Irradiation Embrittlement

Mechanical Properties and Irradiated Assisted Stress Corrosion Cracking

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Outline

- NRC Research Activities
- SSRT Testing
- Fracture Toughness Testing
- Results
- Summary
- Future Work

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 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

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Alloys for SSRT

Heat ID	Description	Objectives
333	Type 304 SS from ABB	Effect of GBE
GBE304	GBE Type 304 SS	
304L	Type 304L SS.	
GBE304L	GBE Type 304L SS	
GBE316	GBE Type 316 SS	
690	Alloy 690	
GBE690	GBE Alloy 690	
623	Type 316LN SS	Effect of Ti
625	Type 316LN SS, Ti-doped	
327	High-purity Type 304L SS with low O	Effect of O
945	High-purity Type 304L SS with high O	
C1 (SA, CW)	Low S, Type 304 SS, high P	
C3 (SA, CW)	Type 304L SS	
C9	High S, Type 304 SS	Effect of S
C12	Low S, Type 304 SS	
L5	304-like alloy with high Ni and Cr	

Common Materials in Halden & BOR-60 Irr. (heats 327 through L5)

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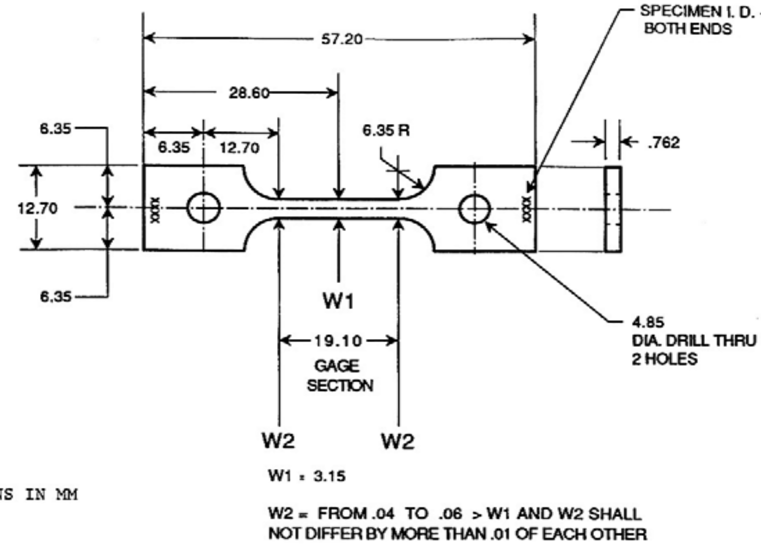
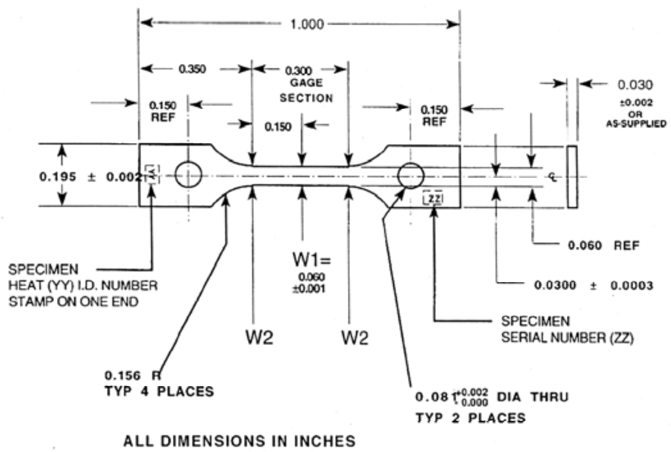
SSRT Specimens

Halden



BOR-60



	Ratio (Halden / BOR-60)
Thickness (*t*)	1
Gauge cross-section (*A*)	2
Gauge length (*l*)	2.5

Elongations are expected to be different between the Halden and BOR-60 specimens ($l/A^{0.5} \approx 1.8$)

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Experimental – Irradiation

- Halden reactor – a boiling heavy water reactor
  - Dry irradiation in He-sealed capsules
  - Irradiation temperature ~ 290°C
  - Dose rate ~ 10^{-7} dpa/s
  - He/dpa ratio for a Typical LWR: ~2-5 appm/dpa.

- BOR-60 reactor – a sodium cooled fast breeder reactor
  - Samples exposed to sodium
  - Irradiation temperature ~ 320°C
  - Dose rate ~ 9×10^{-7} dpa/s
  - He/dpa ratio for a Typical fast reactor: < 0.5 appm/dpa

SSRT Testing

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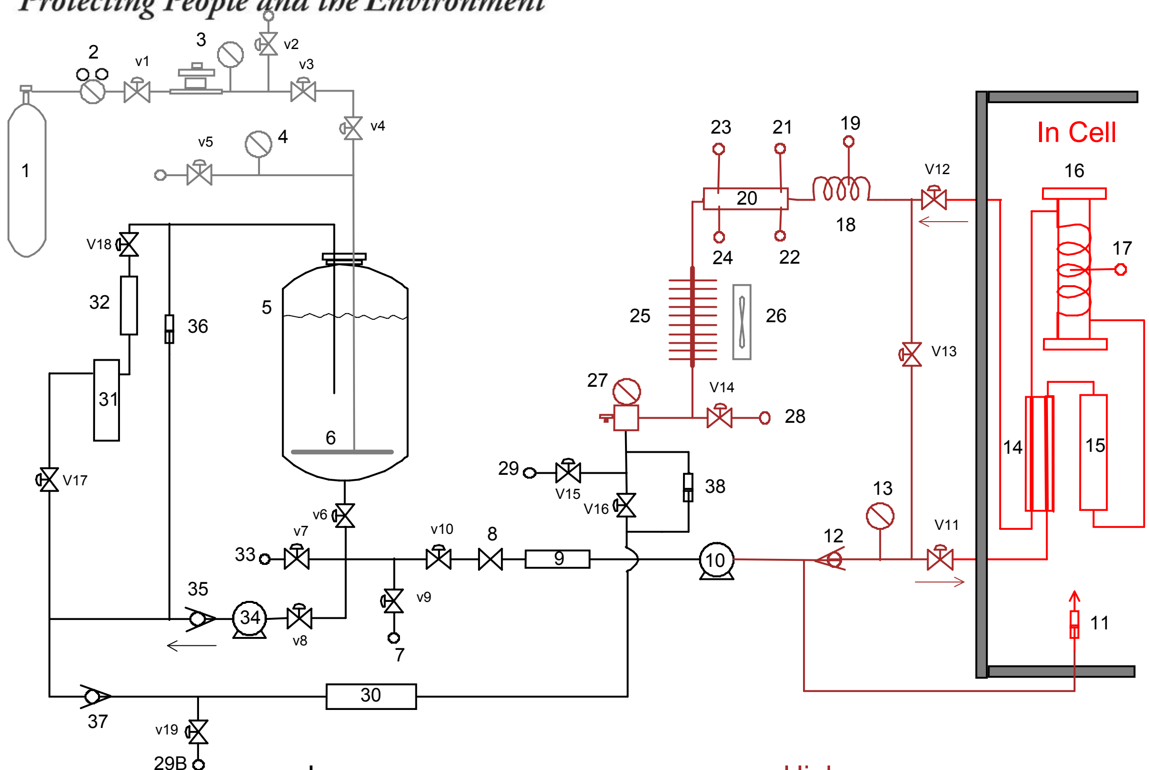
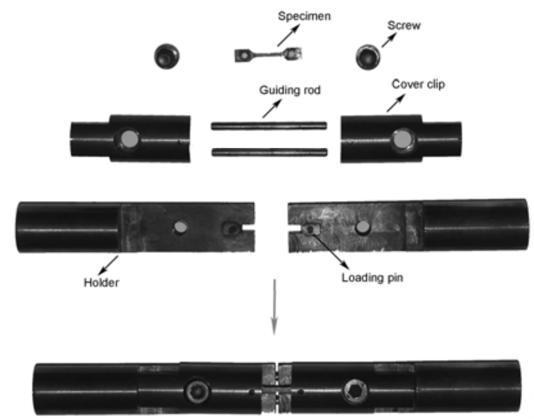


Loading grip for BOR-60 specimen



Temperature - 289° C

Pressure - 9.31 MPa (1350 psig)

pH - 6.4 ~ 7.2

Flow rate – 15~30 ml /min

DO - 8 ppm

Conductivity - 0.06~0.1 μS/cm

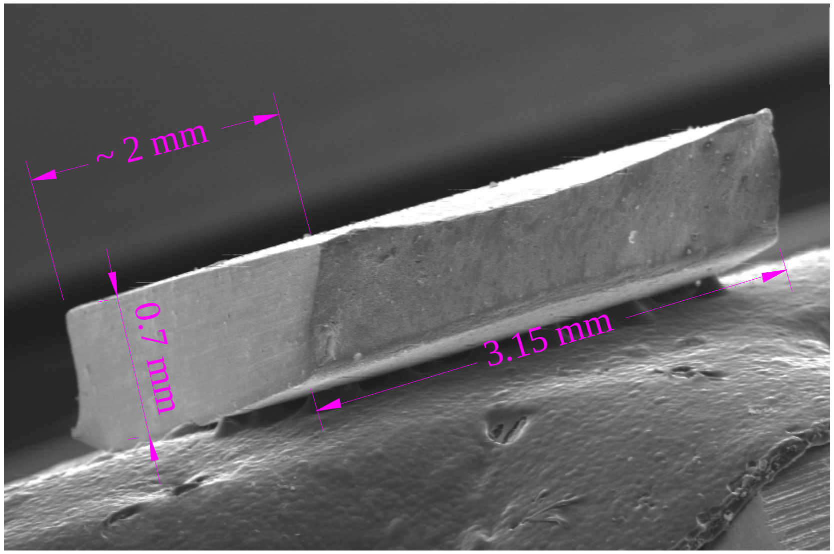
ECP – 150~200 mV (ss)

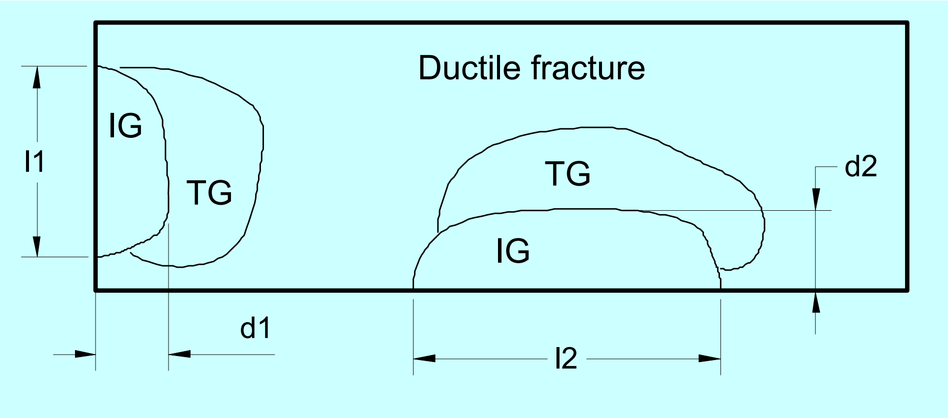
270~310 mV (Pt)

Strain rate: *Halden ~ 3.3x10^{-7} s^{-1}; BOR-60: ~ 7.4x10^{-7} s^{-1}*

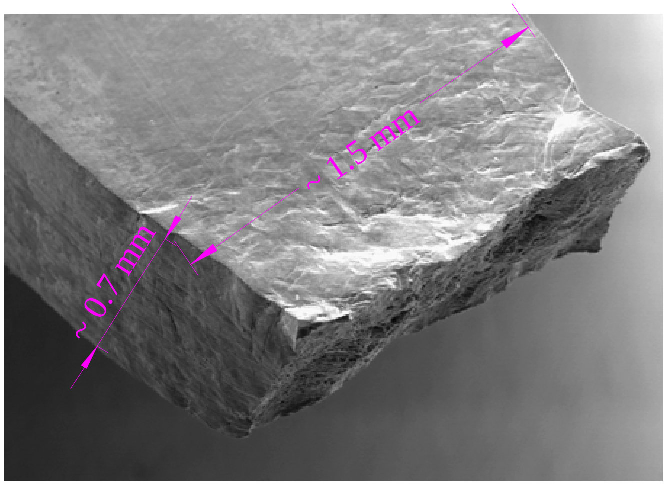
Fractography – SSRT Specimens

Sectioned Halden specimen





BOR-60 specimen



Characterize fracture surface

- IG or TG area fractions
- Number of IG or TG areas

Fracture Toughness Testing

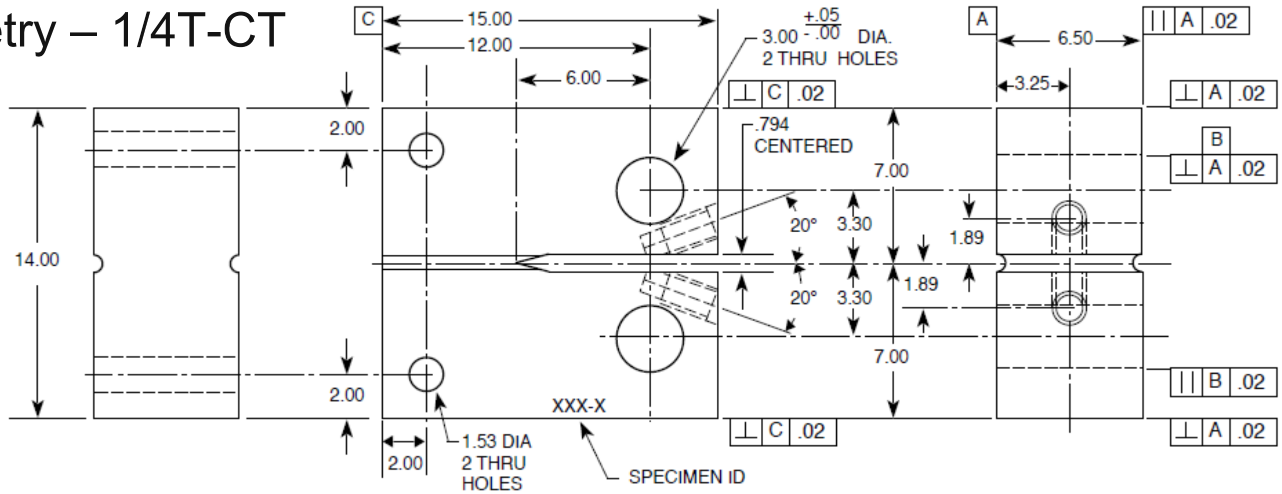
- Weldments
  - 304L submerge arc (SA) weld -- a *double-V butt weld* on Type 304L hot-rolled plates (ASME SA240) using *ER308L* filler rods.
  - 304 shield metal arc (SMA) weld -- a *single-V butt weld* on Type 304 plates using *E308* filler rods.
  - Post-weld thermal treatment -- 500°C for 24 hours (to simulate the effect of low-temperature sensitization).
- Four materials
  - 304L SA HAZ, as-welded
  - 304L SA HAZ, thermally-treated
  - 304 SMA HAZ, as welded
  - 304 SMA HAZ, thermally-treated

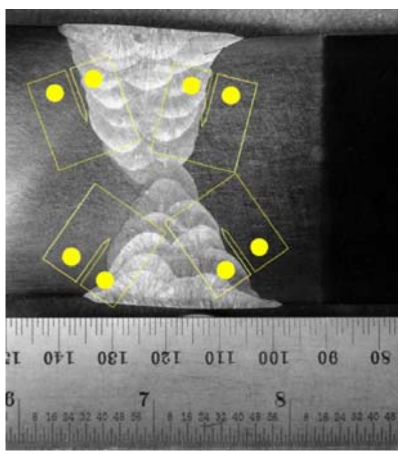
Chemical composition of the weld HAZ materials

Weld	Heat ID	Ni	Si	P	S	Mn	C	N	Cr	Mo	O
304 SMA	10285	8.45	0.60	0.015	0.007	1.90	0.070	0.084	18.56	0.51	0.013
304L SA	GG Top Shell	9.05	0.53	0.027	0.016	1.84	0.013	0.064	18.23	0.44	0.010

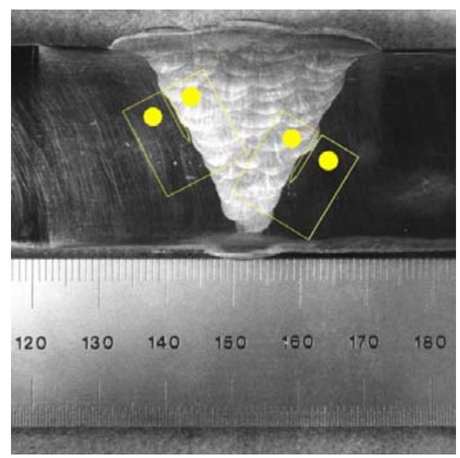
Fracture Toughness Specimens

Specimen geometry – 1/4T-CT





304L SA weld



304 SMA weld

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Fracture Toughness Specimens - Irradiation

Irradiated in Halden reactor in helium-sealed capsules

Irradiation conditions for the weld HAZ compact tension specimens

Material	Heat Treatment	Fast Neutron Fluence E >1 MeV ($x10^{21}$ n/cm^2)	Displacement Damage (dpa)	Irradiation Temperature (°C)
GG 304L SA HAZ	As-welded	0.50	0.75	~290
		1.44	2.15	290-296
	24 h @ 500°C	1.63	2.43	~290
304 SS SMA HAZ	As-welded	0.50	0.75	~290
		1.44	2.15	290-296
	24 h @ 500°C	0.50	0.75	~290
		1.44	2.15	290-296

Fracture Toughness Test Conditions

Temp:	≈290°C
DO:	≈350 ppb with N_2 + 1% O_2 cover gas <30 ppb with 4% H_2 cover gas
Flow rate:	15–25 mL/min
Conductivity:	0.08 - 0.12 μS/cm
K_{max}:	approximately constant by load shedding
K/size criterion:	B and (W-a) ≥2.5*$(K/\sigma_{eff})^2$, where $\sigma_{eff} = (\sigma_y + \sigma_u)/2$ for nonirradiated specimens, $\sigma_{eff} = \sigma_{y\text{-}irr}$ for irradiated specimens
J-R curve tests:	constant extension rate of 0.43 μm/s. Use a blunting line given by $\Delta a = J/(4\sigma_f)$.

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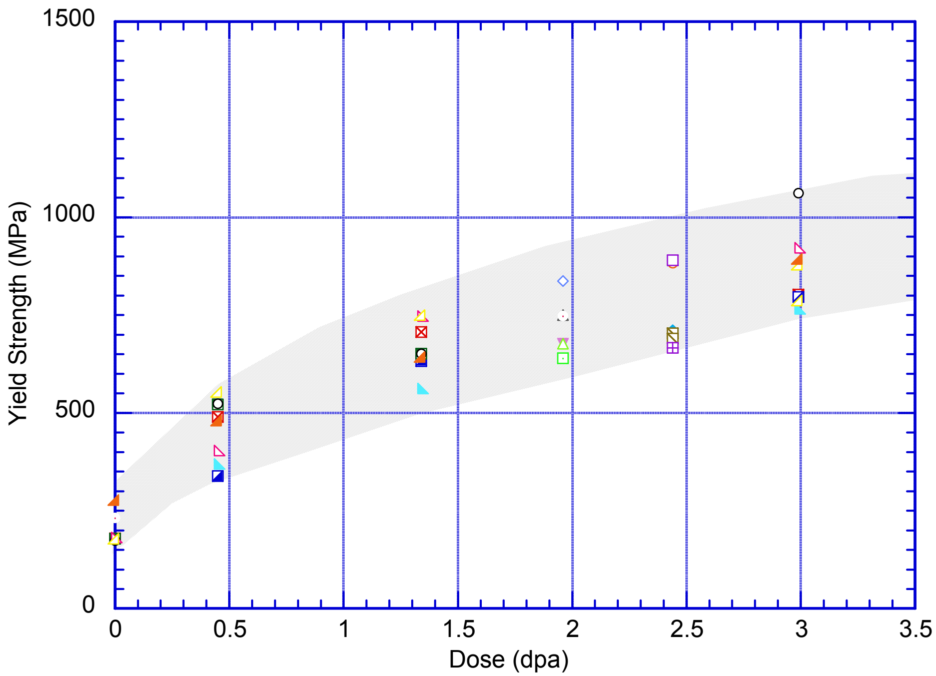
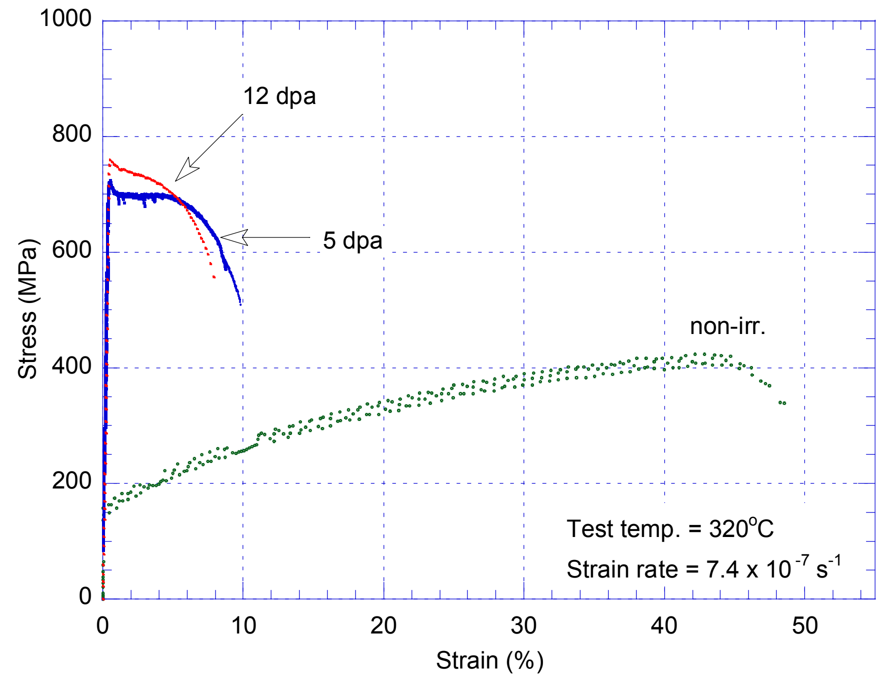
Effect of Irradiation Dose on Yield Strength



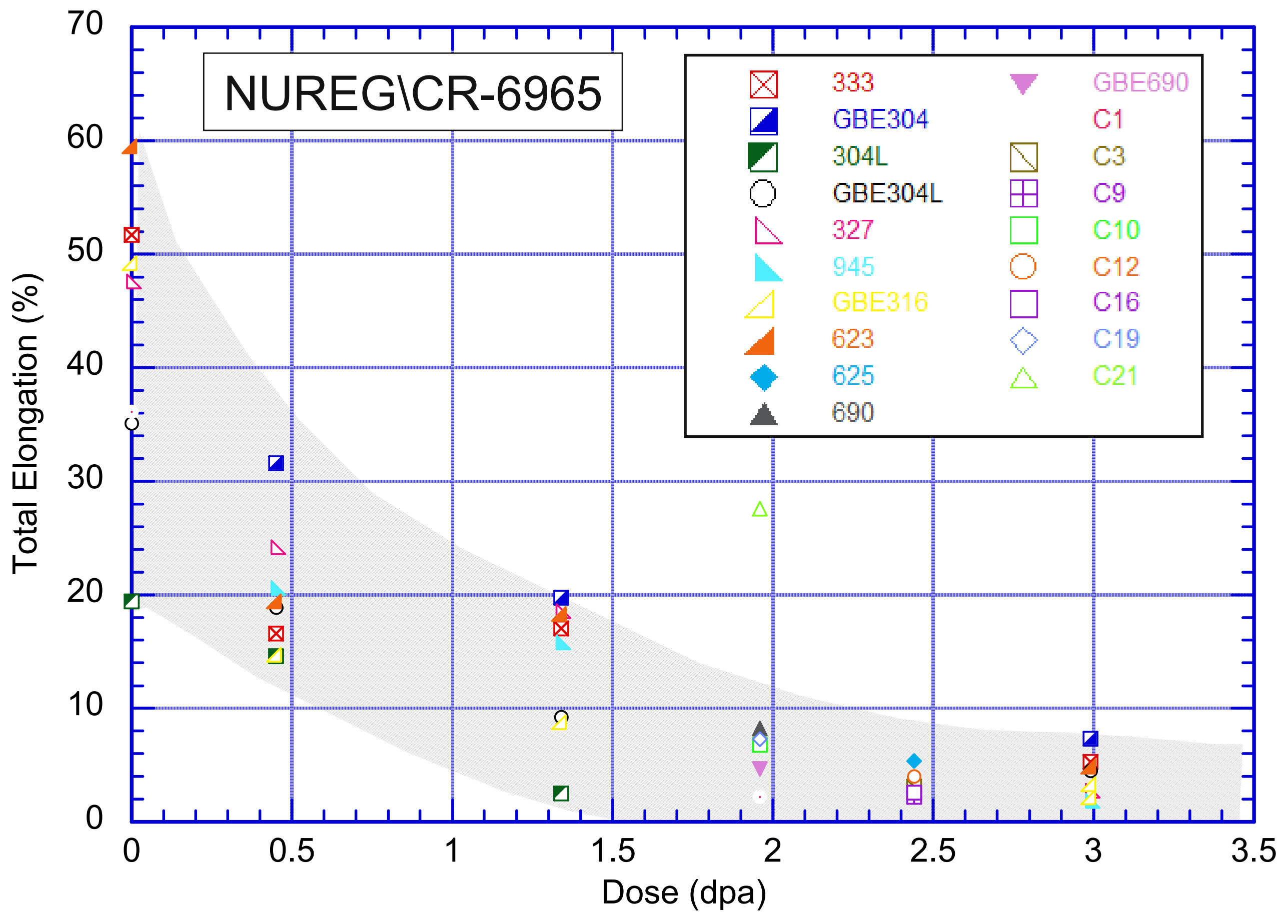
NUREG\CR-6965



316 SS BOR-60 Irradiation

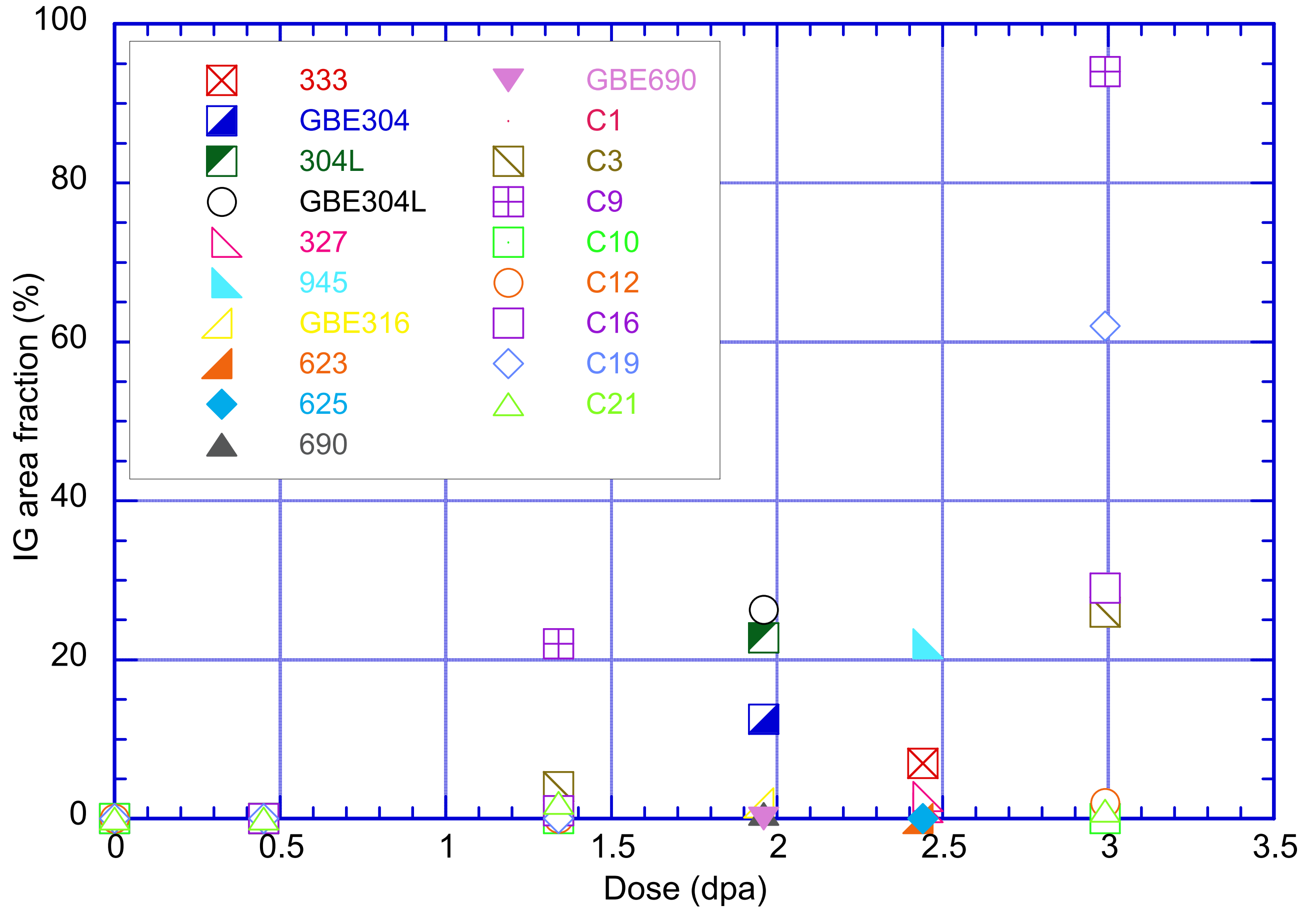
- Irradiation hardening and embitterment start to appear at dose <0.5 dpa.

Effect of Irradiation Dose on Total Elongation



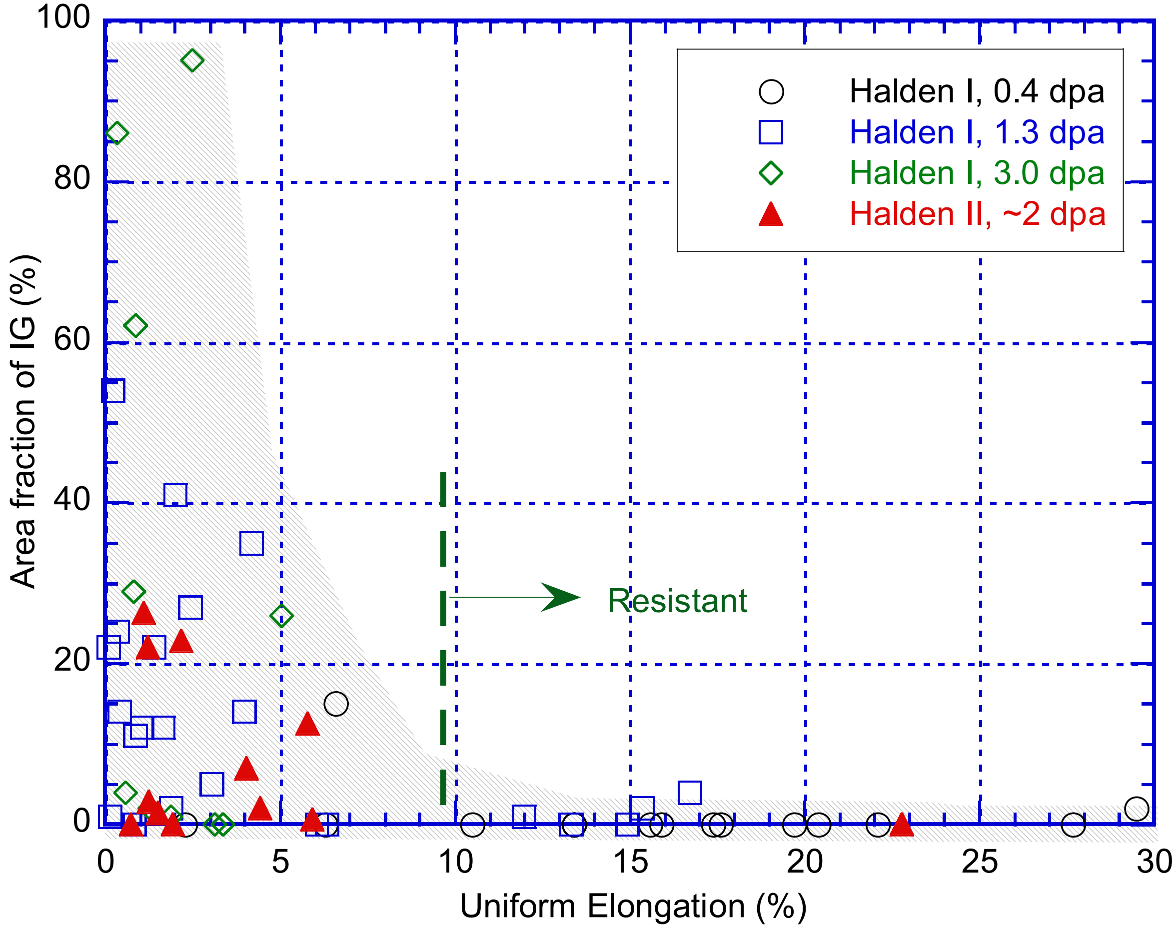
- Irradiation hardening starts to saturate around 3-5 dpa, and loss of elongation reaches a minimum around 2 dpa.

Effect of Irradiation Dose on Intergranular Fracture



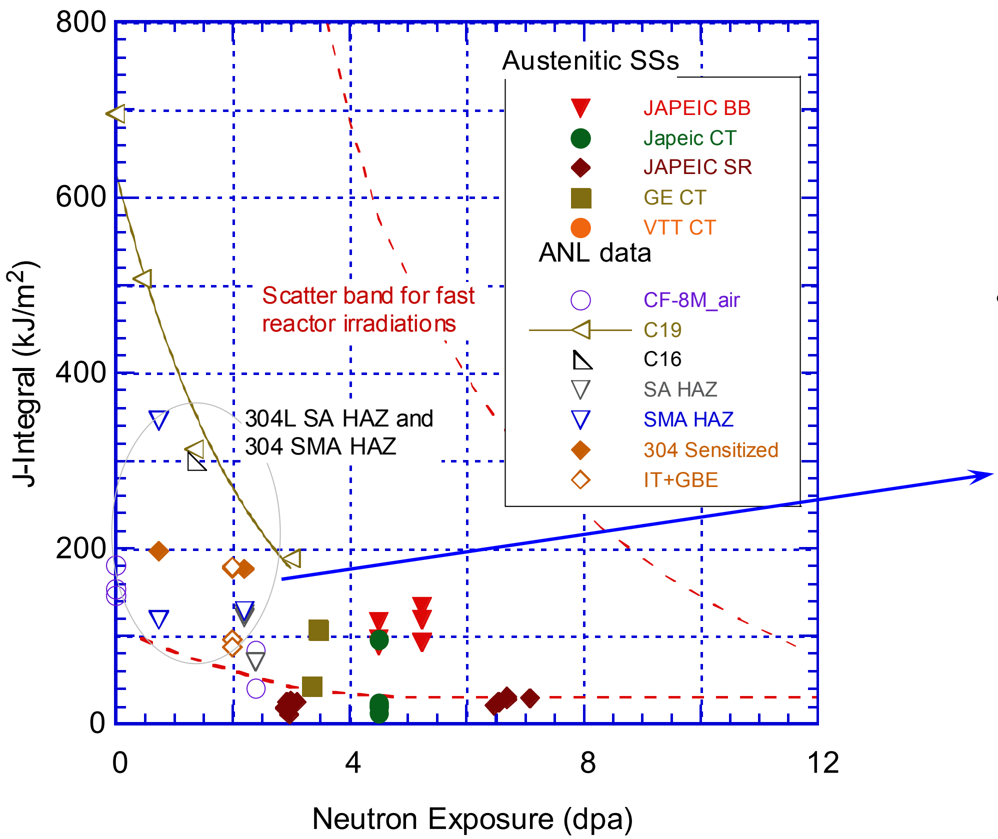
- IG cracking starts to occur at a dose lower than that elongation reaches minimum.

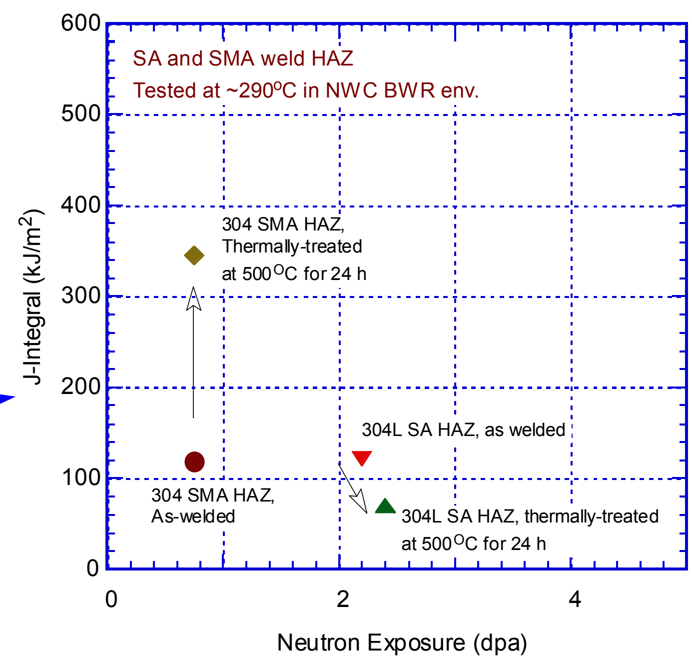
SSRT Testing



NUREG/CR-6965, Halden Phase-II, Alloys 304, 304L, 316L, 690

Fracture Toughness Testing Results





- Fracture toughness data of as-welded and thermally-treated HAZs are within the scatter band.
- Thermal treatment may have improved the fracture toughness of irradiated 304 SMA HAZ at 0.75 dpa

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Summary

- While irradiation hardening and embattlement starts to appears at very low doses, the dose dependence of IG cracking shows a "*threshold*" behavior. IG cracking start to appear before the dose for that elongations reach minimum.
- The post-irradiation strengths (YS and UTS) for the BOR-60 specimens were consistently lower than those of the corresponding Halden specimens. Likely related to Neutron spectrum and damage rate.
- Fracture toughness data for irradiated SA and SMA HAZs are within the scatter band. Thermal treatment may have improved the fracture toughness of irradiated 304 SMA HAZ at 0.75 dpa

Future Work

- High dose specimens
  - Simulate PWR end of life
  - Interest in samples from Zorita
- SSRT testing at 10 and 40 dpa
- TEM specimens up to 40 dpa