Cracking Behavior of Irradiated Cast Austenitic Stainless Steels in Low-Corrosion-Potential Environments

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Cast austenitic stainless steels (CASS)

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- CASS are used in the cooling system of light water reactors for components with complex shapes
  - pump casings, valve bodies, coolant piping, control rod guide tube spacers and housing etc.
- The most widely used CASS steels are corrosion-resistant CF grades
  - Typically CF grade CASS (CF-3, CF-8 and CF-3M ,CF-8M) whose compositions are similar to those of 300-series austenitic SSs.
    - CF-3 and CF-8 contain 19% Cr and 9% Ni
    - CF-3M and CF-8M are Molybdenum- containing steels
  - Because of high Cr content CF Grade steels possess
    - Corrosion and Oxidation Resistance and Mechanical properties
      - The strength and ductility is comparable to Wrought SS

Cast austenitic stainless steels (CASS)

- **Microstructure of CASS**
  - **(δ)-Ferrite and (γ)-Austenite Duplex microstructure**
  - **Duplex Microstructure ➔ provides Mechanical Strength of CASS**
    - **➔ Tensile strength and Yield strength increases with (δ)-Ferrite up to 40% both at Room Temperature and elevated Temperature**
  - **(δ)-Ferrite ➔ Prevent the tendency for Hot Cracking → Welding**
    ➔ Improves the resistance to Sensitization and SCC
- **The Presence of δ- Ferrite**
  - **Detrimental Effect on Fracture Resistance when exposed to 300-500^{o}C.**
  - **It is because ➔ δ - ferrite is vulnerable to Low-Temperature Thermal Aging**
    - **As a result both tensile strength and ductility are reduced**
- **Mechanism for Loss of FT due to Thermal Aging in CASS**
  - **Nucleation of Cr–rich α' phase (by spinodal decomposition) and growth of α‘ - phase,**
  - **precipitation of nickel– and silicon–rich G phase, γ- (austenite), and $M_{23}C_6$carbides**
  - **Large $M_{23}C_6$ carbides and/or Cr_2N nitrides precipitate at the ferrite/austenite phase bound**

Note: Thermal aging: It is process that involves heating a material at a constant temperature for long period (in this case heating to 400°C and keep at that temperature for ~ 10,000 hrs.)

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Properties of CASS

- **The thermal aging embrittlement of CASS has been studied extensively**
- **Limited data exist in the open literature for thermal aging and neutron-irradiated CASS**
- **No data exists on the interaction between both thermal aging and neutron irradiation in CASS materials**
  - ➢ **Due to both cost and the experimental difficulties associated with the measurement**
- **The effect of neutron irradiation**
  - – **Formation and growth of lattice defects leads to higher strength, lower ductility and toughness**
  - – **Degradation of δ - ferrite much faster than for austenite**
    - ***fluence of ~ 10^{17} n/cm^2 $\rightarrow$ δ - ferrite and 10^{20} n/cm^2 $\rightarrow$ γ - austenite (NRC- NUREG 7027)***
    - ***fluence of 10^{17} - 10^{19} n/cm^2 $\rightarrow$ δ - ferrite and 2X 10^{20} – 6.7 X10^{20} n/cm^2 $\rightarrow$ γ - austenite (Industry - MRP-227 Meeting at USNRC Nov. 19th 2013)***
    - ***Note: 10^{17} n/cm^2 ~ 0.00015 dpa and 2X 10^{20} – 6.7 X10^{20} n/cm^2 ~ 0.3 – 1 dpa***

Objective

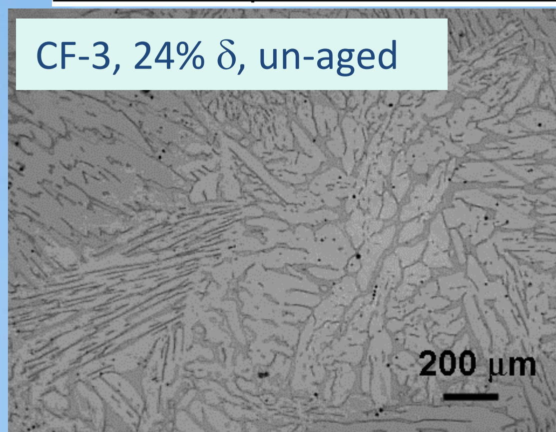
- The objective of this investigation is

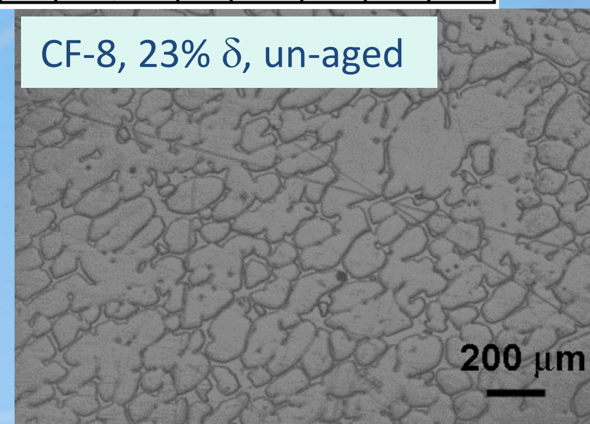
1. to assess the extent of embrittlement of CASS from
   - neutron irradiation (dose 0.08 dpa)
   - thermal aging (400°C, ~ 10,000 hrs)
   - neutron irradiation and thermal aging

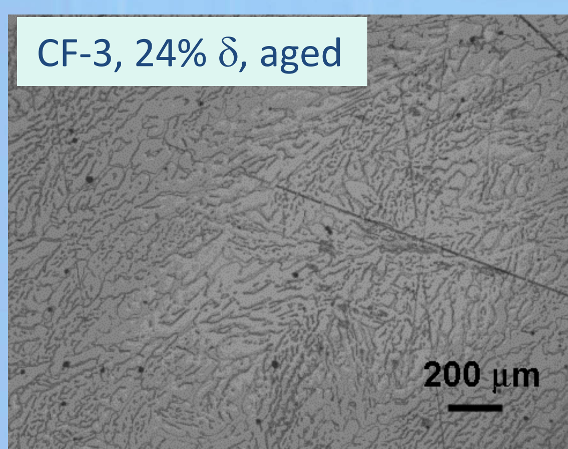
2. to evaluate their stress corrosion cracking (SCC) performance in low electrochemical potential (ECP) environments
   - simulated PWR water with 2ppm Lithium and 1000 ppm Boron
   - high-purity water with dissolved oxygen (DO) < 10 ppb; conductivity ~ 20 μS/cm

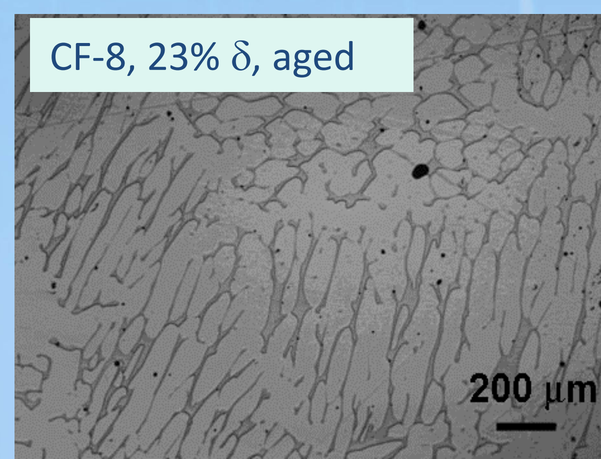
Materials

Cast Steel Grade	Ferrite Content	Heat ID.	Spec. ID	Thermal Aging Condiion	Elemental Composition (wt. %)								
					Mn	Si	P	S	Mo	Cr	Ni	N	C
CF-3	24%	69	A	Unaged	0.63	1.13	0.015	0.005	0.34	20.18	8.59	0.028	0.023
			B	10,000 hrs @ 400°C									
CF-8	23%	68	C	Unaged	0.64	1.07	0.021	0.014	0.31	20.46	8.08	0.062	0.063
			D	10,000 hrs @ 400°C									



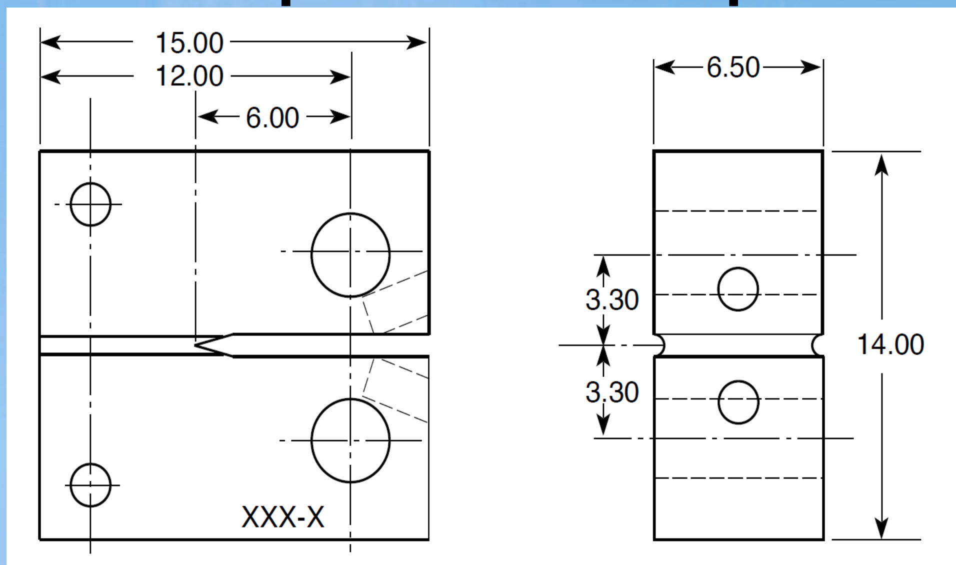




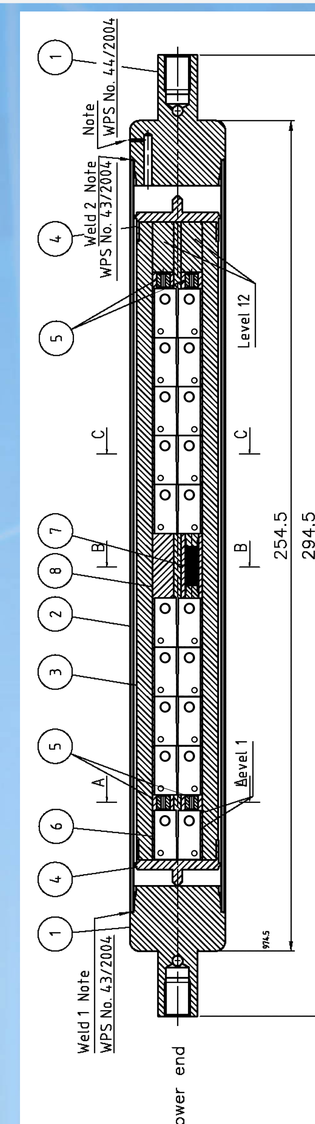


Specimens and Irradiation

- **1/4T-Compact Tension specimens**

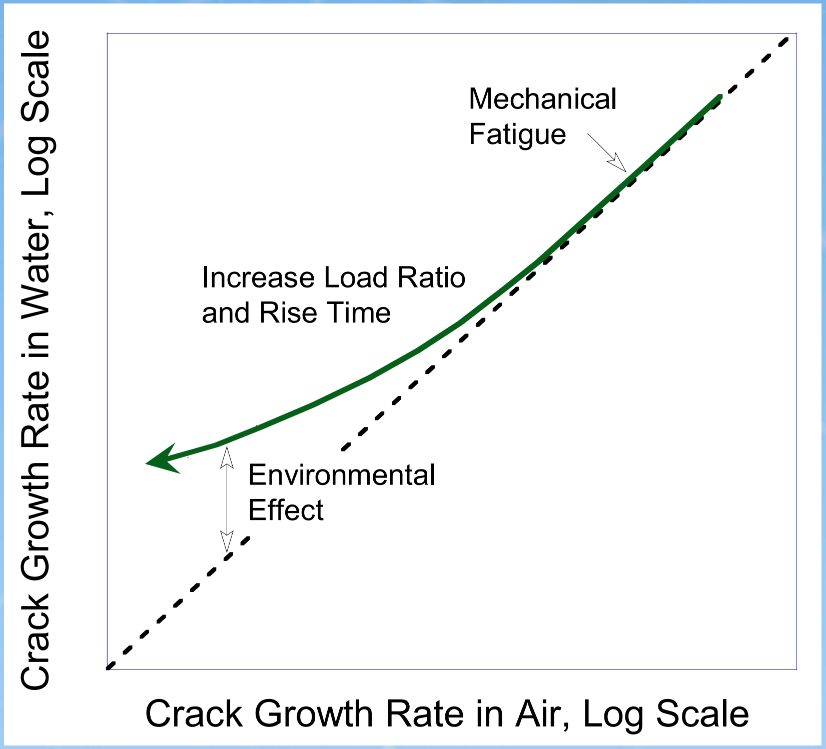


- **Irradiated in helium-filled capsule at Halden**
  - **Irradiation temperature: ~315°C**
  - **Dose rate: 10^{-7} dpa/s,**
  - **Dose: 5.0E19 n/cm^2 (E>1MeV), 0.08 dpa.**



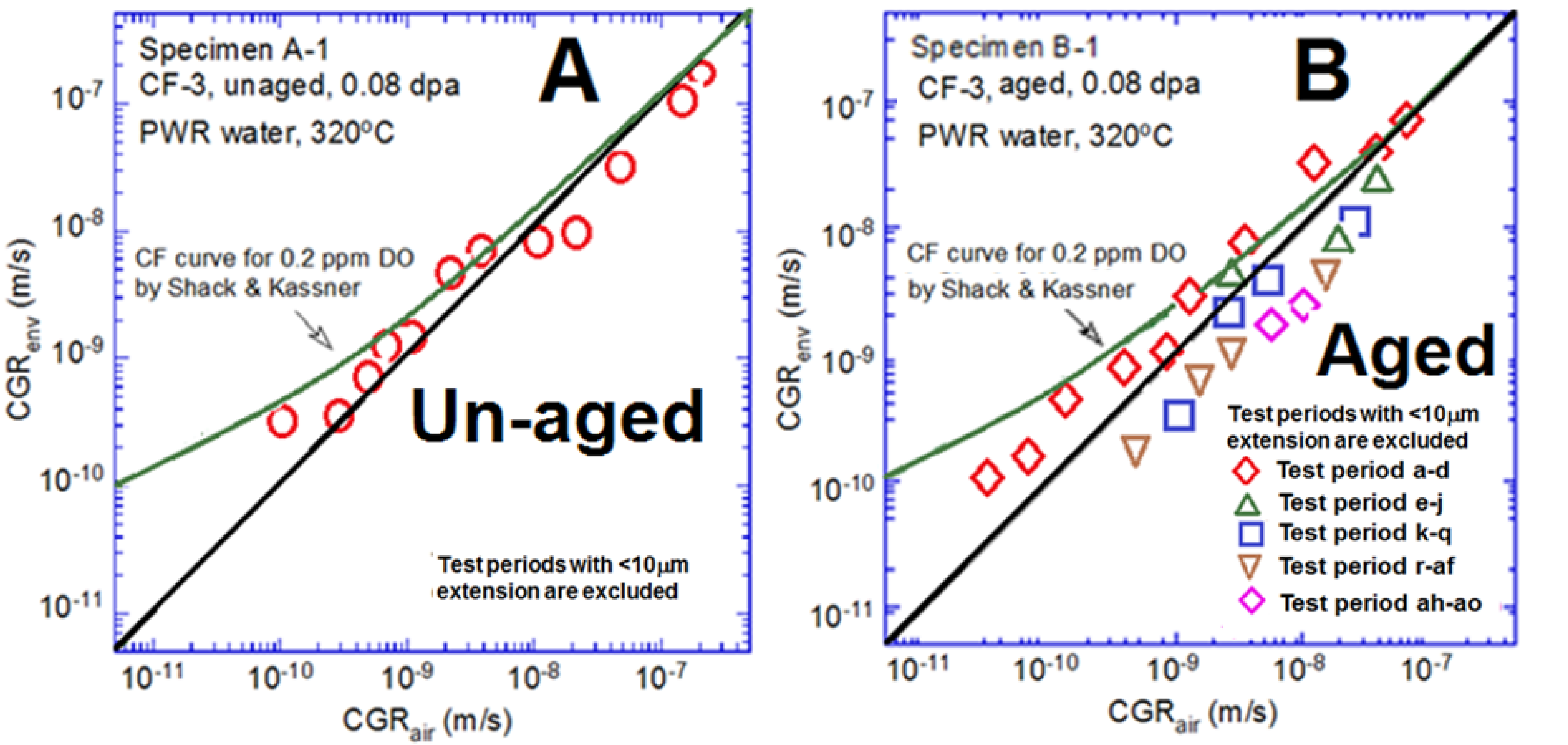
CGR and JR curve tests

- **CGR tests:**
  - **Precrack in test environments, and transition to SCC test.**
  - **Constant-load CGR tests with and without periodic partial unloading (PPU).**



- **JR curve tests:**
  - **Use SCC starter cracks, and test in the environments at ~320°C.**
  - **A very slow deformation rate, ~0.43 μm/s, is used.**
  - **A blunting line of $J/4\sigma_f$ is used in the analyses.**
  - **Limited by sample size, the J values determined cannot be validated for J_{IC}.**

CGR Test Results for un-aged and Aged CF-3 CASS Irradiated to 0.08 dpa

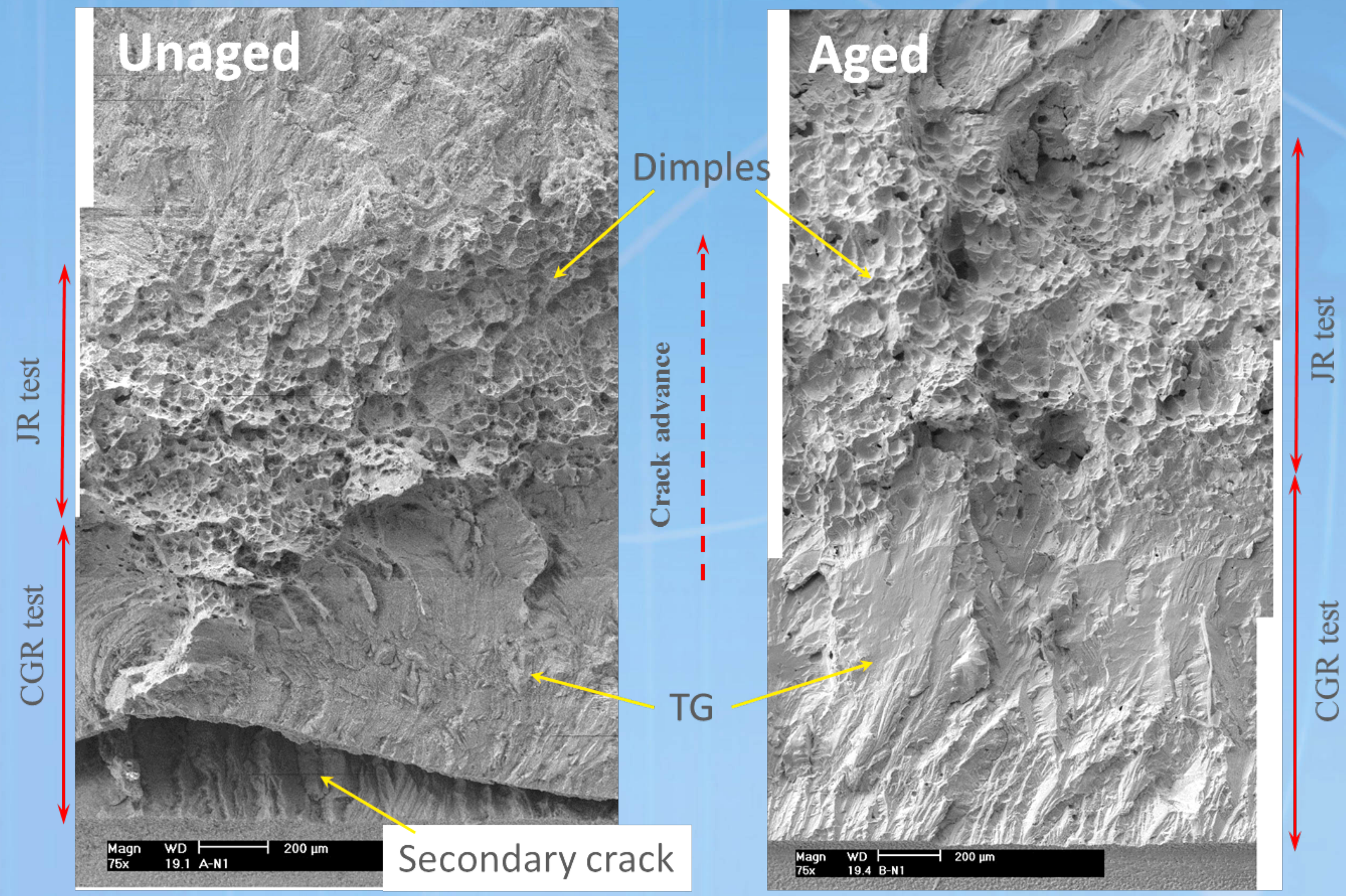


Crack growth rate test for CF-8 (A) un-aged and (B) aged CASS irradiated to dose of 0.08 dpa. Test environment and temperature PWR water, 320°C.

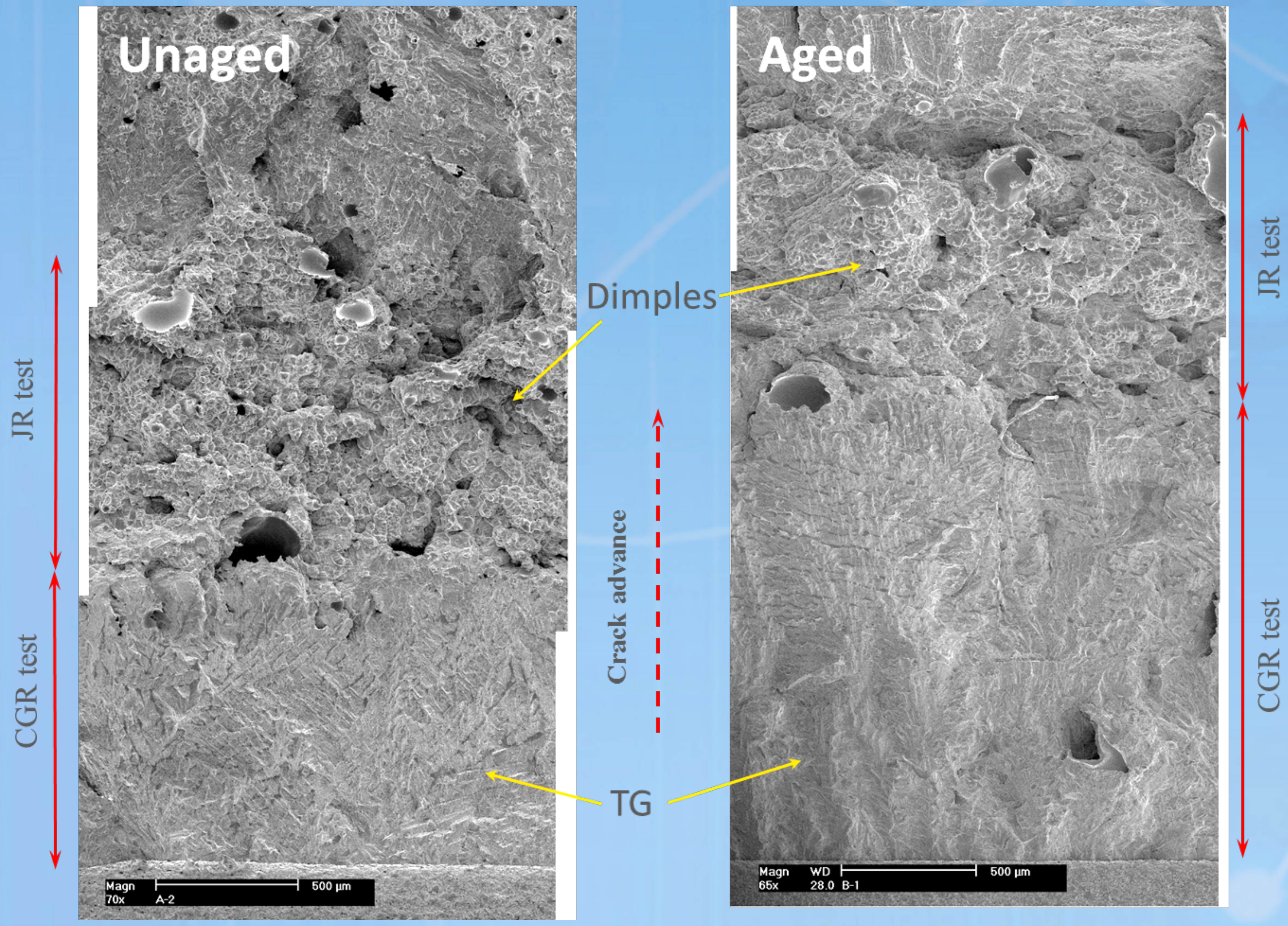
Note: Possible reasons for CGR data below the divide line

1. *Test error*
2. *Crack may not be straight or crack surface has multiple contacts. Therefore DCPD did not respond correctly*
3. *Crack was arrested*

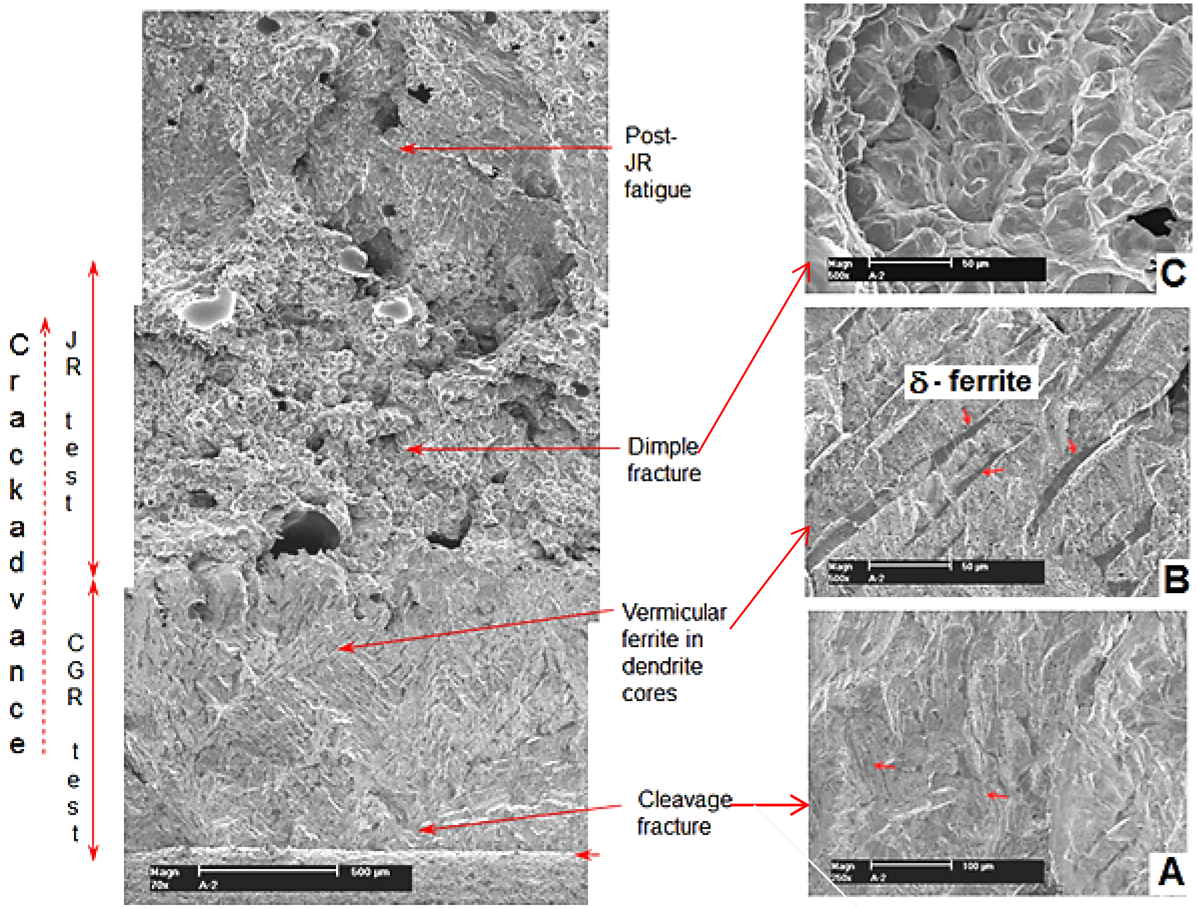
Fracture Surface of Unirradiated - Unaged and Aged CF- 3 CASS Samples,



Fracture Surface of irradiated (0.08 dpa) - Unaged and Aged CF- 3 CASS Samples,



Fracture surface of unaged CF- 3 CASS sample irradiated to 0.08 dpa



Fracture surface of CF-3 sample irradiated to 0.08 dpa and tested in low DO environment at 320°C. (A) Cleavage at the begining of CGR test, (B) fracture surface showing the δ - ferrite deformed to lesser extent than austenite and (C) ductile dimple morphology in the JR test region.

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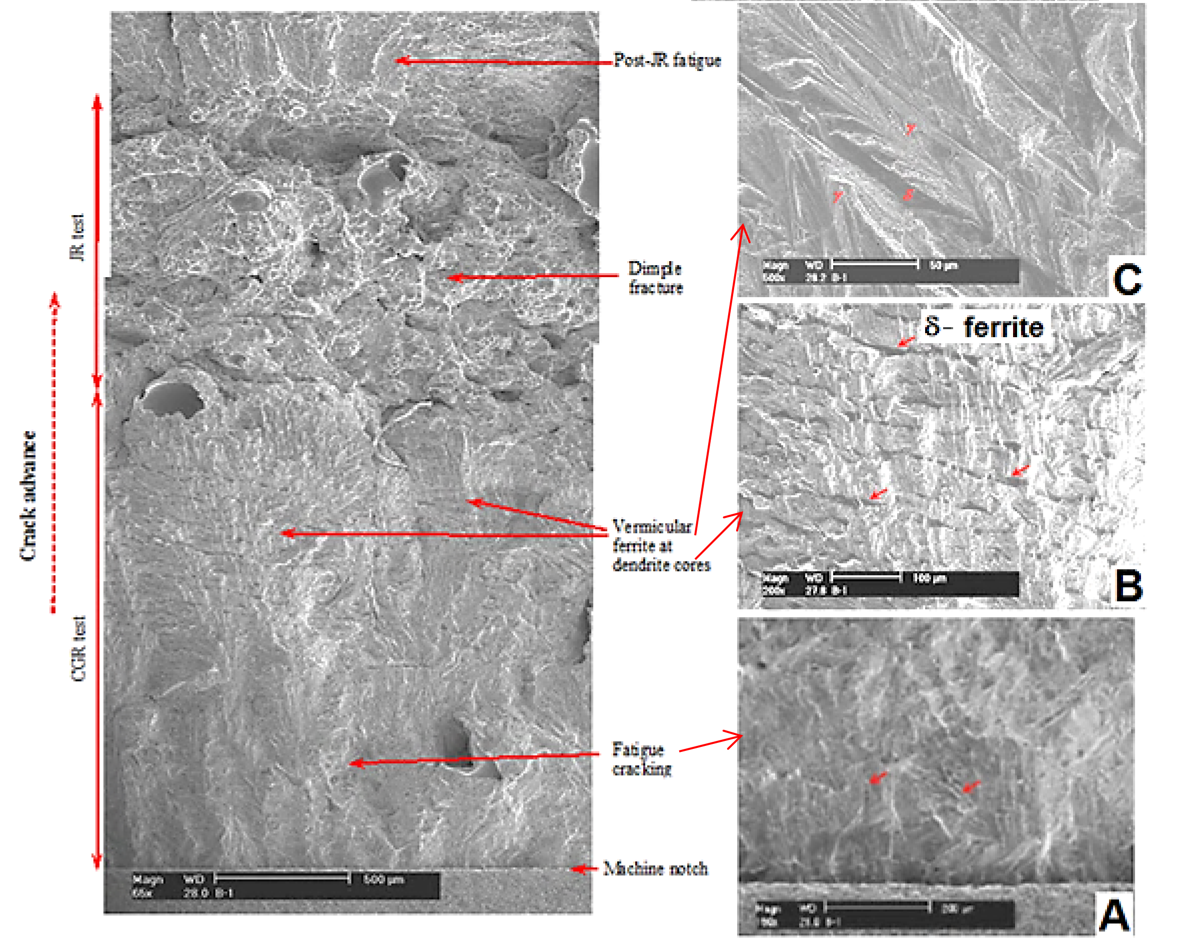
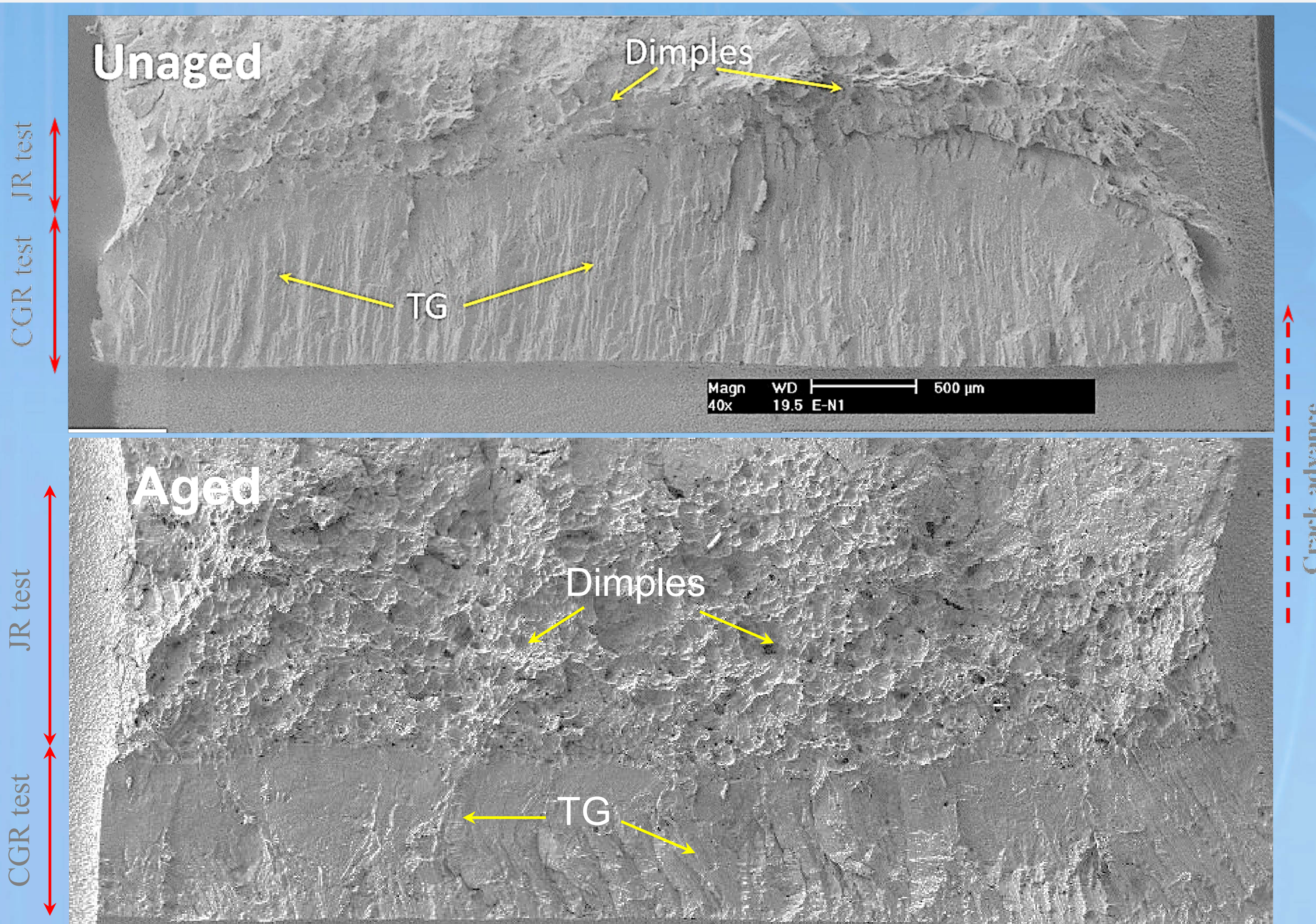
Fracture surface of aged CF- 3 CASS sample irradiated to 0.08 dpa



Fracture surface of aged CF-3 sample. Sample was aged at 400°C for 10,000 hours and was irradiated to 0.08 dpa. (A) cleavage steps in pre-cracking, (B) δ – ferrite dedrites core and (C) δ- ferrite is surrounded by heavily deformed austenite.

Fracture Surface of Unirradiated - Unaged and Aged CF- 8 CASS Samples,



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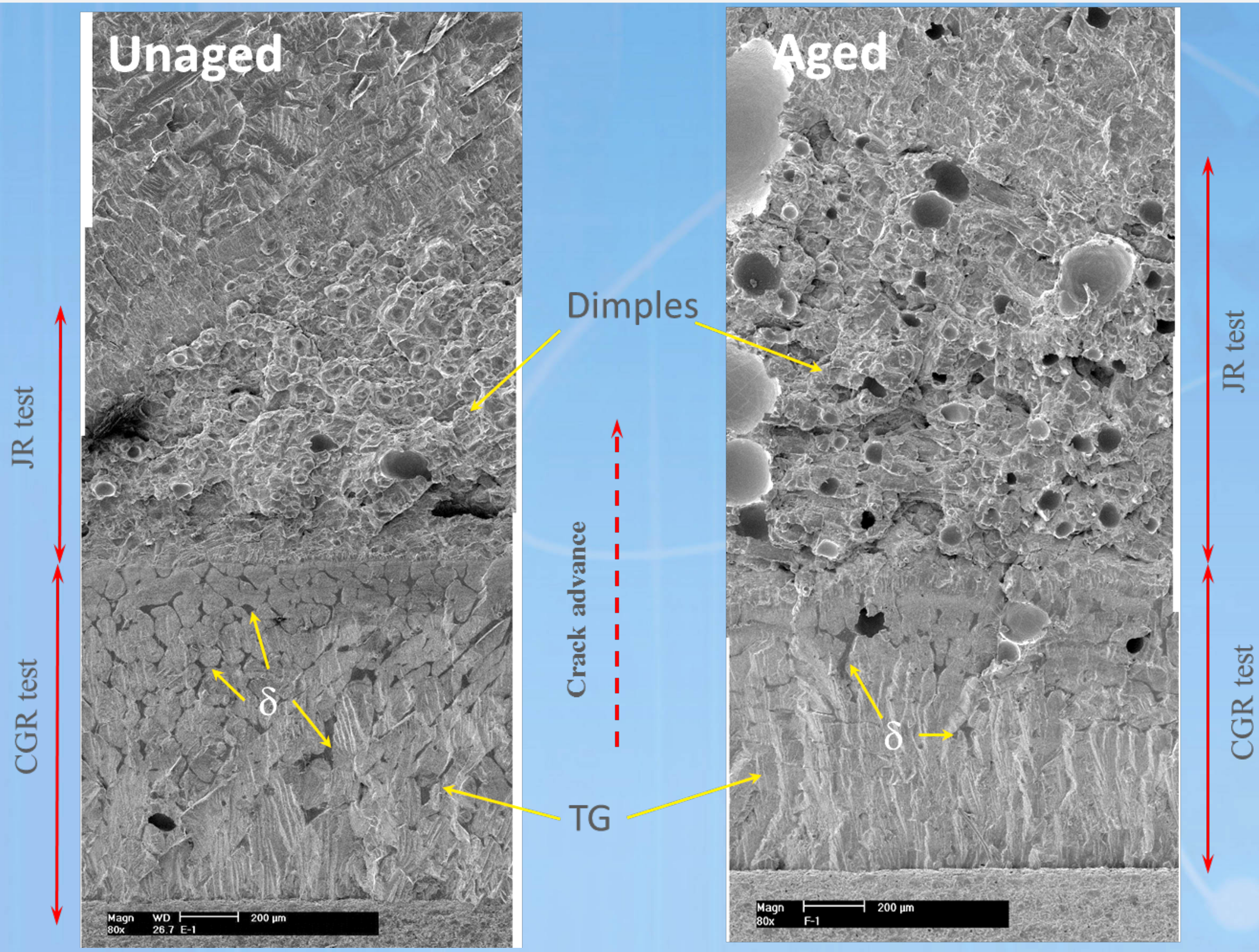
Fracture Surface of irradiated (0.08 dpa) - Unaged and Aged CF- 8 CASS Samples,



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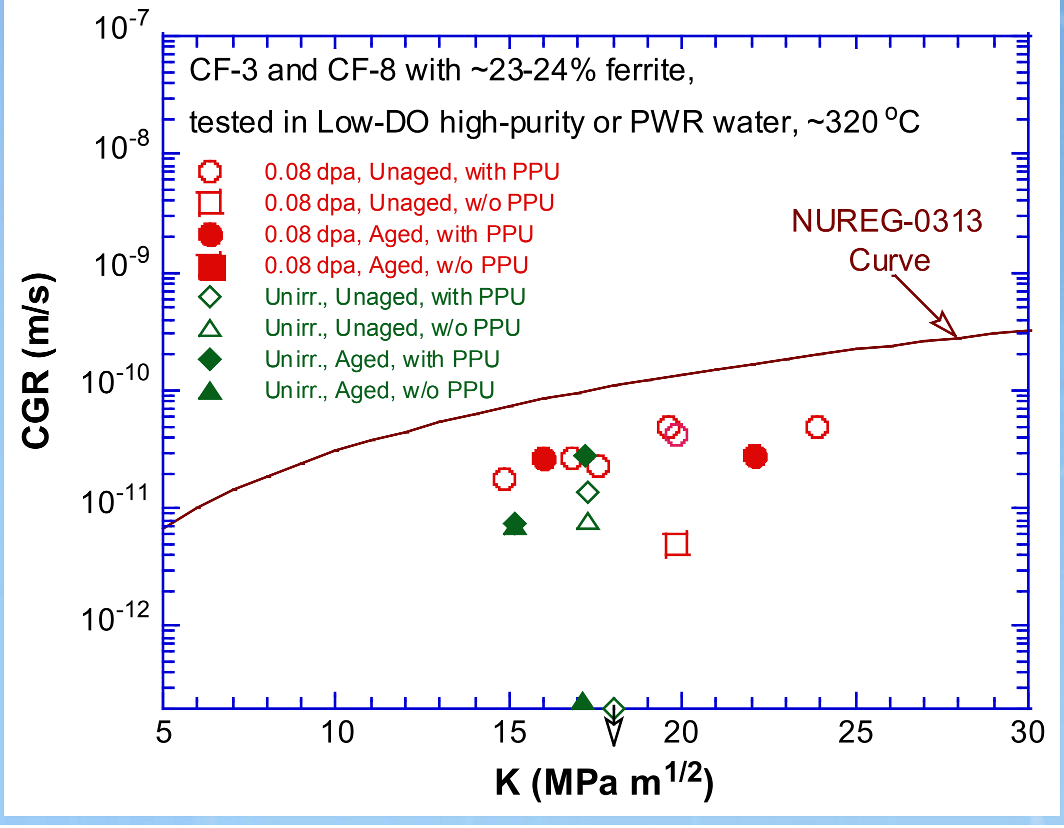
SCC CGR Results



- **Neutron irradiation (~0.08 dpa) does not appear to elevate the cracking susceptibility significantly in low-corrosion-potential environments.**
- **Good SCC resistance for both aged and unaged CASS and are both below NUREG-0313 line.** ***Note: some data points have not been corrected.***

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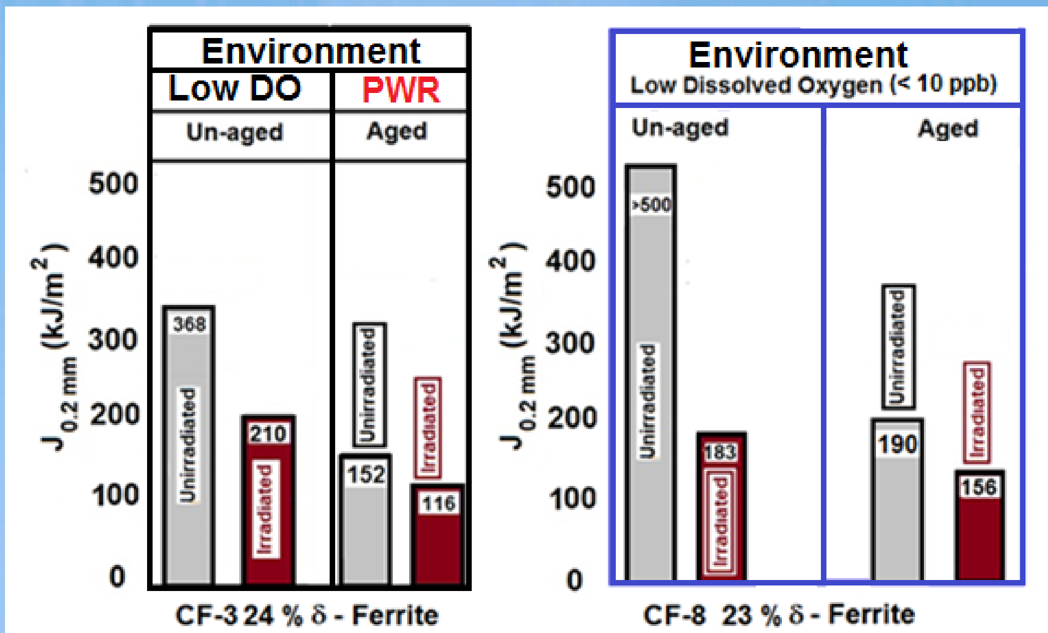
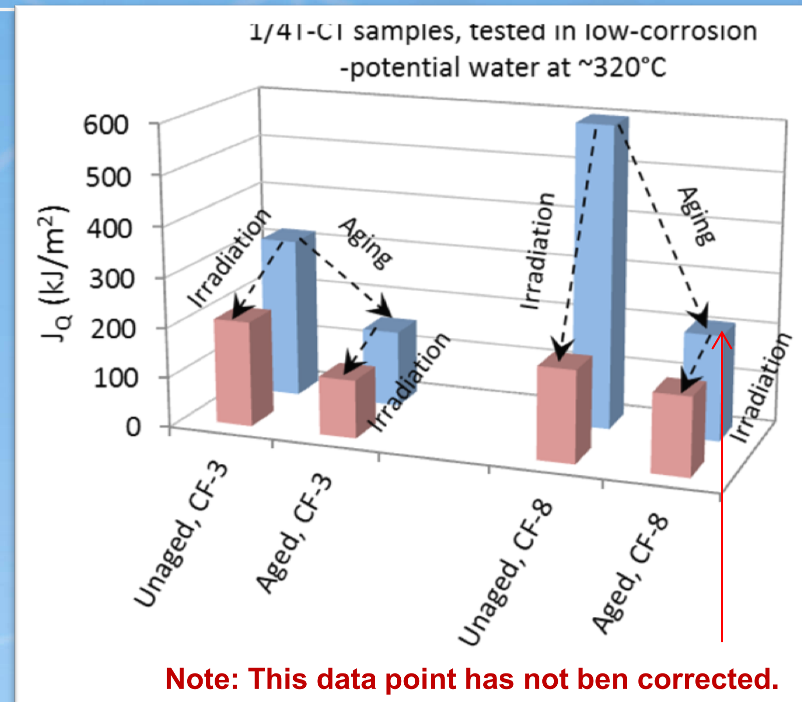
Fracture Toughness





- Thermal aging effect on the fracture toughness more significant for CF-8 than CF-3 CASS.
- The irradiation embrittlement of both CF-3 and CF-8 CASS is greater for un-aged materials than for thermally aged materials.
- A combined effect of thermal aging and irradiation damage can reduce the fracture resistance of CASS further.

Summary

– Cracking behaviors of thermally aged and unaged CASS are similar in both unirradiated and irradiated samples.

– All CASS specimens investigated here failed in a ductile (dimple) fracture mode during the fracture toughness /JR curve tests.

– Neutron irradiation, even at 0.08 dpa, had a significant impact on the fracture toughness under low-corrosion-potential environments of CASS.

– The fracture toughness of both CF-3 and CF- 8 CASS is higher in un-aged condition than in thermally aged condition.

– A combined effect of thermal aging and neutron irradiation is further decrease in the fracture resistance of both CF-3 and CF-8 CASS.