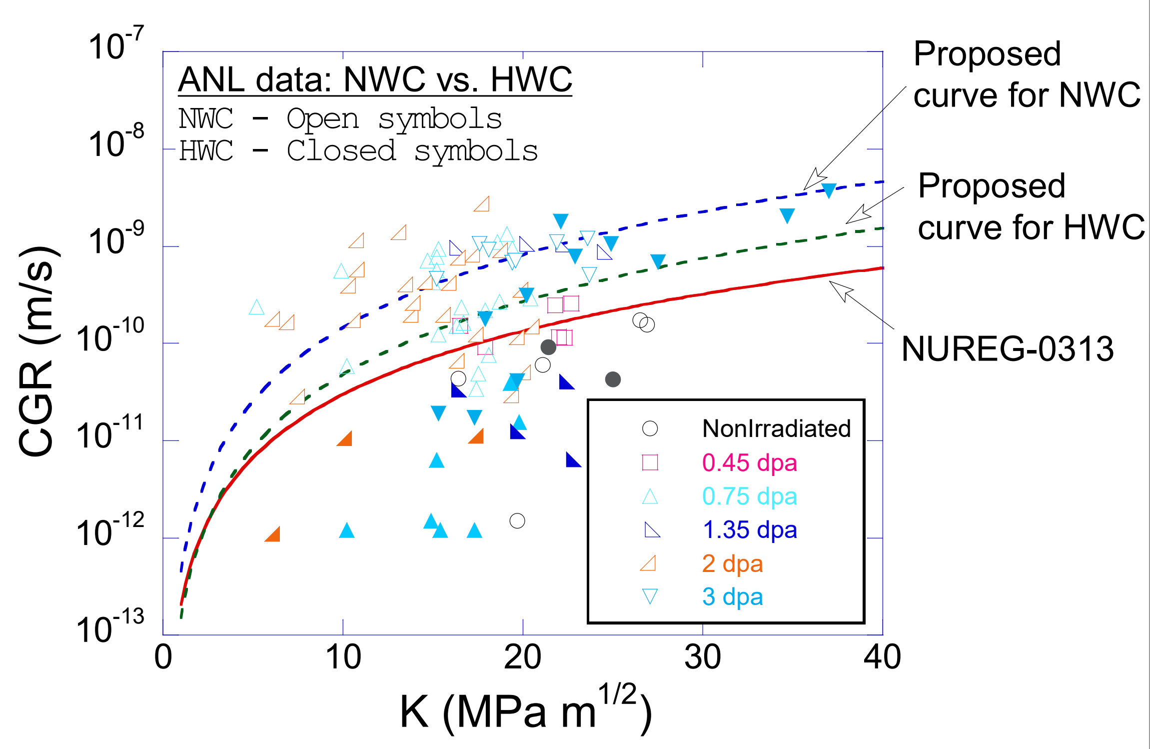
PWR, 47 dpa (SS347)



- In BWR NWC, extensive IG cracking can be observed, especially in samples with elevated oxygen and sulfur contents.
- In PWR, IG cracking is largely absent – attributing to the low corrosion potential of PWR environment.
- Low corrosion potential does not provide a complete immunity to SCC.

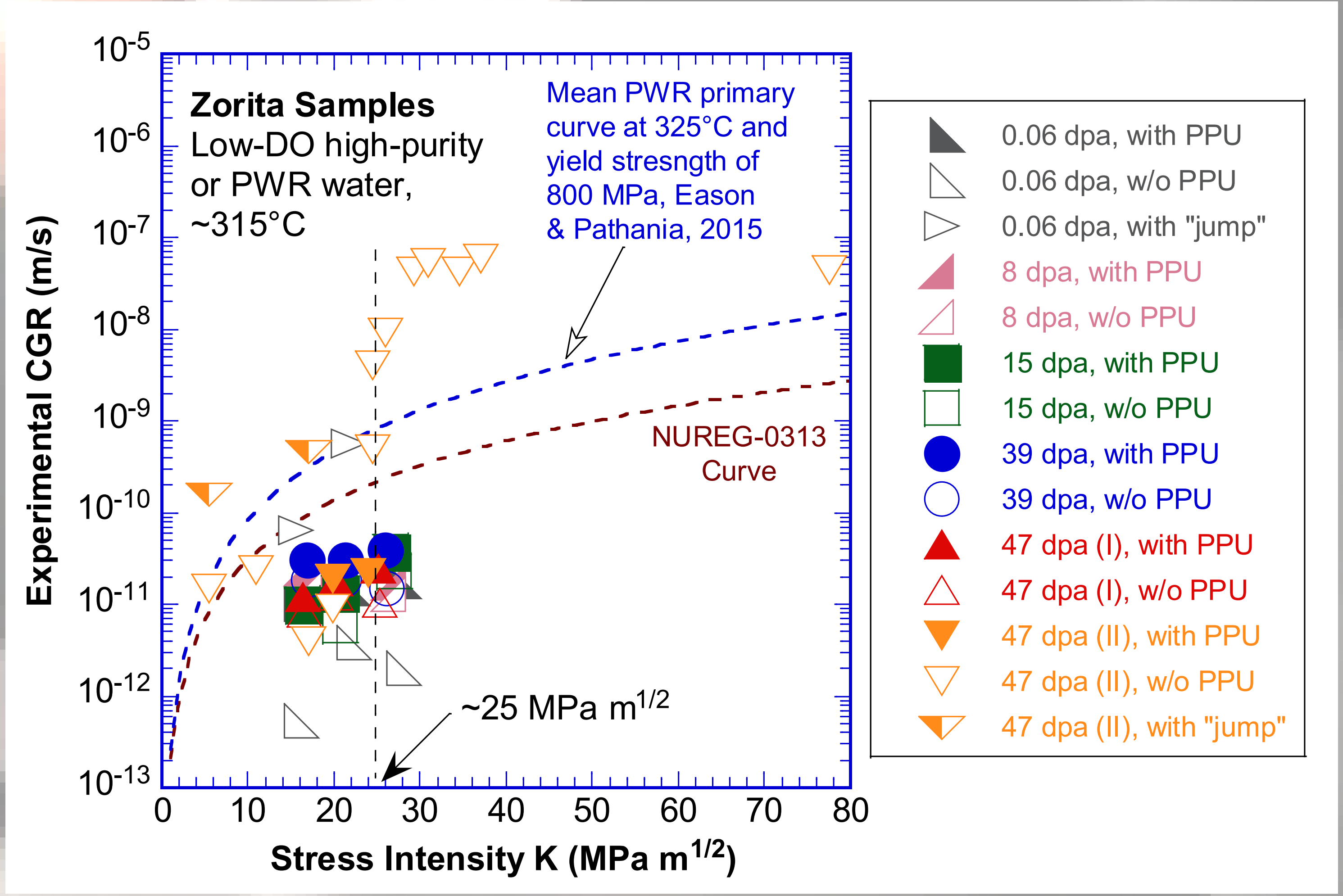
Crack Growth Rate Test Results





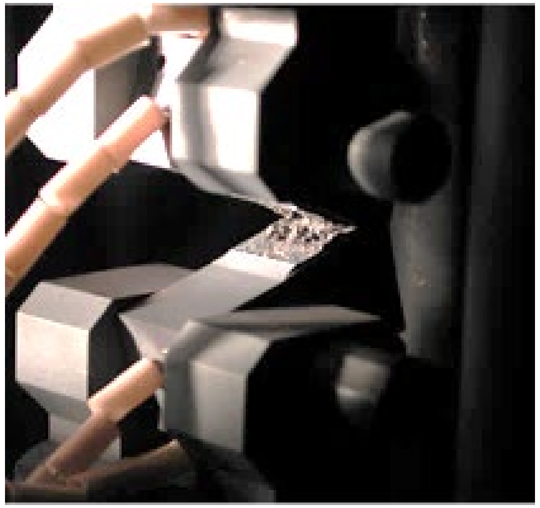
- Cyclic CGRs in NWC were much higher than that obtained in HWC, suggesting an effect of the low corrosion potential.
- A similar effect of HWC can also be seen in the SCC CGR results.
- However, the effect of HWC is uncertain for high Ks and relatively high doses.

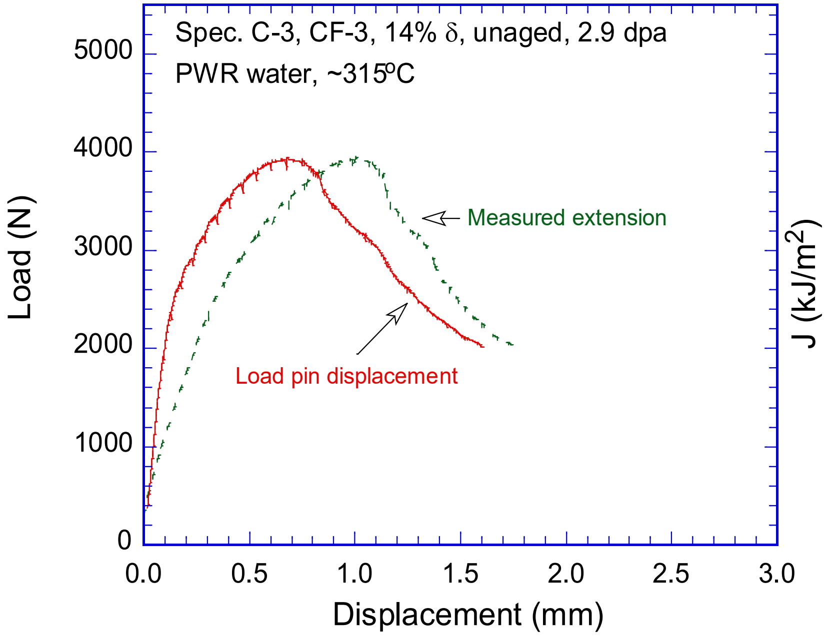
Very high CGRs in highly irradiated materials

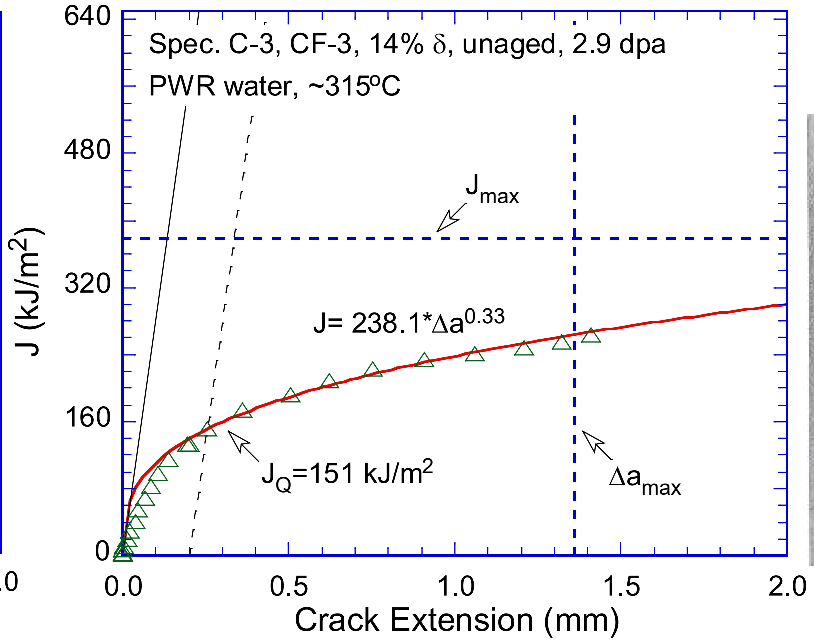


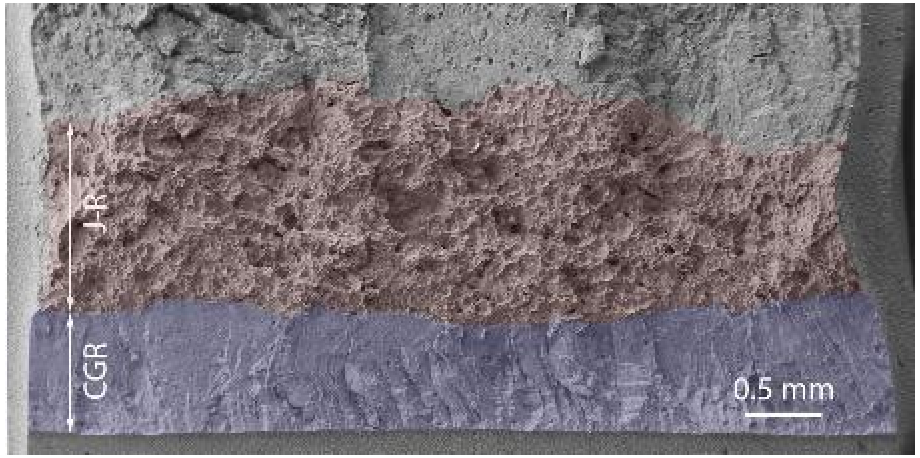
Fracture Toughness J-Resistance curve test

- Use a SCC starter crack
- Test in environment with a slow displacement rate (~0.43 μm/s)
- Monitor the crack length using potential drop method
- Use a blunting line of J/4σf in the J-R analysis

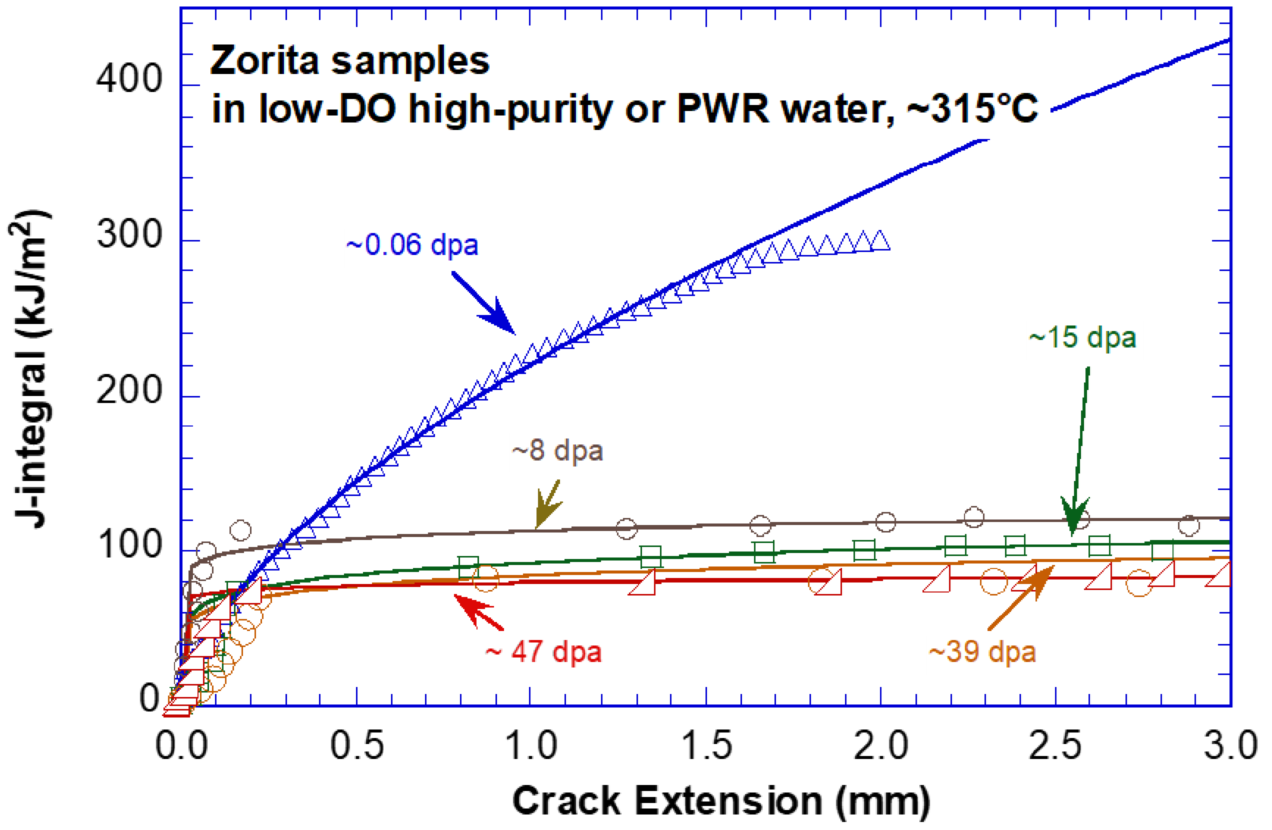








Specimens with high CGRs also show embrittlement.



The cracking mechanisms in SCC crack growth and J-R curve tests could be related and have a same mechanistic origin.

Summary

- **SSRT tests showed a strong effect of low DO on IASCC**
  - Extensive IG cracking during SSRT tests in BWR NWC, and much less brittle fracture morphology in PWR water -- a beneficial effect of low-DO environment in suppressing IASCC.
  - Low-DO did not eliminate IASCC completely, and some IG cracking were indeed observed in highly irradiated samples tested in PWR water.
- **Similar effect of low-DO environment in CGR tests**
  - Under cyclic loading, the extent of environmental enhancement was lower in BWR HWC or PWR than in BWR NWC.
  - Under constant load, SCC CGRs were much lower in BWR HWC and PWR water than in BWR NWC.
  - The beneficial effect of low DO environment diminished at high Ks and high doses -- indicating a connection between irradiation embrittlement and IASCC susceptibility.

Acknowledgments:
Loren Knoblich and Ed Listwan are acknowledged for their contributions to the experimental work.
This work is sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, under Agreement Enterprise-Wide NRC-HQ-25-14-D-003, Task Order Number NRC-HQ-60-17-T-002.

Thank you

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