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EPRI Research on Crack Growth and Fracture Toughness of Irradiated Stainless Steels

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Overview of EPRI Research on Irradiated Stainless Steels

- Primary Systems Corrosion Research Program
  - CIR Program
  - Develop a mechanistic understanding of IASCC
  - Studies on fast reactor irradiated materials
- BWR Vessel and Internals Project
  - Crack growth and fracture toughness studies on BWR materials
- Material Reliability Project
  - Crack initiation, crack growth and fracture toughness studies on PWR materials
- EPRI also participates in the Halden IASCC research program

Primary Systems Corrosion Research Studies

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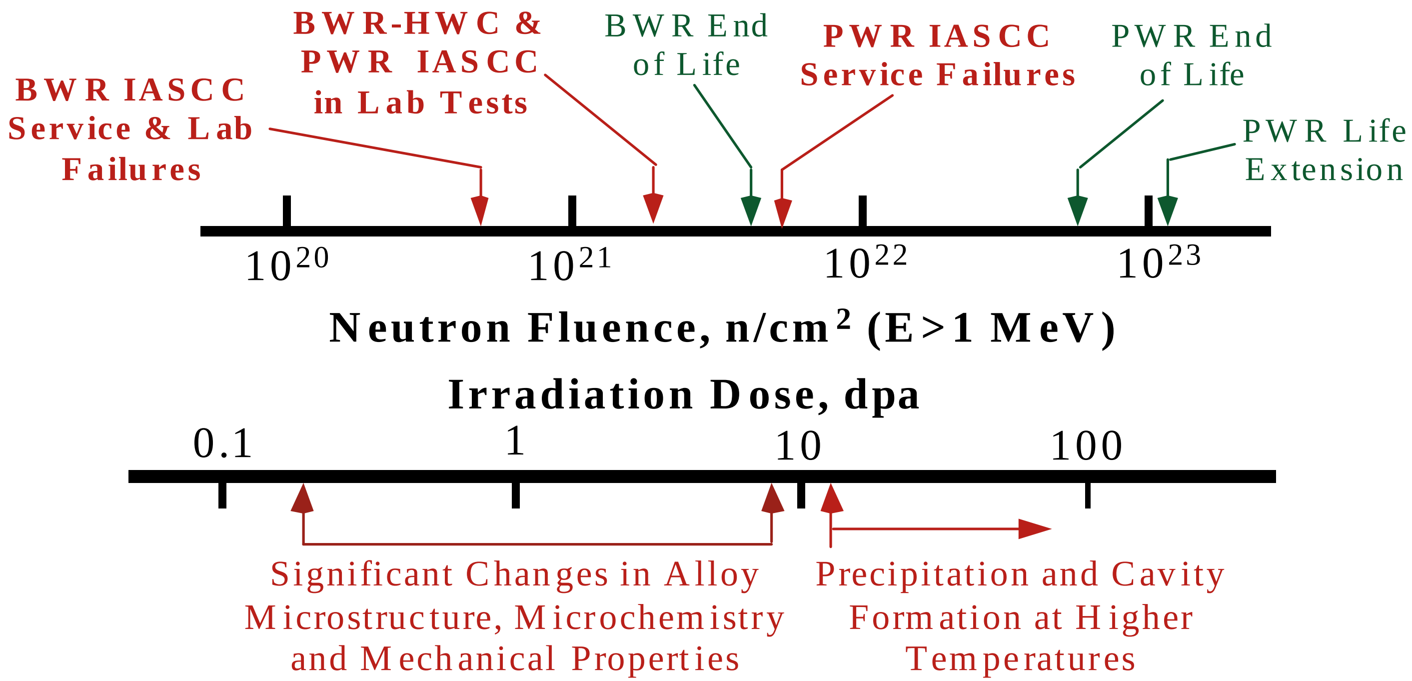
Characteristics of IASCC in Austenitic Stainless Steels (Bruemmer)



Note : ~15 dpa ≡ 10^{22} n/cm^2 E ≥ 1 MeV (for PWR and BWR neutron spectra)

~7 dpa ≡ 10^{22} n/cm^2 E ≥ 0.1 MeV (for PWR and BWR neutron spectra)

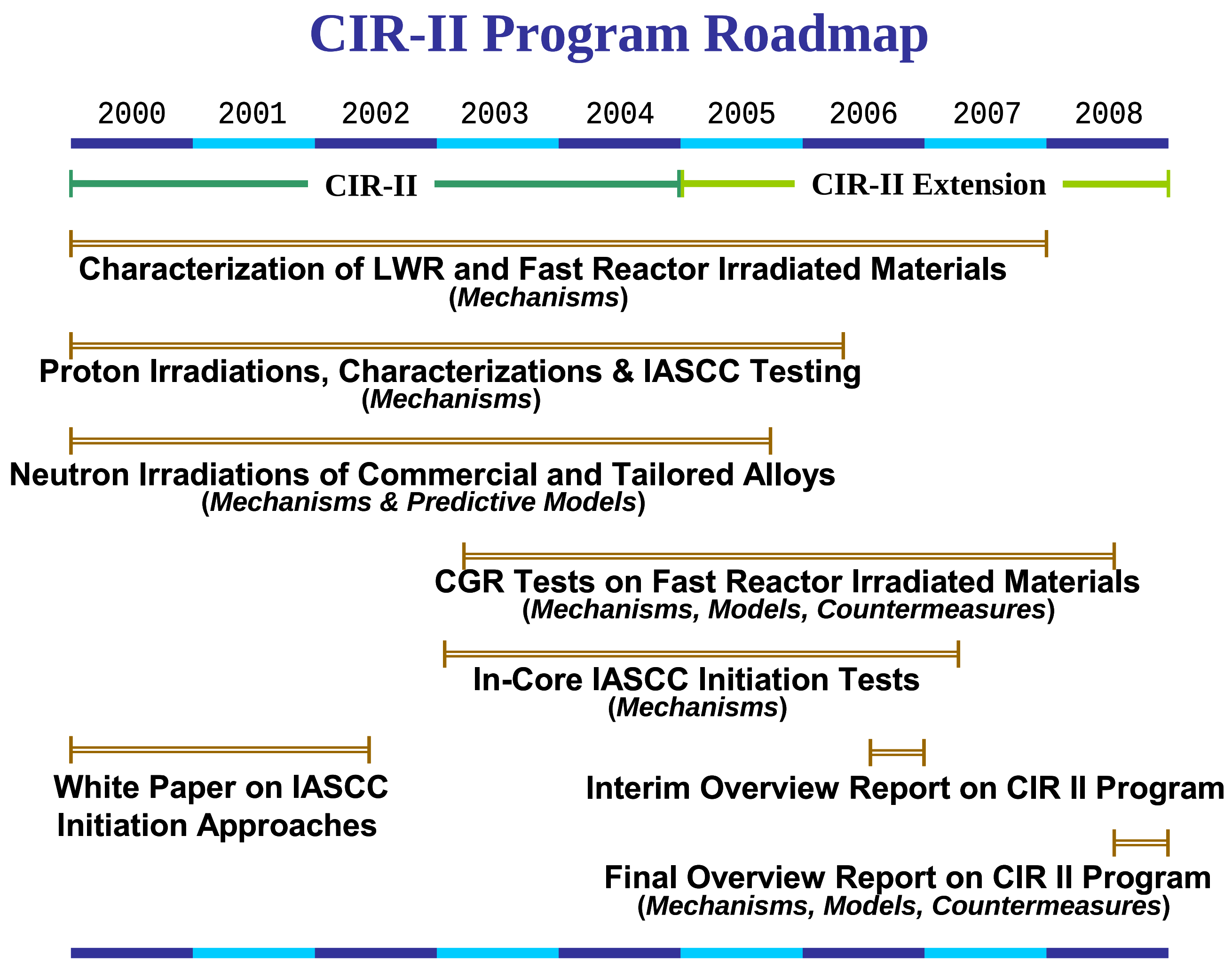
CIR Program

Objectives

- Develop a mechanistic understanding of IASCC;
- Derive a predictive model of IASCC, if possible based on a mechanistic understanding
- Identify possible countermeasures to IASCC.

- CIR members include utilities, vendors, nuclear safety authorities and national research laboratories
- Focus on IASCC of BWR and PWR components
- CIR I: 1995-2000
- CIR II: 2000-2005
- CIR II Extension: 2005-08

CIR-II Program Roadmap



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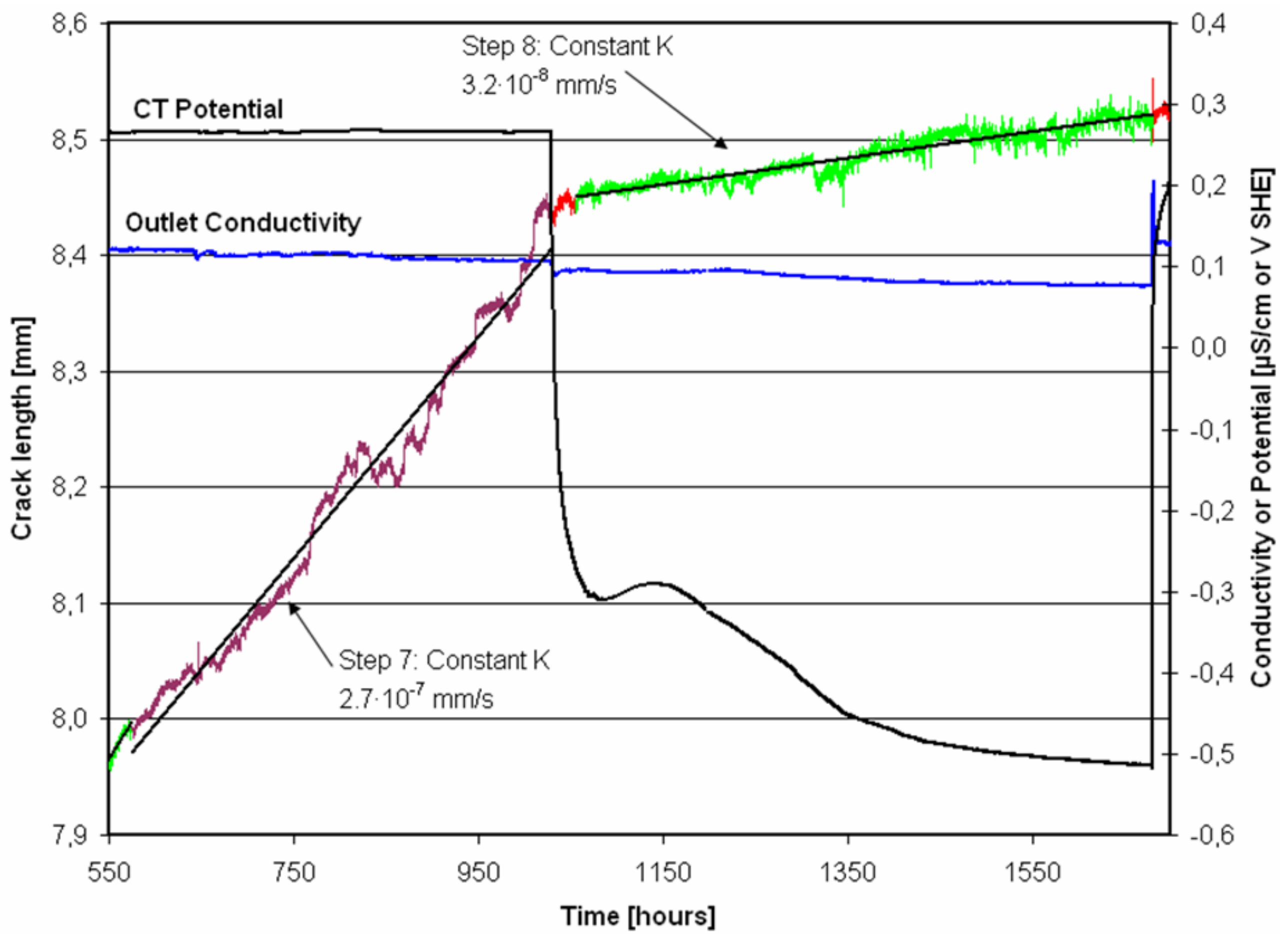
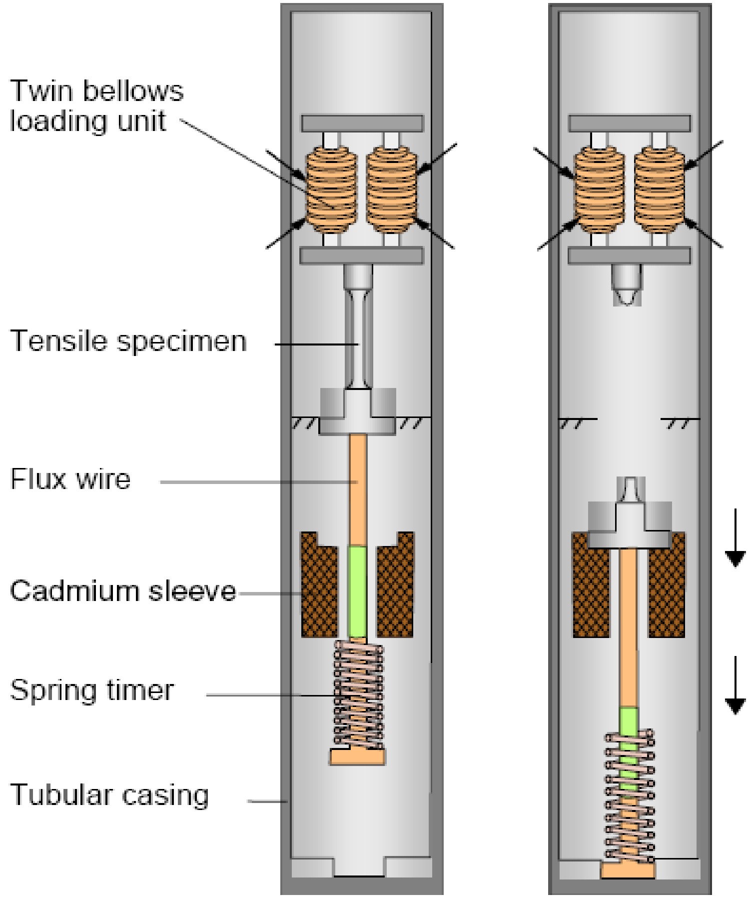
Crack Growth Tests: Type 304L, (5.5 dpa) in BWR Water in NWC and HWC (Jenssen)



Halden In-core Constant Load IASCC Test Device



Failure times determined from displacement of ^{59}Co flux monitor wires and Cd-10%Ag shields when the specimen breaks

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Assessment of Progress to Achieving CIR Program Objectives

Mechanistic Understanding of IASCC

- The significant influence of increased hardness and tensile strength on IASCC has been demonstrated and quantified
- Role of initial cold work in retarding IASCC has been demonstrated
- Grain boundary chromium depletion in oxidizing BWR water and silicon enrichment in both BWR and PWR primary coolants appear to play a major role in IASCC susceptibility
- The role of localized plastic deformation (as judged from stacking fault energy) has contributed to understanding variability in IASCC susceptibility in different alloys
- This knowledge could be used to optimize the chemical composition and initial metallurgical state of austenitic stainless steels for BWR and PWR internals

Assessment of Progress to Achieving CIR Program Objectives

Predictive Modeling

- No overall predictive model for IASCC has yet been devised although various important potential component elements have been realized
- Such a predictive model for IASCC could in principle be mechanistic or parametric provided that the form of the latter can be justified on the basis of sufficient mechanistic understanding
- Since the evolution of mechanical properties as a function of neutron fluence affects IASCC susceptibility and growth, equations developed in the CIR program could be used to predict irradiated yield strength
- Since the mechanical properties of stainless steels already in service would be needed, correlations developed in the CIR program for the change in yield stress as a function of the change in hardness (which could be determined in situ) would be very useful

Assessment of Progress to Achieving CIR Program Objectives

<u>Predictive Modeling (Contd.)</u>

- Modeling IASCC growth rates of irradiated stainless steels in BWR environments will most likely be based the slip / oxidation model incorporating the effect of grain boundaries chromium depletion and silicon enrichment as a function of neutron fluence
- The effect of the increase in yield strength and loss of ductility with fluence are incorporated via their effects on crack tip strain rate
- Need to evaluate if crack growth model can be extended to PWR environments
- Component life prediction could also be based on parametric modeling of % YS vs. failure time data at different fluence levels
- As crack initiation time is dominated by the time necessary to reach the required fluence, it is critical to have reliable estimates of stress on a component as a function of irradiation time

Future Work

- Complete parametric crack initiation and growth studies
- Use data from CIR and other programs to develop more reliable models for IASCC initiation and growth
- Quantify trends in crack growth rates with increasing fluence
- Use data from crack growth tests on solute addition alloys to identify favorable and detrimental elements and potential countermeasures

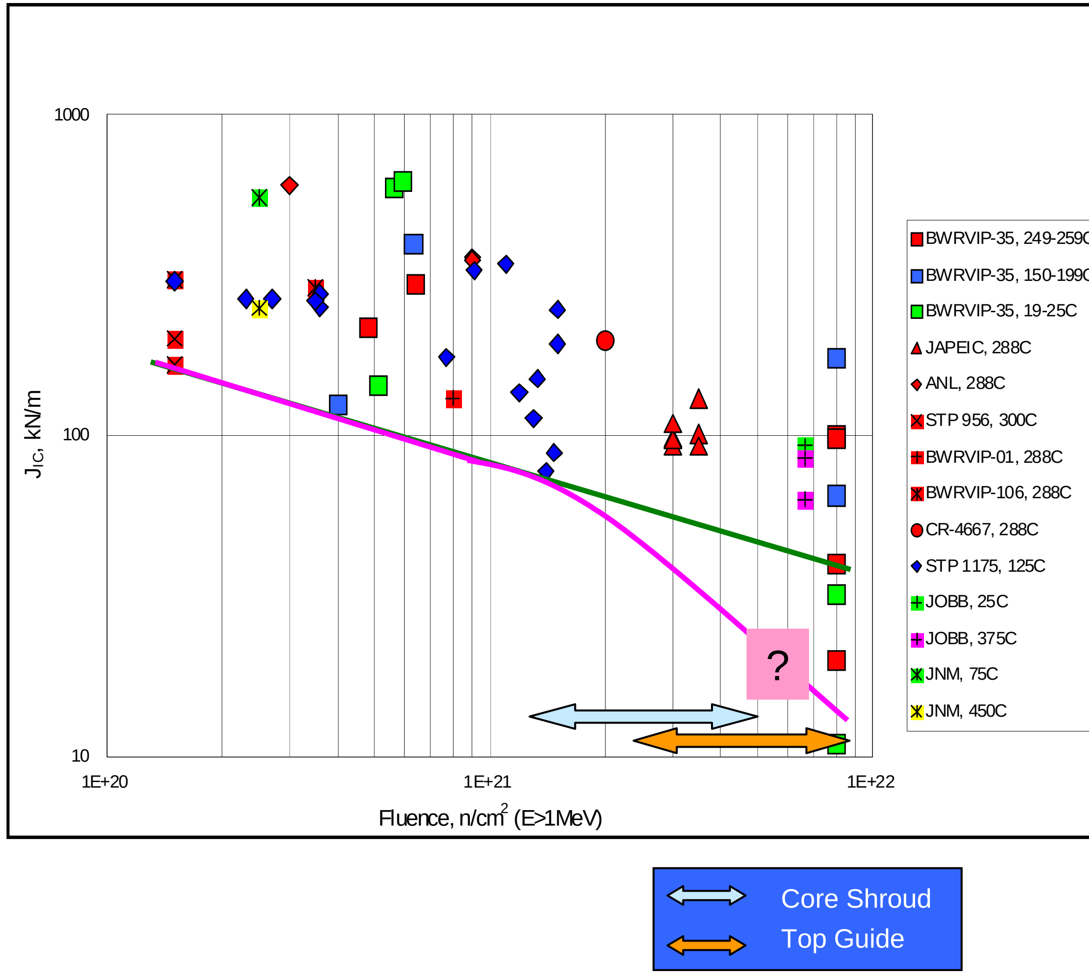
BWRVIP Studies on Crack Growth and Fracture Toughness of Irradiated Stainless Steels

Introduction

- Austenitic stainless steels in BWRs core structures can experience significant fracture toughness reductions at elevated fluence levels
- EPRI identified certain gaps in fracture toughness data at fluences that will become relevant to evaluation of component serviceability
- Project initiated in 2005 to generate additional fracture toughness data of highly irradiated stainless steel
- Irradiated austenitic stainless steels retrieved from disposed BWR internal components

Fracture Toughness Data of Stainless Steels

- Fracture toughness is critical to flaw evaluations and repair decisions
- High priority for more test data at BWR conditions to characterize the material dependence, and the possible temperature dependence, of the fracture toughness transition.



Testing Organizations

- GE and Studsvik selected as primary contractors to conduct testing
  - GE Team
    - GE Vallecitos – crack growth testing
    - Battelle – material characterization
    - University of Michigan – post test SEM
  - Studsvik Team
    - Studsvik – fracture toughness and crack growth testing
    - Nippon Fuels – fracture toughness testing, microstructural and microchemical examination for all fracture toughness specimens

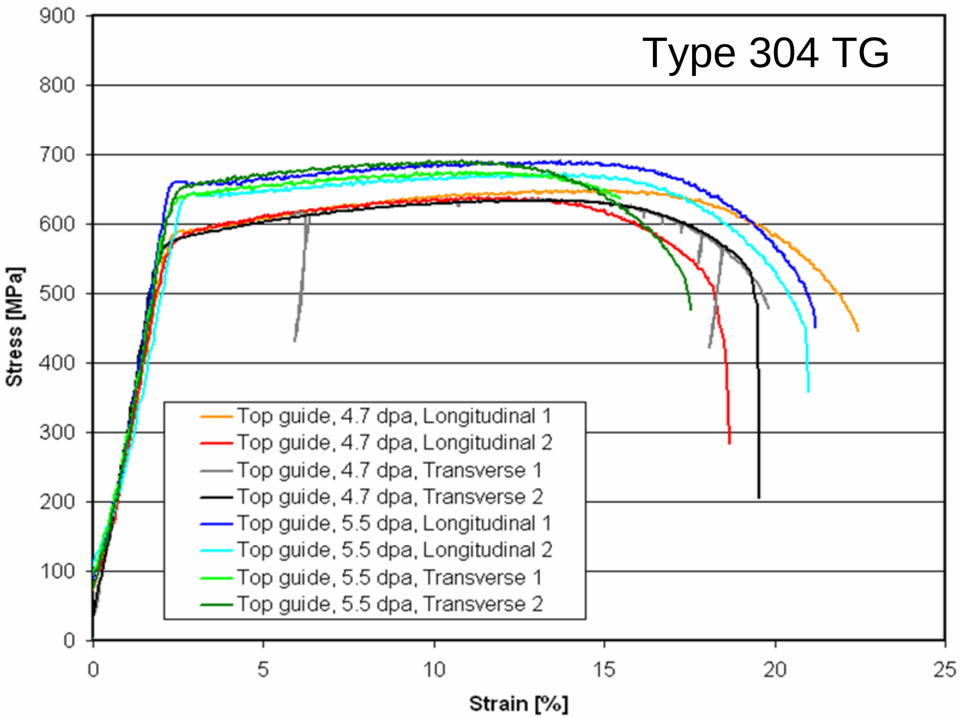
Irradiated Material Fracture Toughness Test Matrix

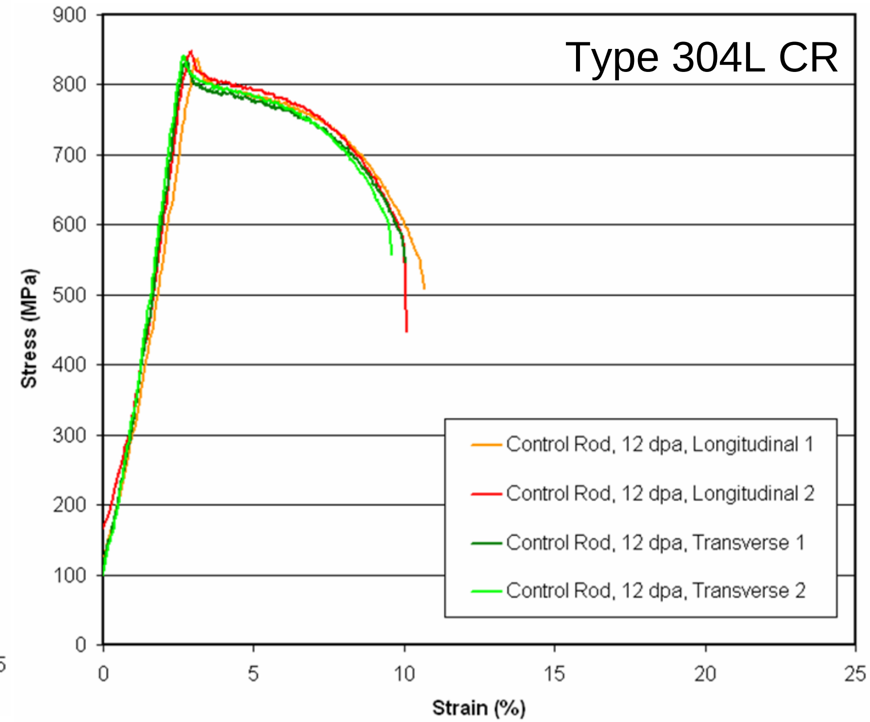
Material	Source	Fluence dpa	# of specimens	Orientation	Lab
304	TG/Forsmark	~1.5	1 + 1	Longitudinal	Studsvik & NFD
304	TG/Forsmark	~1.5	1 + 1	Transverse	Studsvik & NFD
304	TG/Forsmark	~1.6	2	Longitudinal	Studsvik
304	TG/Forsmark	~1.6	2	Transverse	Studsvik
316L	CR/Oskarshamn	~5 - 7	3	Longitudinal	Studsvik
316L	CR/Oskarshamn	~5 - 7	3	Transverse	Studsvik
316L	CR/Oskarshamn	~5 - 7	1	Weld	Studsvik
304L	CR/Barsebäck	12	2	Longitudinal	Studsvik
304L	CR/Barsebäck	12	2	Transverse	Studsvik
304	CR/TEPCO	8	2	Longitudinal	NFD
304	CR/TEPCO	8	2	Transverse	NFD

Yellow: completed

Tensile Test Results

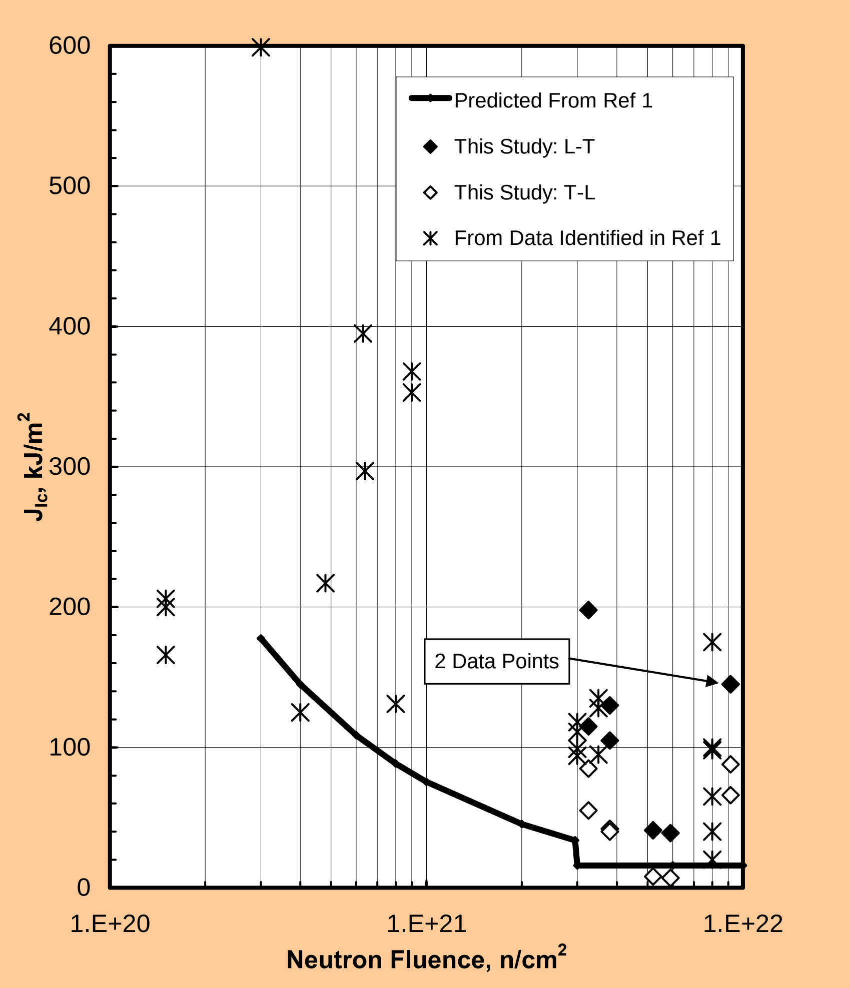
- Significant radiation hardening was observed for all materials
- Strain hardening capacity was lost in all materials except the Type 304 TG.





Fracture Toughness Results

- J_{IC} results
  - J_{IC} data obtained from this study and from Ref 1.
  - Predicted curve for J_{IC} vs. neutron fluence using Ref. 1
- Data obtained from this study are bounded by the prediction methodology with the exception of the two T-L specimens with a J_{IC} of ~40 MPa√m at a fluence of ~5.5 10^{21} n/cm^2



Ref. 1. R.G. Carter and R.M. Gamble, “Assessment of the fracture toughness of irrradiated stainless steel for BWR core shrouds”, Fontevraud 5, September 25, 2002, Fontevraud, France.

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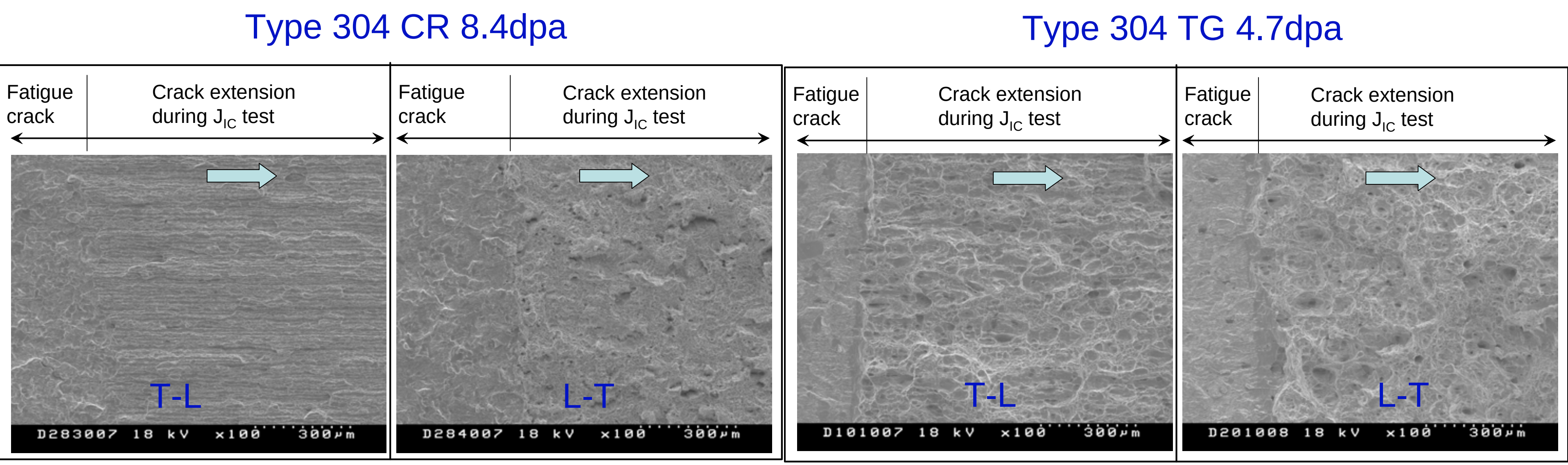
Effect of Orientation on Fracture Toughness

- Fracture toughness is lower in the T-L orientation
  - Fracture surfaces different between T-L and L-T orientations
  - Configuration of fracture surface related to the material orientation affects the fracture toughness

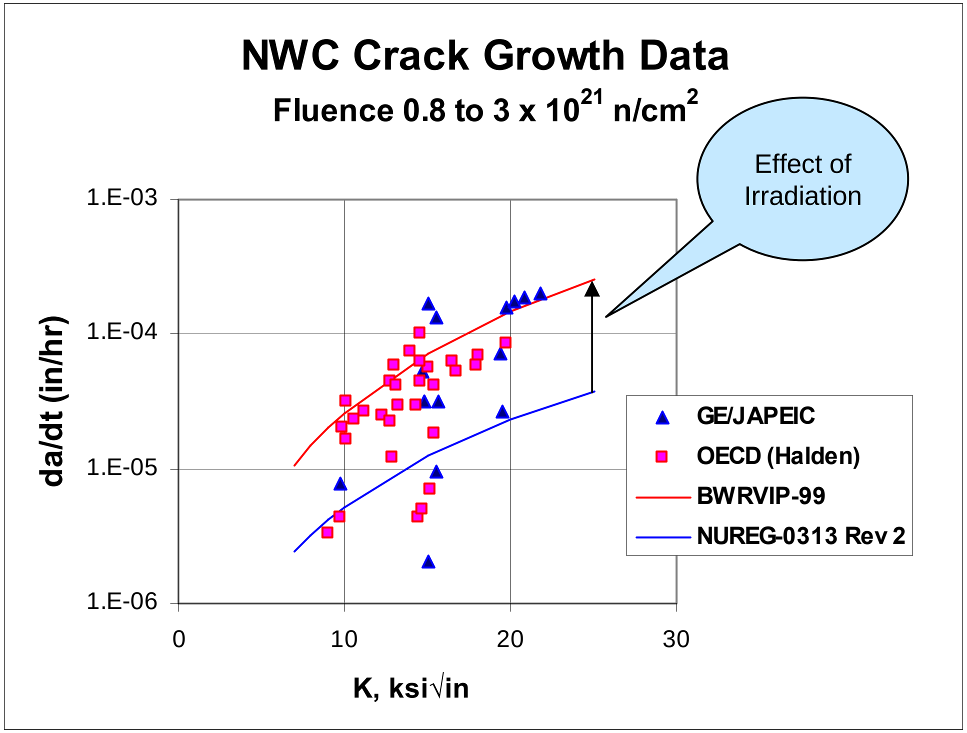


Summary

- Fracture toughness and microstructural/microchemical data generated for BWR-irradiated stainless steel materials
- Significant radiation hardening was observed for all materials
- Orientation effects are apparent with the T-L direction resulting in consistently lower fracture toughness
- Existing correlation of J_{IC} vs. fluence bounds most conditions except two T-L specimens at ~ 5.5 10^{21} n/cm^2

Normal Water Chemistry (NWC) Crack Growth Rate Data

- Irradiation at intermediate fluence accelerates SCC growth rate in stainless steels by a factor of 5 or more
- There are insufficient data at higher fluences to support evaluations in the long term



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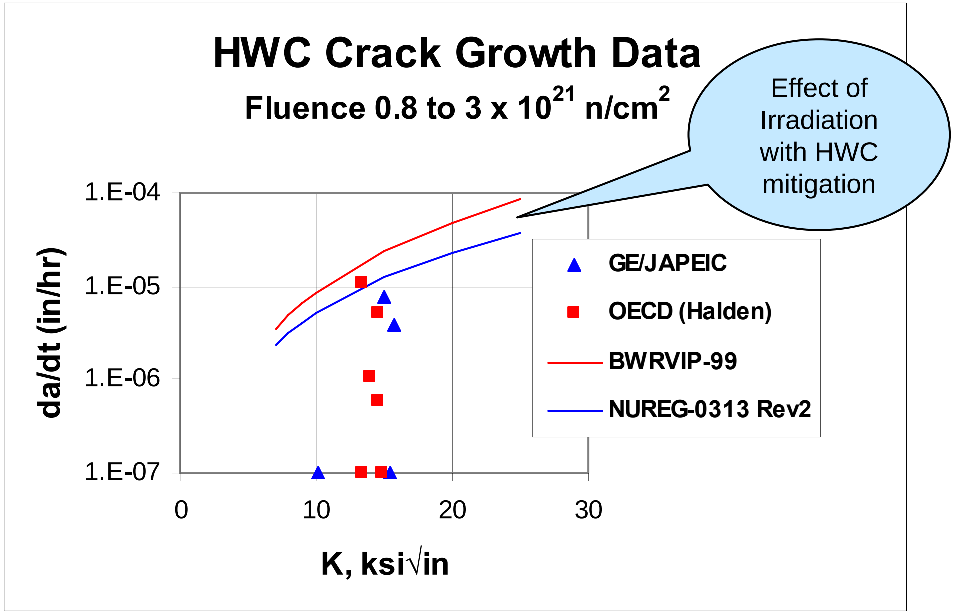
Hydrogen Water Chemistry (HWC) Crack Growth Rate Data

- HWC reduces SCC growth rates
- There are insufficient data at higher fluences to support evaluations in the long term



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Crack Growth Test Matrix Studsvik/NFD

	Material	Source	Fluence, dpa	Fluence (estimated) 10^{21} n/cm^2
Test #1	304L	Control Rod Blade	3.5	2.3
Test #2	304L	Control Rod Blade	7	3
Test #3	304L	Control Rod Blade	10	7
Test #4	316L	Control Rod Blade	5-7	3.3-4.7
Test #5	304L	Control Rod Blade	12	8
Test #6	304 HAZ	Core Shroud	0.8	0.5
Test #7	304 Weld	Core Shroud	0.8	0.5
Test #8	316	Top Guide	0.7 or 1.4	0.5 or 0.9

Studsvik: Test Sequence for CGR Measurements

Table 3-2
Test Sequence for Crack Growth Measurements in NWC and HWC at Different Stress Intensities

Step	Water Chemistry	Stress Intensity MPa√m	R	Frequency, f Hz	Crack Increment mm
1-6	IG transitioning, see Table 3-1				1.2
7	2 ppm O_2, pure water, 288°C	11	1	Constant K_I	0.4
8	100 ppb H_2, pure water, 288°C	11	1	Constant K_I	0.2
9	2 ppm O_2, pure water, 288°C	11	1	Constant K_I	0.1
10	2 ppm O_2, pure water, 288°C	Ramp → 14	0.6	0.001 sine	0.2
11	2 ppm O_2, pure water, 288°C	14	1	Constant K_I	0.4
12	100 ppb H_2, pure water, 288°C	14	1	Constant K_I	0.2
13	2 ppm O_2, pure water, 288°C	14	1	Constant K_I	0.1
14	2 ppm O_2, pure water, 288°C	Ramp → 18	0.6	0.001 sine	0.2
15	2 ppm O_2, pure water, 288°C	18	1	Constant K_I	0.4
16	100 ppb H_2, pure water, 288°C	18	1	Constant K_I	0.2
17	2 ppm O_2, pure water, 288°C	18	1	Constant K_I	0.1

$R = K_{min}/K_{max}$

Studsvik: CGR Measurements 3.5 dpa, (K = 14 MPa√m)

HWC Reduces CGR by Factor of ~ 5.8

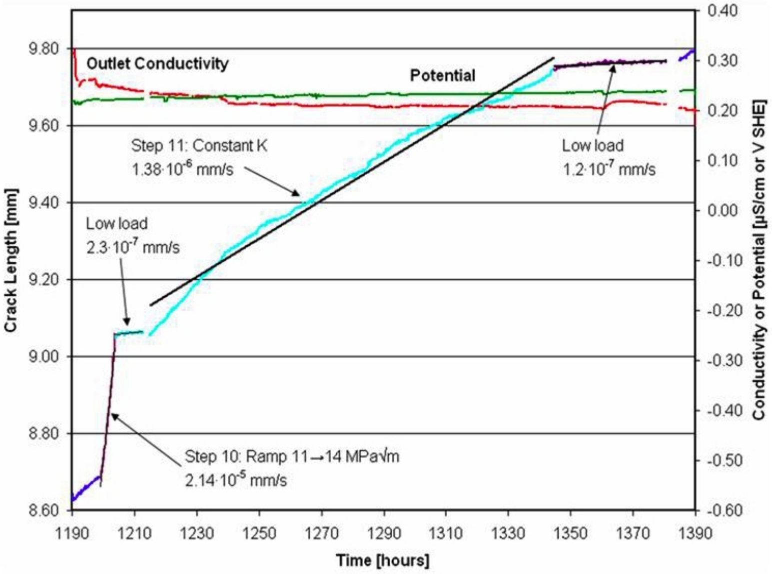

Figure 4-6
Crack Length versus Time (Non-Linear Correction) during Steps 10 and 11

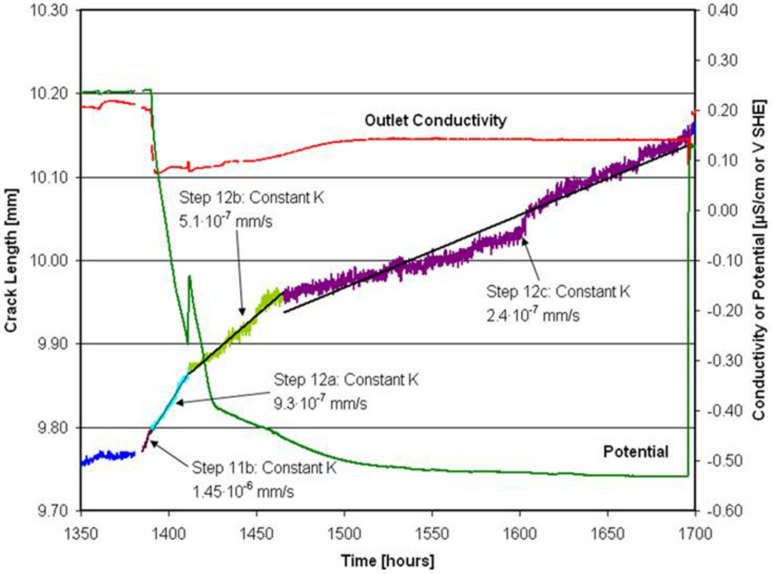

Figure 4-8
Crack Length versus Time (Non-Linear Correction) during Steps 11 and 12

Summary of Crack Growth Rate Testing

- Initial testing on Type 304L, 3.5 dpa material shows that hydrogen injection reduces crack growth rate at K values of 11-18 MPa√m
- Tests continuing into 2009
- Test data will be used to revise and update BWRVIP-99 report

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