Irradiation Assisted Stress Corrosion Cracking

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Outline

- IASCC Mechanisms
- NRC Research Activities
- Effect of Hydrogen Water Chemistry on IASCC CGR
- Testing of Grain Boundary Engineered Specimens
- Radiation Induced Segregation
- HAZ Testing
- Summary
- Gaps in Understanding of IASCC
- Future Work

IASCC Mechanisms

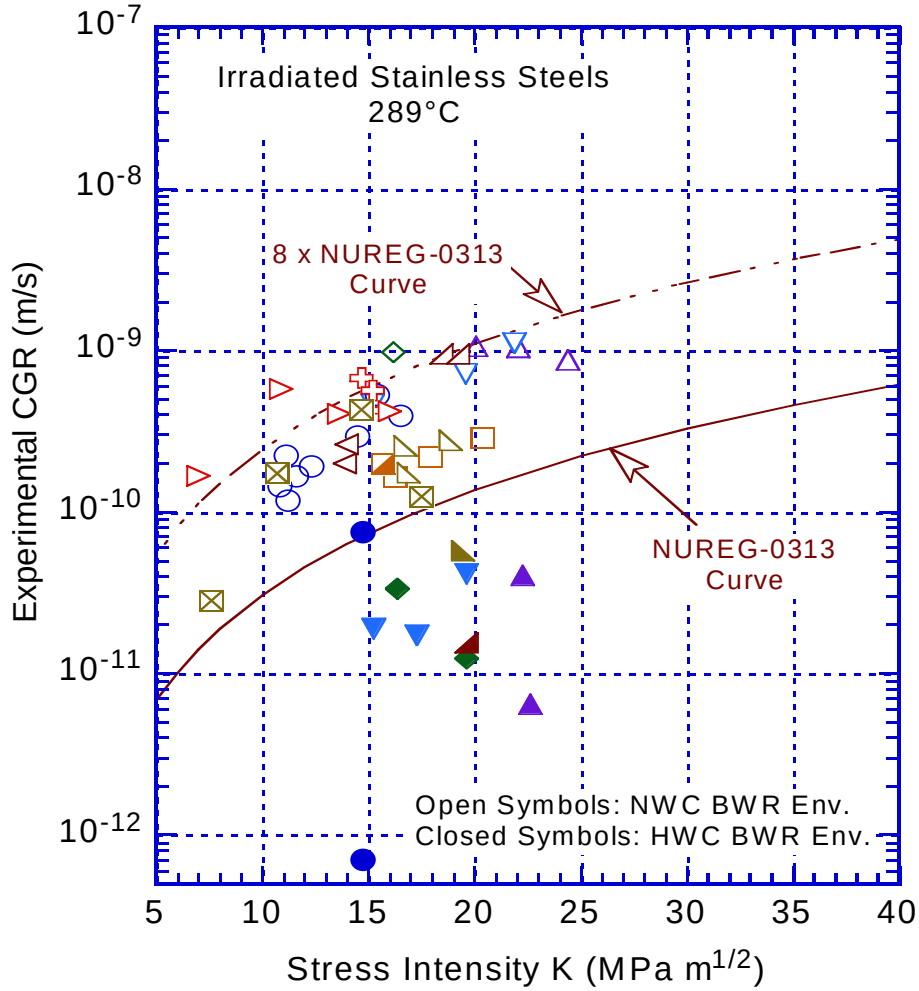
Theories suggested to explain detrimental effect of irradiation on SCC can be classified into 5 categories:

- Solutes depletion or enrichment at grain boundaries caused by radiation-induced segregation (RIS).
- Hardening and loss of ductility due to irradiation defects.
- Localized plastic flow due to cleared dislocation channels.
- Void swelling, Irradiation creep
- Corrosion potential change due to radiolysis (in-situ effect)

NRC Research

- NRC IASCC research focused on the following areas
  - Evaluate effectiveness of SCC mitigations
    - *Hydrogen Water Chemistry*
    - *Grain Boundary Engineering*
  - Evaluate CGR models for BWRs and PWRs
  - Evaluate the causes, mechanisms and effects of EAC on BWR internals
  - Effect of welding, thermal processes, and cold work on crack growth rates
  - Review and evaluation of EAC in vessel internal components and emerging aging degradation issues
  - Radiation embrittlement at relevant to PWR conditions
  - Radiation and thermal embrittlement of cast austenitic stainless steels

Hydrogen Water Chemistry



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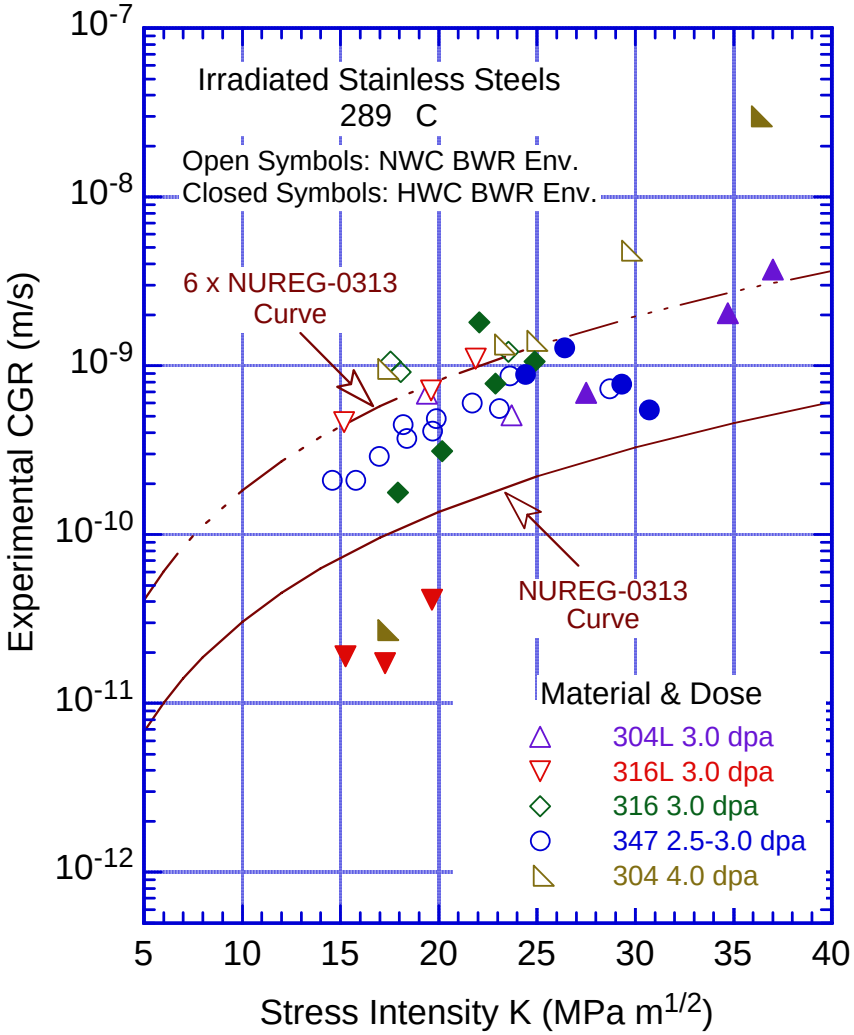
Material & Dose

- 304L 1.35 dpa
- 316L 1.35 dpa
- 316 1.35 dpa
- 316NG 1.4-2.0 dpa
- 304 Sensitized 0.75 dpa
- 304 sensitized 2.16 dpa
- 304L SAW HAZ 0.75 dpa
- 304L SAW HAZ 2.16 dpa
- 304 SMAW HAZ 0.75 dpa
- 304 SMAW HAZ 2.16 dpa
- 304 SMAW HAZ TT 0.75 dpa
- CF-8M Aged 2.46 dpa
- 304L 1.35 dpa
- 316L 1.35 dpa
- 316 1.36 dpa
- 304 SMAW HAZ 0.75 dpa
- 304 SMAW HAZ TT 0.75 dpa
- 316NG 1.4-2.0 dpa

Hydrogen Water Chemistry



- K/size criterion:
  B_{eff} and $(W - a) \geq 2.5\ (K/\sigma_{eff})^2$
- σ_{eff} was suggested to take:
  - $(\sigma_{irr} + \sigma_{nonirr})/2$ - by P. Andresen
  - $(\sigma_{irr} + \sigma_{nonirr})/3$ - by A. Jenssen
- Those high CGRs in HWC are questionable
- Need to resolve the apparent diminishing benefit of HWC at high values of K

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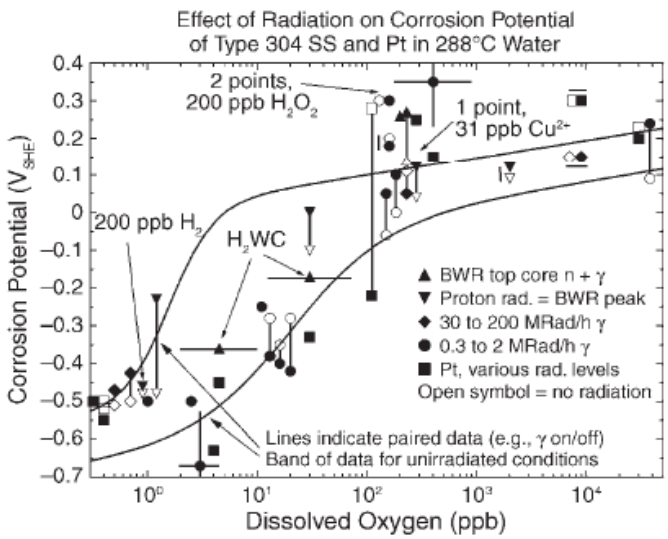
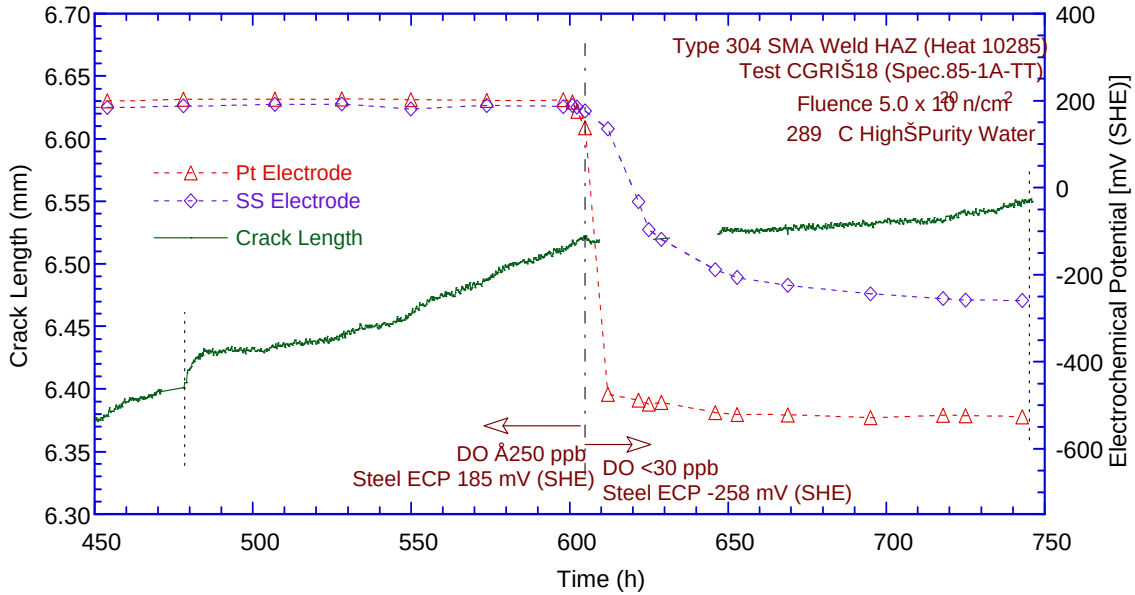
Corrosion Potential



Andresen et al., 1994



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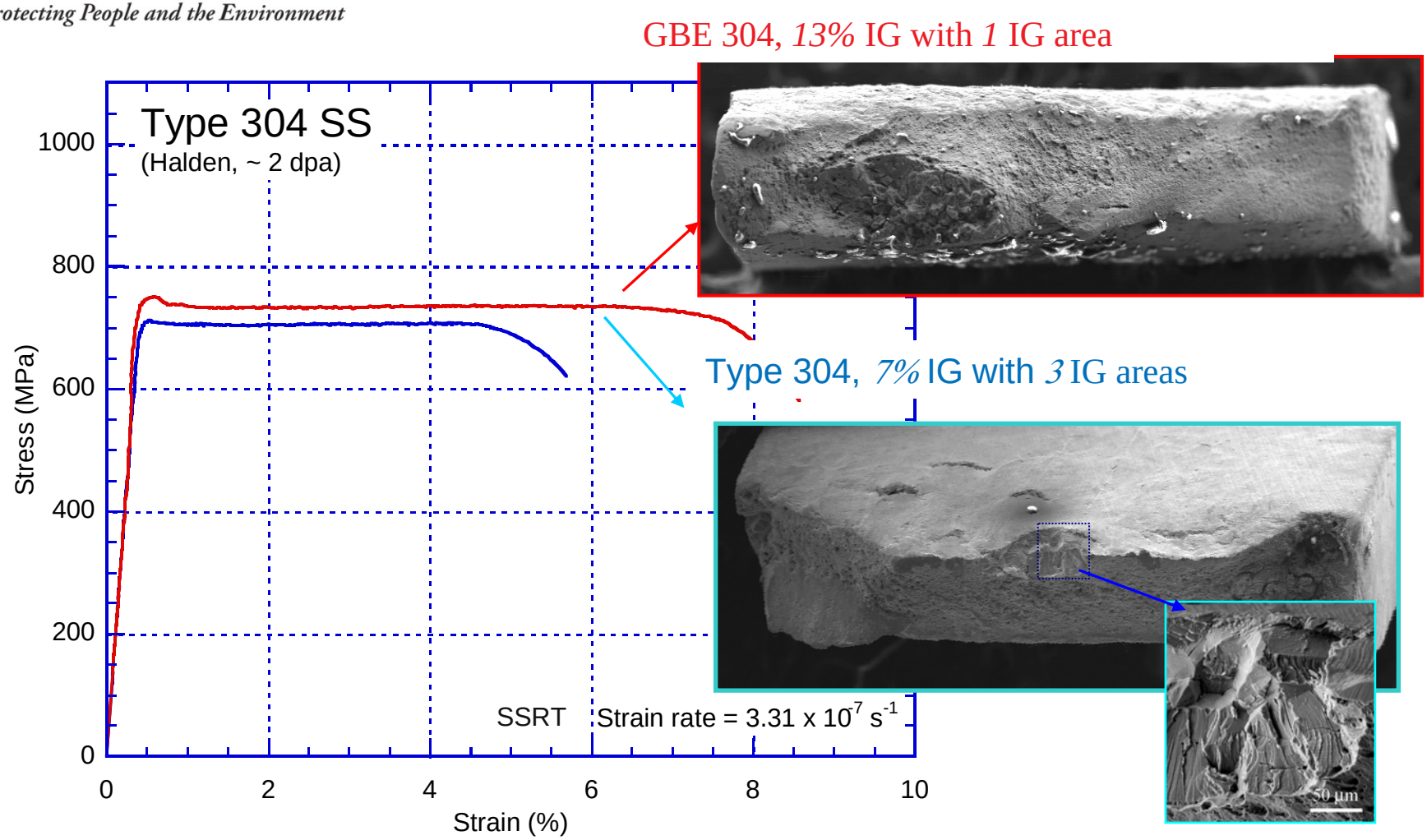
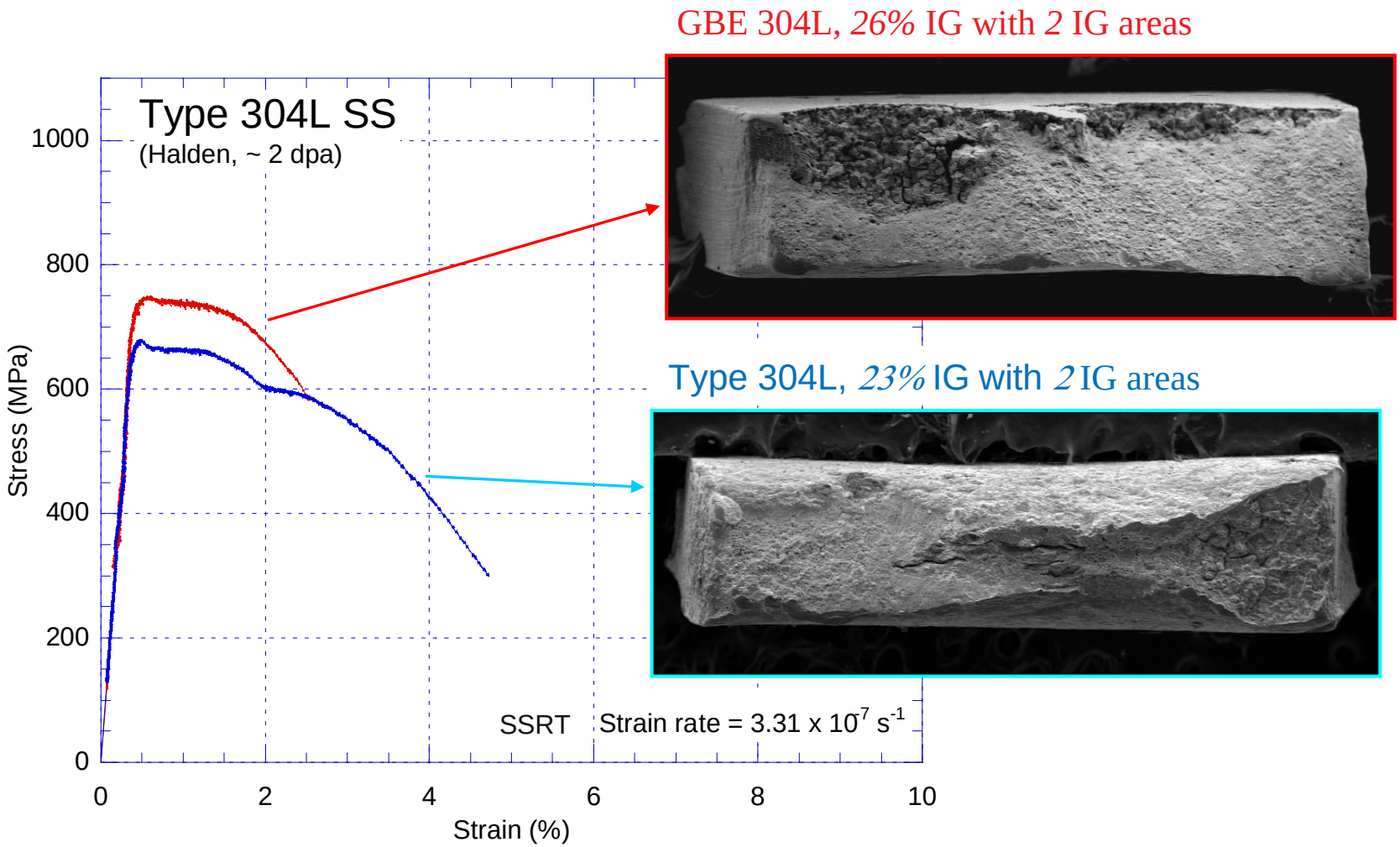
- $H_2O \rightarrow O_2, H_2O_2, HO_2, e_{aq}^-, H, OH, H_2$
- Concentration is proportional to $(flux)^{1/2}$
- Elevated corrosion potential, especially for intermediate DO level

GBE Results Type 304 SS



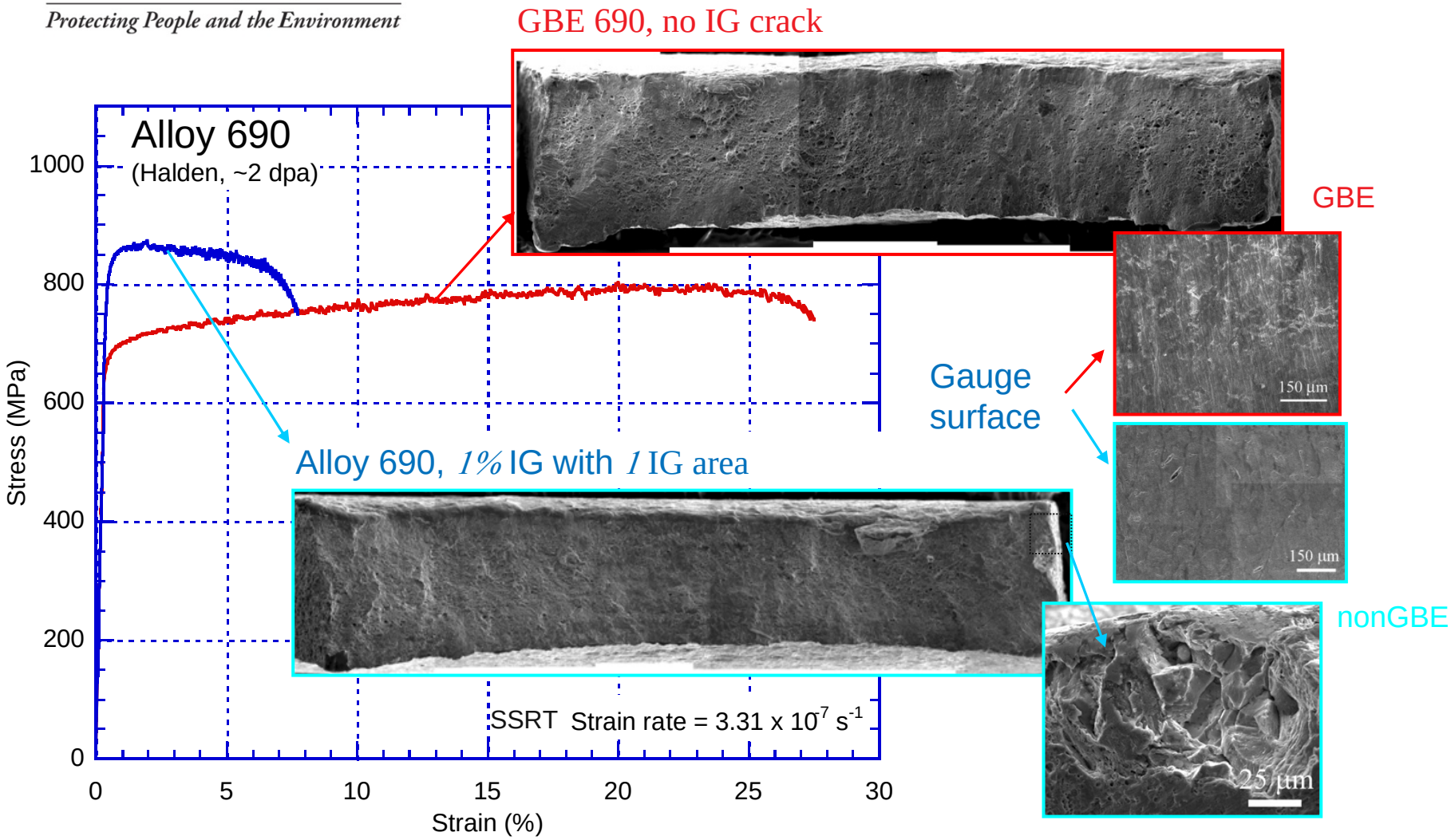
- IG area fraction is slightly higher in GBE 304, but there is more IG areas in nonGBE 304.
- TG cracking is more severe in nonGBE 304.

GBE Results Type 304L SS



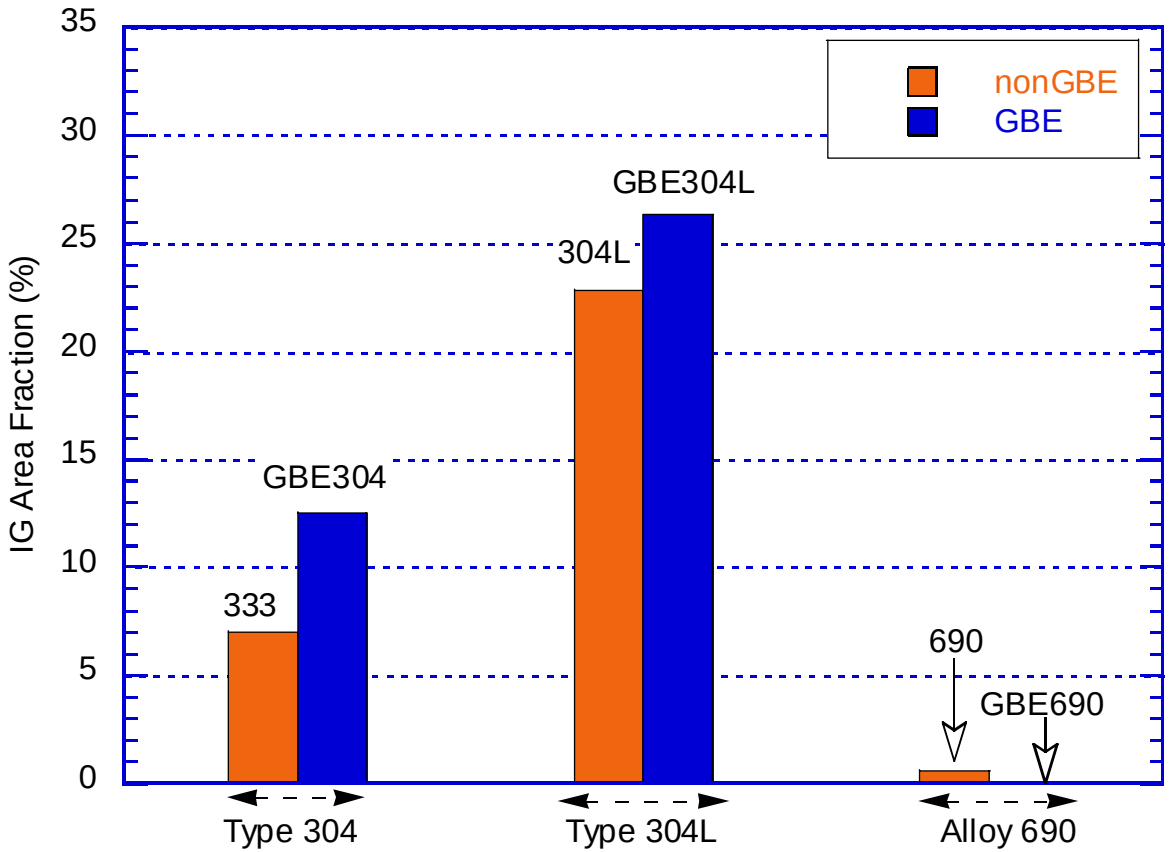
- IG area fraction is higher in GBE 304L, number of IG areas is the same in both materials.
- TG cracking is observed along the centerline of the nonGBE 304 specimen.

GBE Results Alloy 690



- GBE 690 shows a larger elongation and retains considerable amount of strain hardening.
- No IG crack in GBE 690, while a small IG area is found in the nonGBE 690.

GBE Results Summary



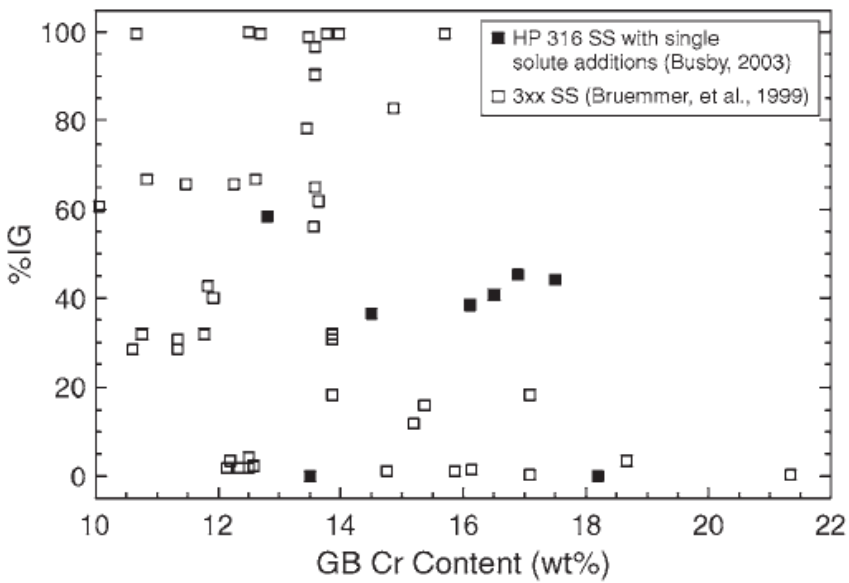
GBE CSL (Σ≤29) fractions

	nonGBE	GBE *
Type 304	58	67
Type 304L	64	66
Alloy 690		71

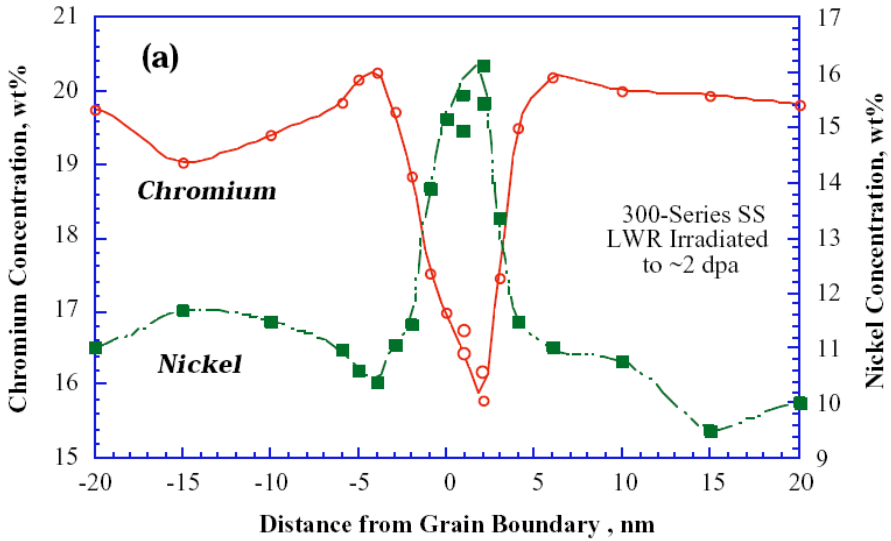
* Provided by vendor

- With about ~65% CSL fraction (Σ≤29), GBE treatment does not appear to improve IG crack in Type 304 or 304L SSs
- With about ~70% CSL fraction (Σ≤29), GBE treatment seems to suppress IG cracking and increase elongation in Alloy 690 at ≈2 dpa

Radiation Induced Segregation - Chromium



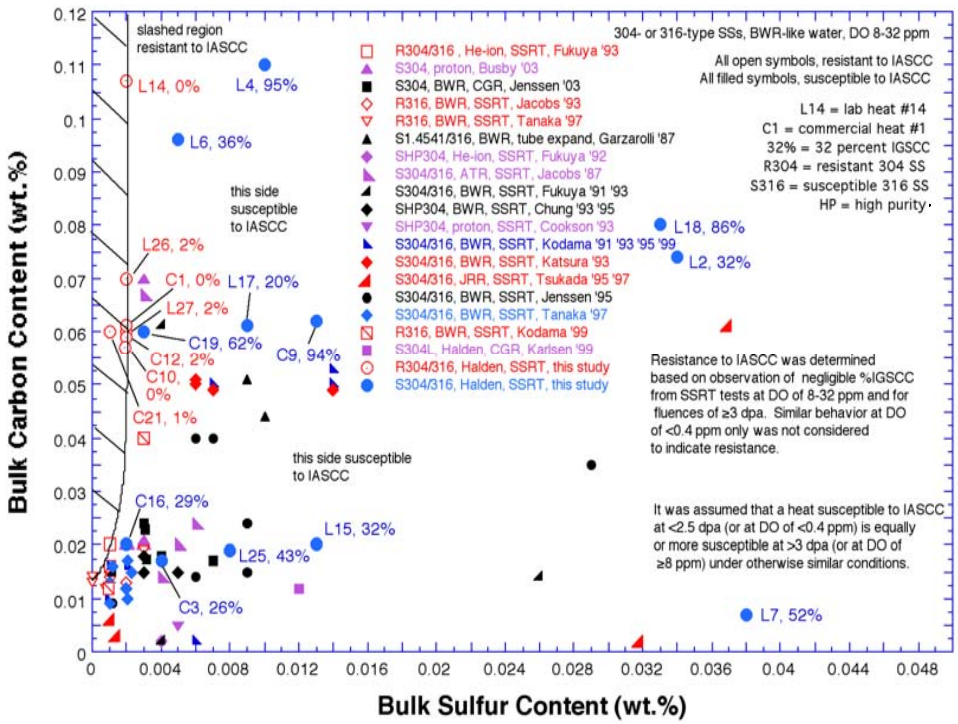
Was, 2007



Bruemmer, 1996

- Cr depletion is similar in both sensitized and irradiated SSs and, by analogy, RIS is suggested to play an important role in IASCC.
- Some experimental results seem suggest a less important role of Cr depletion

Radiation Induced Segregation - Carbon and Sulfur



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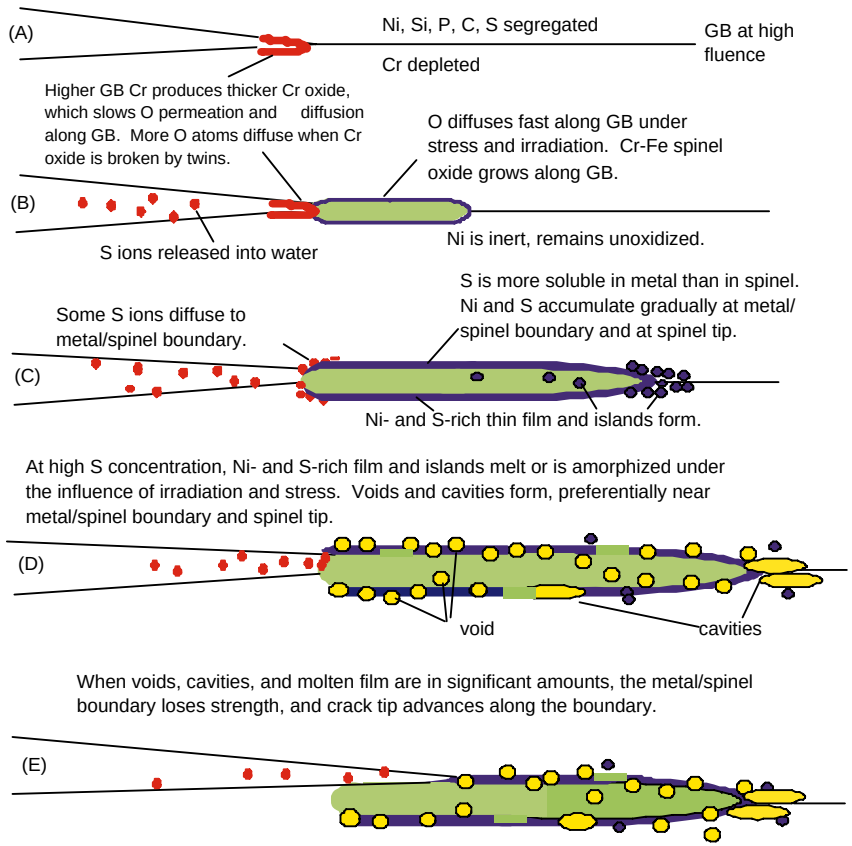
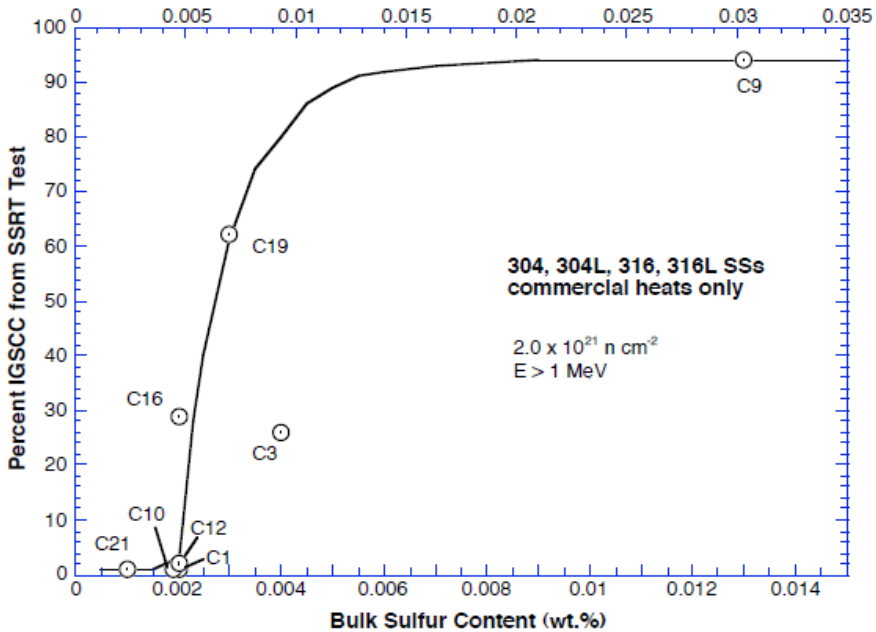


(F) When S-rich Ni film and islands are amorphized or melt, Ni-S polyhedral cage is destroyed, S is freed from the cage and diffuses back into metal matrix. Altered distribution of S is observed when the tip is examined after discharge or test.

Radiation Induced Segregation - Carbon and Sulfur



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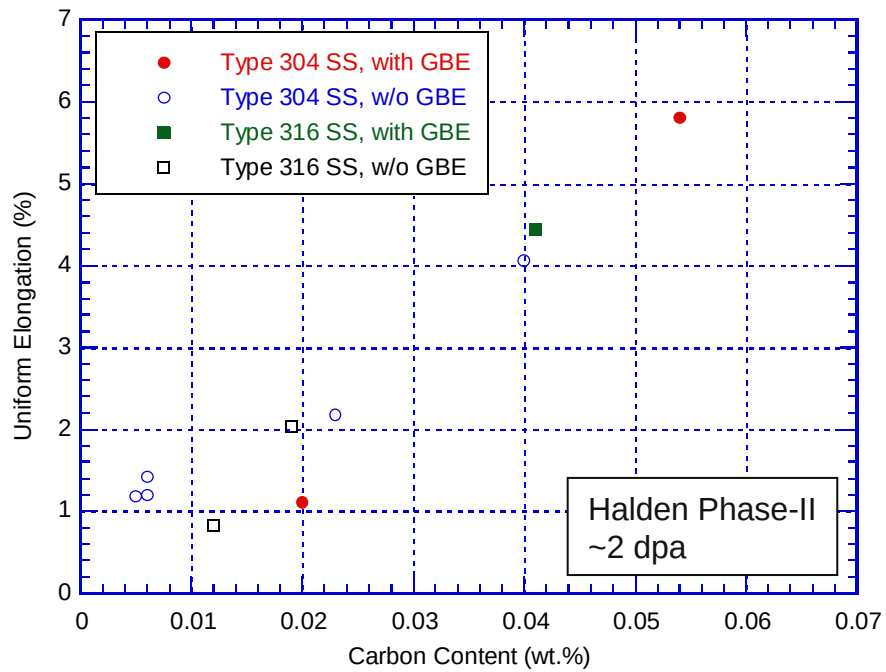

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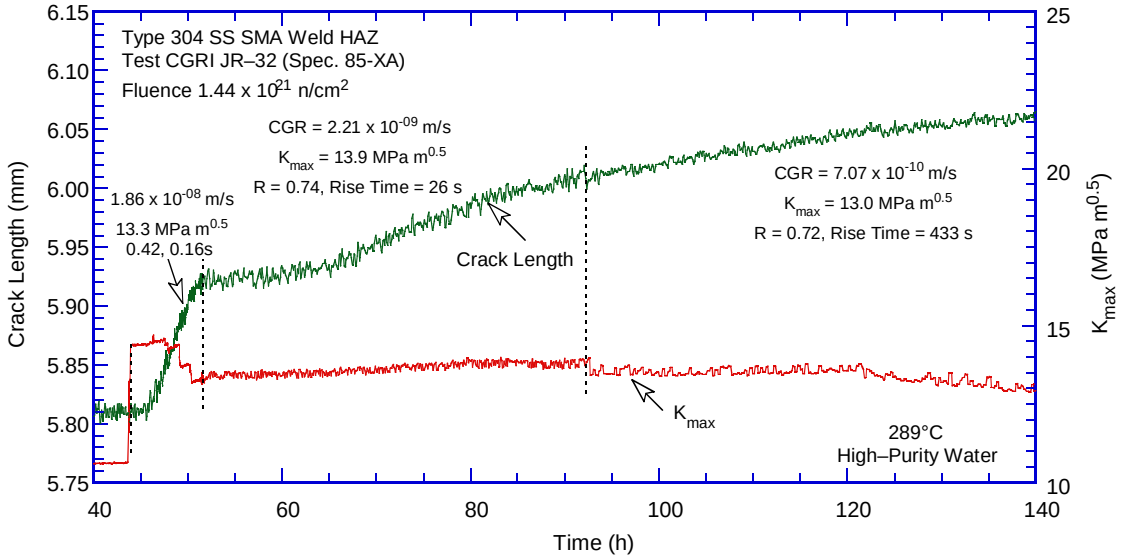
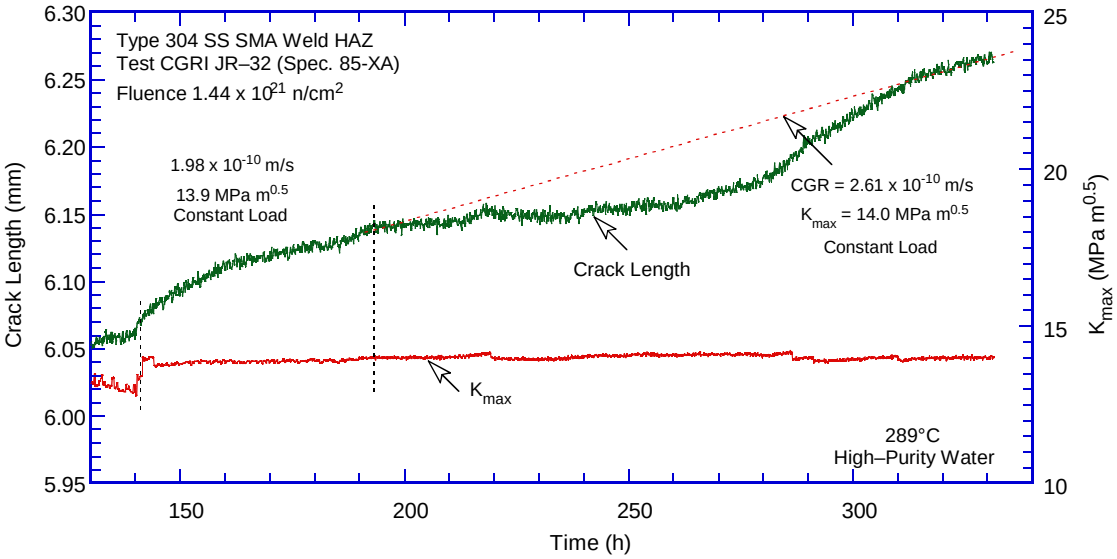
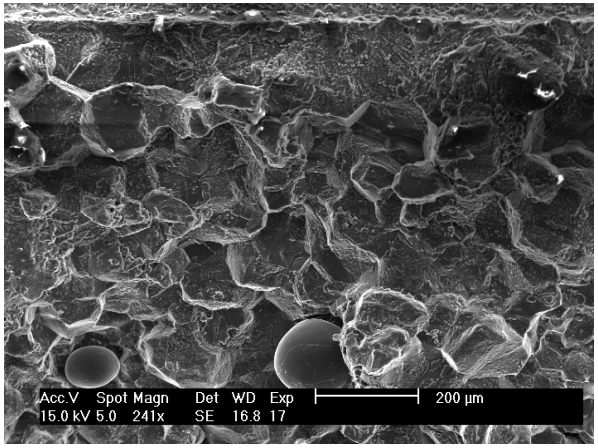
- Small concentrations of Sulfur (within compositional specification) shown to be detrimental
- Beneficial effect of Carbon

HAZ Crack Growth Rate Testing

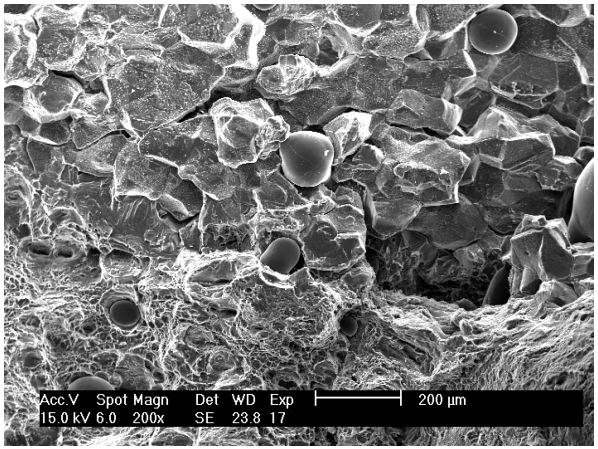




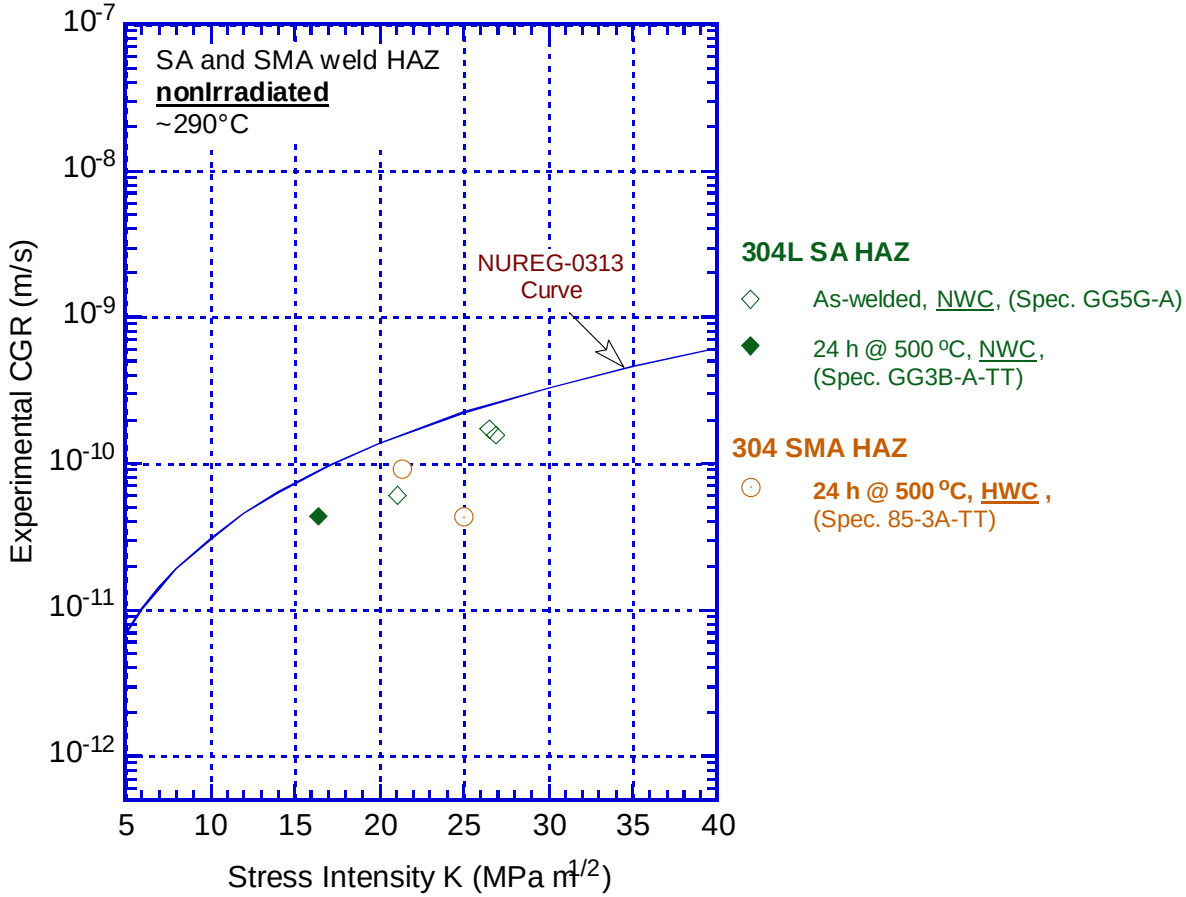
304 SMA HAZ, 2 dpa



Crack advance direction

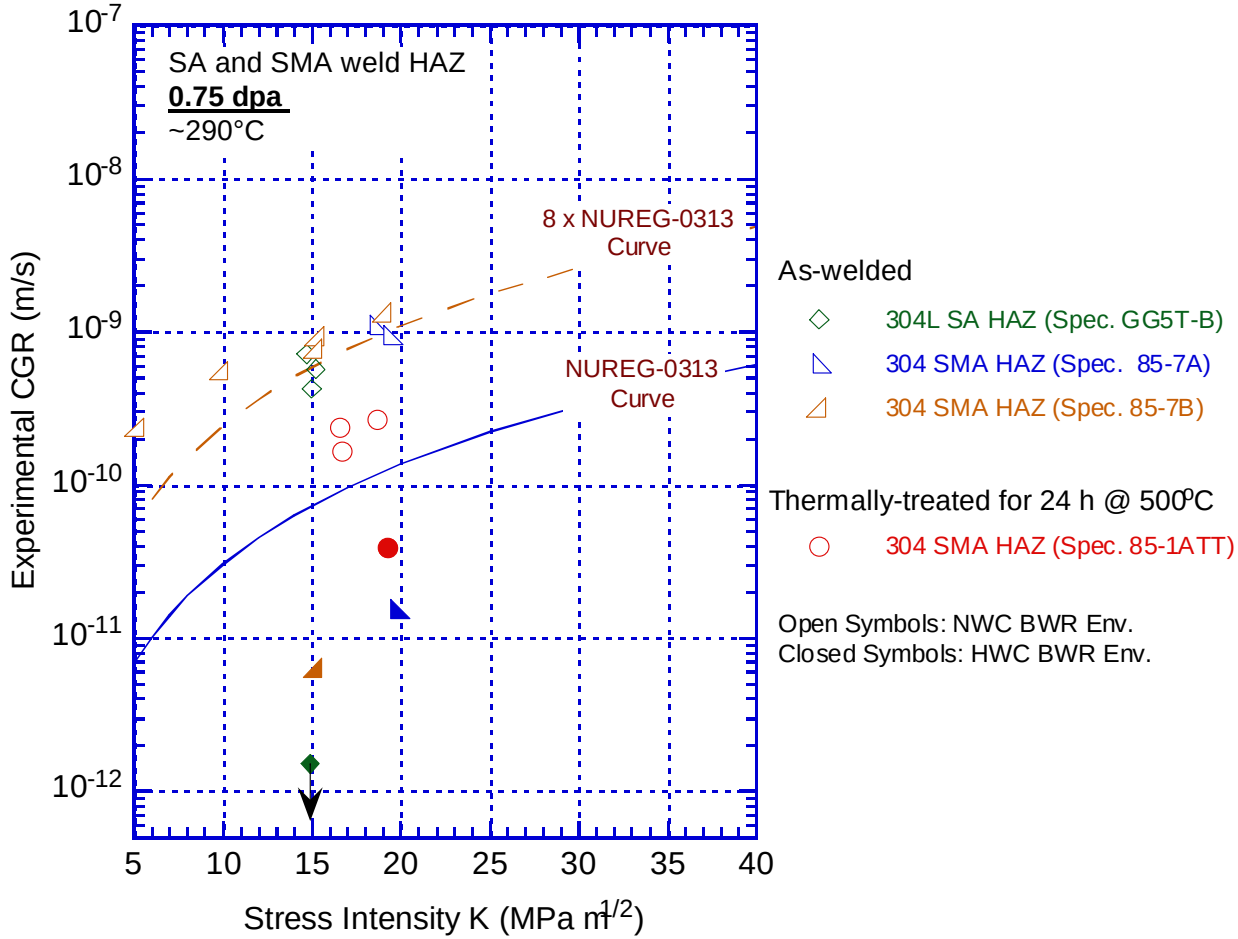


Non-Irradiated HAZ Specimens



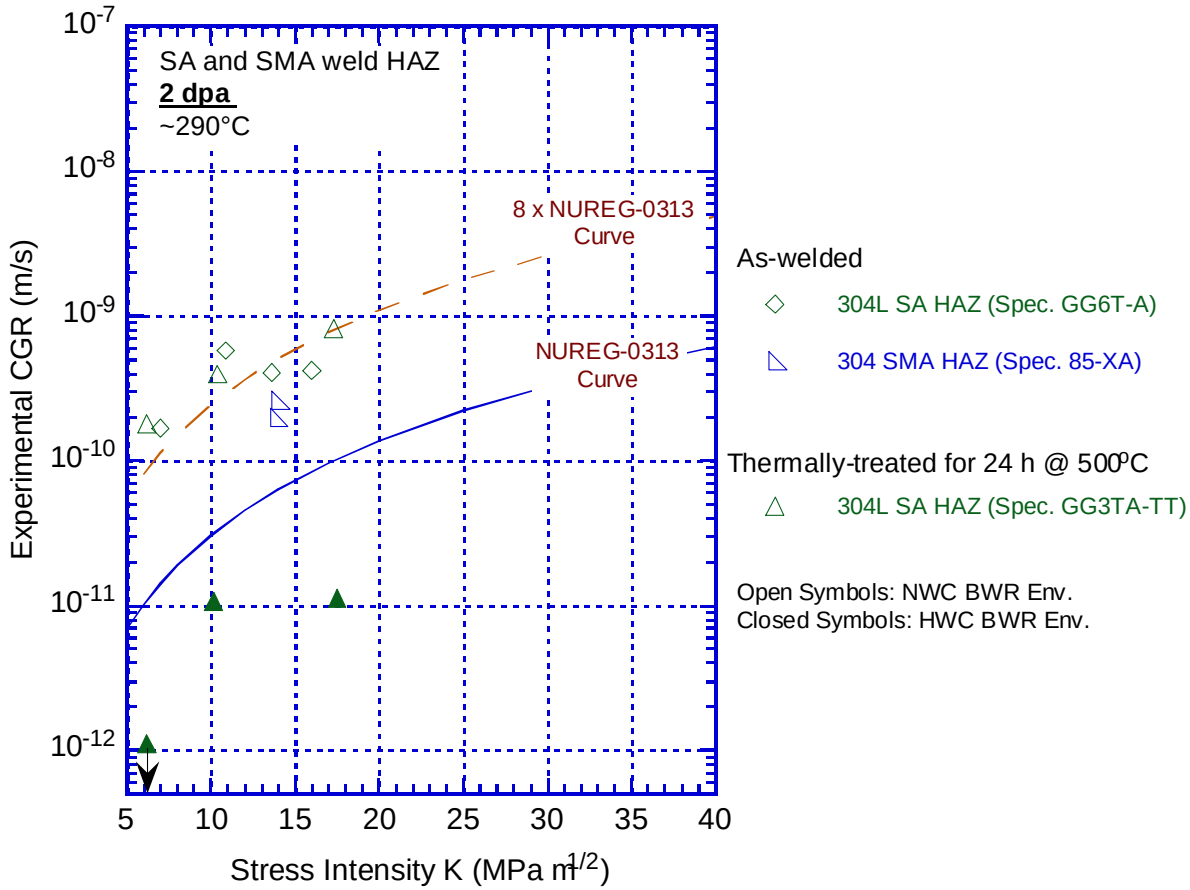
- NUREG-0313 curve bounds the nonirradiated HAZ CGR data.
- No difference between as-welded and thermally-treated SA HAZ

Irradiated HAZ Specimens



- Constant-load CGRs are considerably higher (8 - 10 times) than the NUREG-0313 curve at 0.75 dpa
- Thermal-treatment (500° C for 24 h) does not elevate IASCC susceptibility

Irradiated HAZ Specimens



- CGRs at 2 dpa are similar to that at 0.75 dpa
- The beneficial effect of HWC is evident

Summary

- Irradiation effects that affect IASCC:
  - RIS (Cr, Ni, Mo, Si, S, P …)
  - Irradiation hardening and embrittlement
  - Deformation mode
  - Void swelling and irradiation creep (may be not at LWR temp.)
  - Radiolysis
- Work in progress to address regulatory needs:
  - New irradiation to address synergistic effect of irradiation and thermal aging
  - Verify dose limit for the onset of IASCC
  - Effects of fabrication processes
  - Measure fluence effects and determine saturation dose
  - Effects of material chemistry, Effects of irradiation condition

Gaps in Understanding of IASCC

- Dose dependence of IASCC
- IASCC behavior under annealing
- Flux and temperature effects
- In-situ vs. ex-situ behavior,
- Irradiation effect on crack initiation and early stage of growth
- The relation between the deformation mode and IASCC
  - SFE, twining and channeling deformation mode in highly irradiated materials

Future Work

- Evaluate IASCC in PWR
  - Evaluate IASCC susceptibility in PWR environment as a function of fluence, material chemistry, and processing condition (e.g., SA or CW)
  - Void swelling behavior in austenitic SSs,
  - Synergistic effects of thermal and radiation embrittlement of cast SSs
  - Effectiveness of mitigation measures, e.g., GBE & low-S content

- Technical Approach
  - SSRT tests (5, 10, 40 dpa BOR-60 specimens)
    - To evaluate IASCC susceptibility (IG fraction) in PWR environment
  - TEM disks (<40 dpa BOR-60 specimens)
    - To assess void swelling at doses and temperatures relevant to PWRs
  - CGR/JR tests (new Halden irr., 4 CIR specimens, GE specimens, Zorita or others)
    - To evaluate IASCC CGRs at PWR relevant condition
    - To evaluate synergistic effects of thermal and radiation embrittlement