Environmentally Assisted Cracking of Structural Materials in Light Water Reactors

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Talk Structure

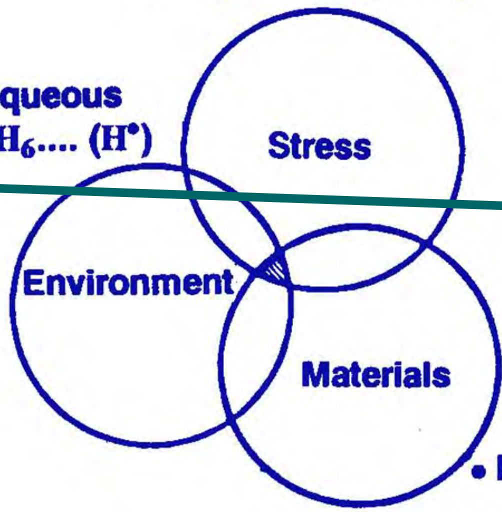
- *History of industrial and nuclear SCC.*
- *Complexity of environmental effects with ~10 categories, involving ~7 major disciplines and hundreds of variables.*
- *Lore based on poor data and wishful optimisms, driven by Pressure Vessel Code requirement of "immunity".*
- *Inadequate experiments.*
- *SCC "initiation" vs. growth.*
- *Underlying mechanisms, sub-processes and SCC prediction.*

I want to acknowledge Peter Ford & GE & international colleagues, especially the International Cooperative Group on EAC.

Spectrum of Environmental Cracking

- Static & Dynamic (monotonic & cyclic)
- Cracking on Smooth Specimens at <1 ksi
- Range of frequency, ΔK, $\Delta\sigma$....

- Aqueous & non-aqueous
- Gaseous: H_2, C_2H_6.... (H°)
  - N_2O_4
  - Steam
  - O_2, Air ?
- Liquid Metals



- Metallic & Non-metallic (glasses, plastics, ceramics)
- Crystalline & Amorphous
- High strength & Ductile
- Alloys & Pure Metals

ENVIRONMENTAL CRACKING

- Rates $<10^{-12}$ to 10^{0} m/s
- Stress Corrosion Cracking
- Corrosion Fatigue
- Hydrogen Embrittlement
- (Liquid Metal Embrittlement)
- (Environmental Creep-Fatigue)

A large universe encompassing:

Range of loadings…

Liquids & gases…

Ceramics & glasses…

Range of growth rates…

Many names….

Within this universe, we'll focus on Fe-Ni-Cr alloys in ~300 °C water

SCC of Boilers – Origin of ASME Boiler Codes

April 27, 1865: S S Sultana, a Mississippi River steamboat, sank after 3 or 4 boilers exploded and killed ~1,500 of 2,400 passengers

Below is the Glover Shoe Factory, leveled on March 20, 1905

Equipment Failures

SCC Failure, Hinkley Point Nuclear Steam Turbine

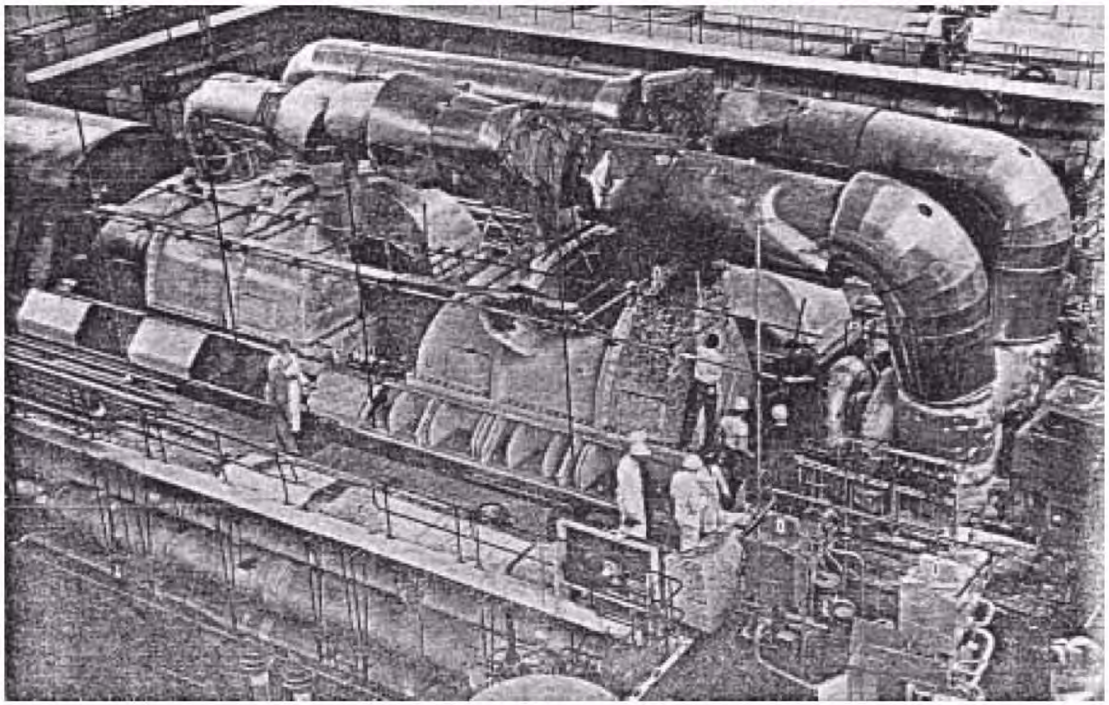


Fig. 2 Appearance of the No.5 unit after the failure.

Failure of 3Cr-0.5Mo steel (acid open hearth, low fracture toughness) occurred after 1.6 mm of SCC growth

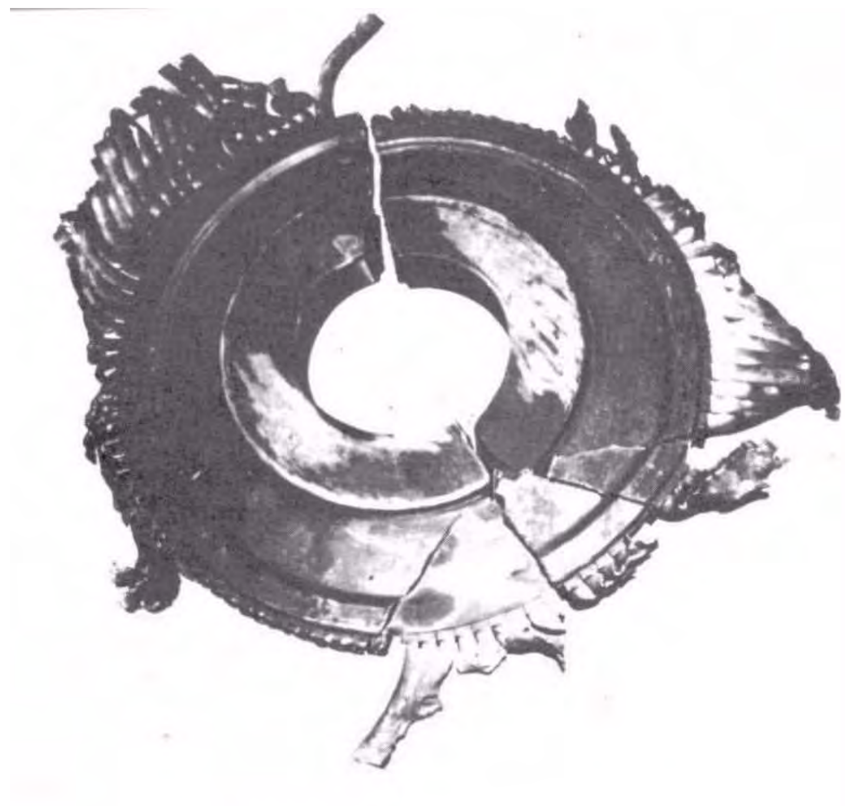


FIG.7 FRACTURED LP No3 DISC FROM 200 MW REHEAT TURBINE

It is interesting to study small cracks that destroys huge machines that provide most of the world's electricity, and can injure or kill thousands of people.

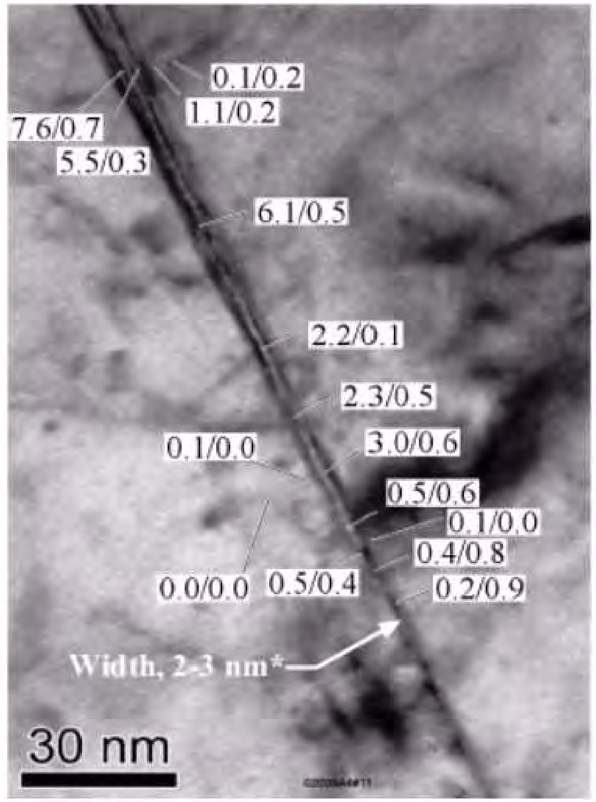
SCC in LWRs

From equipment manufacture and failure, to laboratory testing, to atomic scale analysis.

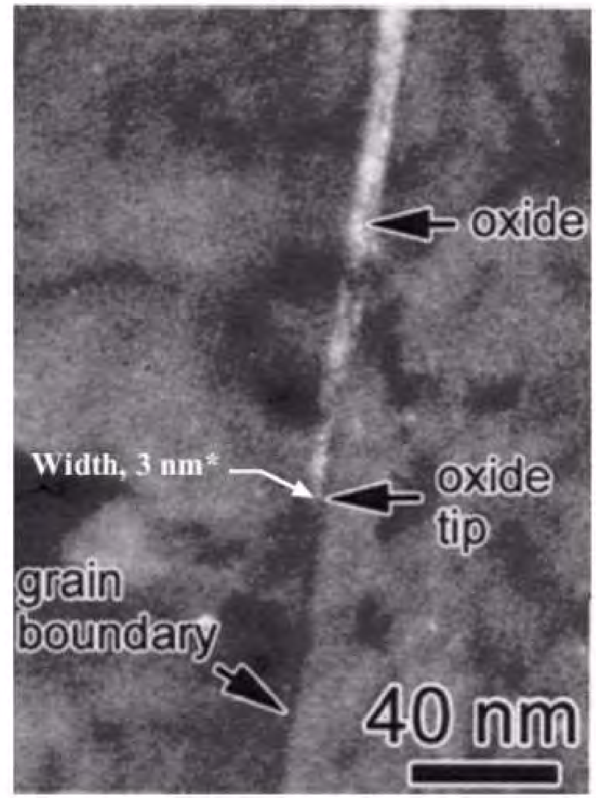
High resolution images of cracks growing in huge commercial nuclear steam generators where SCC had occurred.

Pb/Cu values are shown.

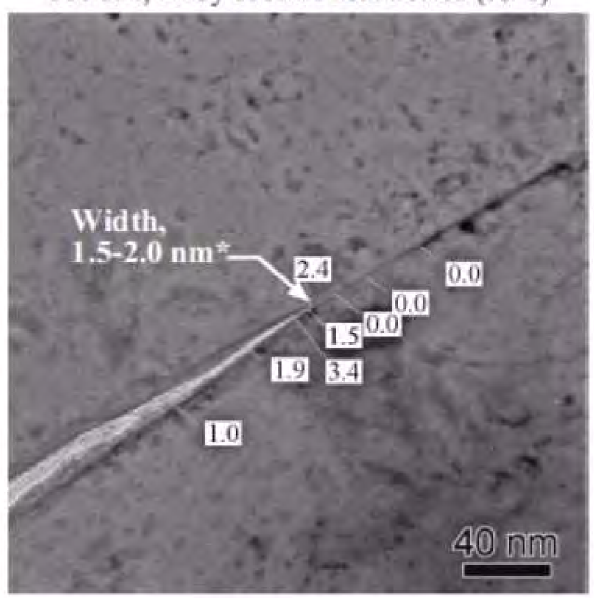
Farley-1 steam generator, secondary side, Alloy 600 (%Pb/%Cu)



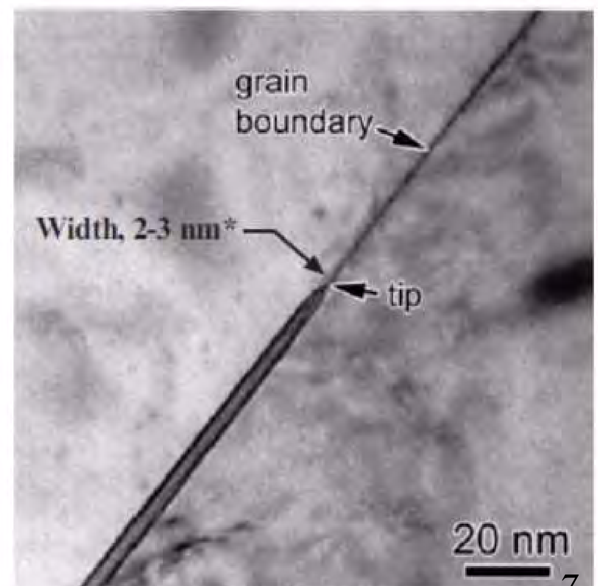
Farley-1 steam generator, secondary side, Alloy 600



Seabrook-1 steam generator, nominal Alloy 600 bal., Alloy 600MA heat treated (%Pb)



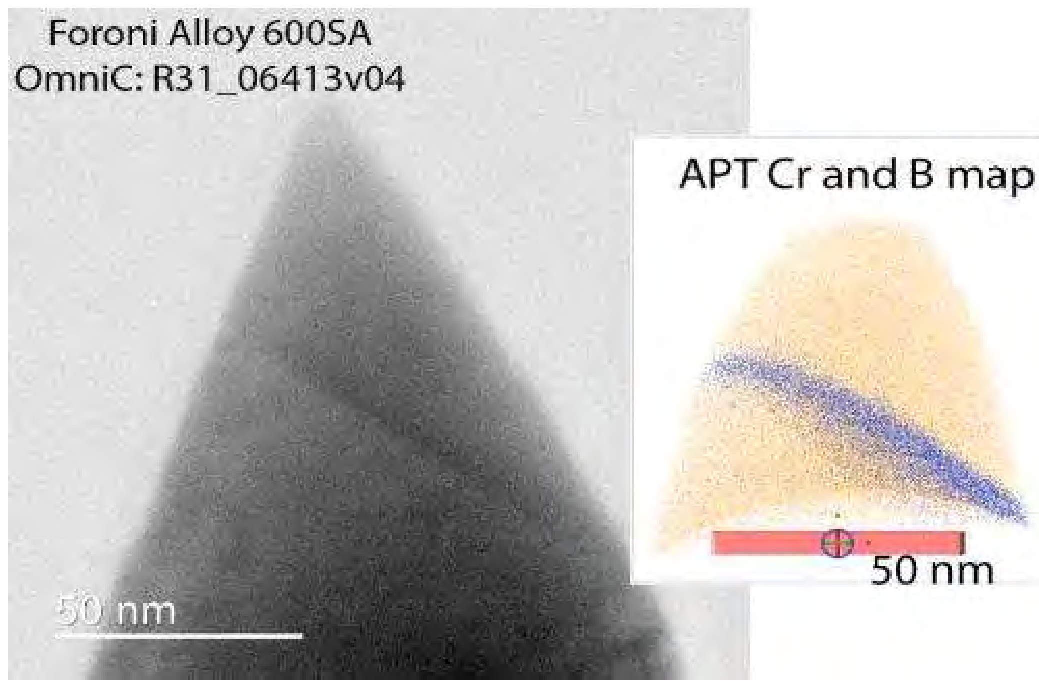
CIEMAT laboratory test, Alloy 600, 320°C



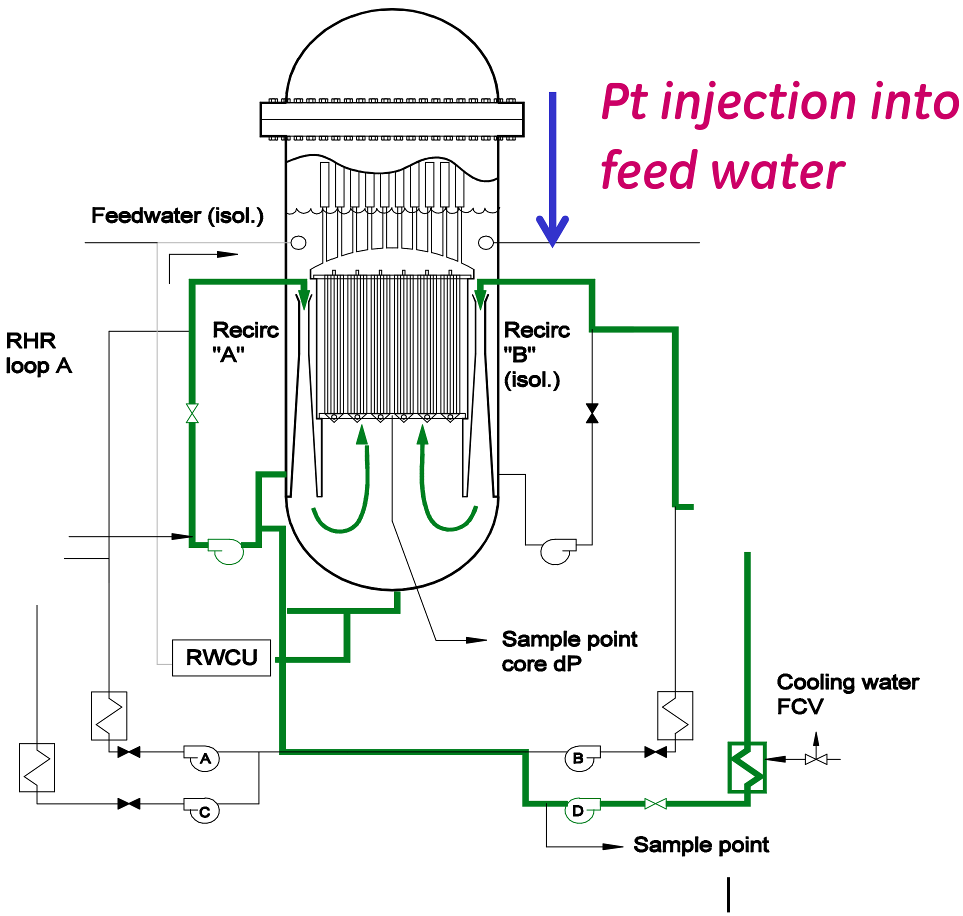
SCC in LWRs

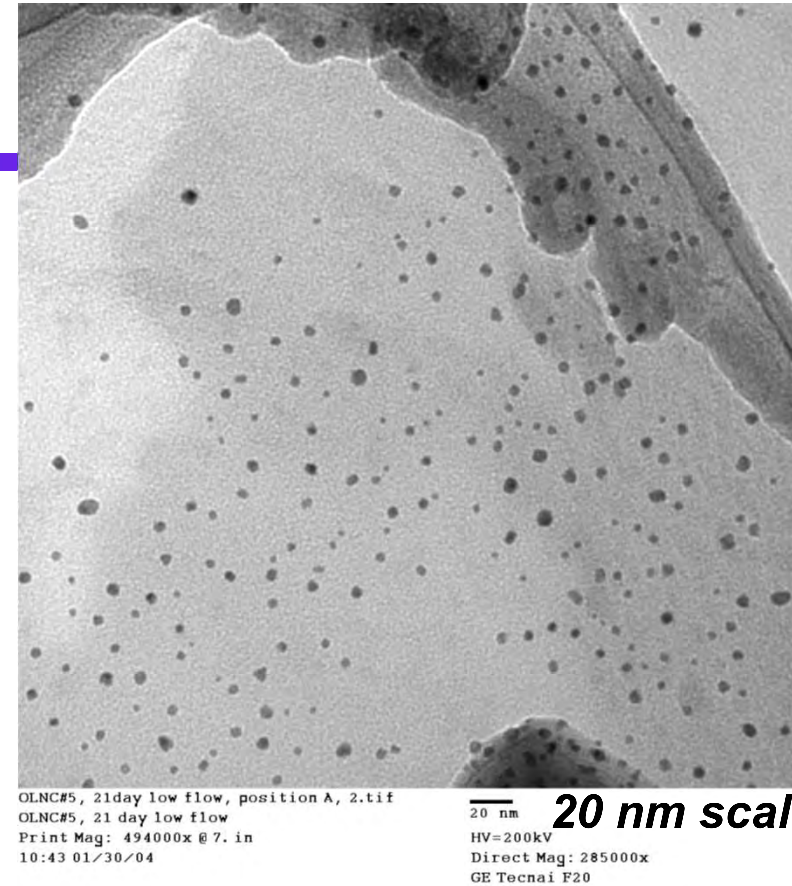
AOD / VIDP n°	07027	
VAR / ESR n°	31907	
Steel making process: E.A.F./A.O.D. + V.A.R.		
Chemical analysis		
% w	Heat	Product
C		0,01
MN		0,46
SI		0,22
CR		15,6
NI		75,1
MO		0,03
S		0,0002
P		0,0092
CU		<0,01
CO		0,011
AL		0,22
TI		0,28
B	→	0,0023
FE		7,92

Boron segregation to grain boundaries as measured by Atom Probe Microscopy

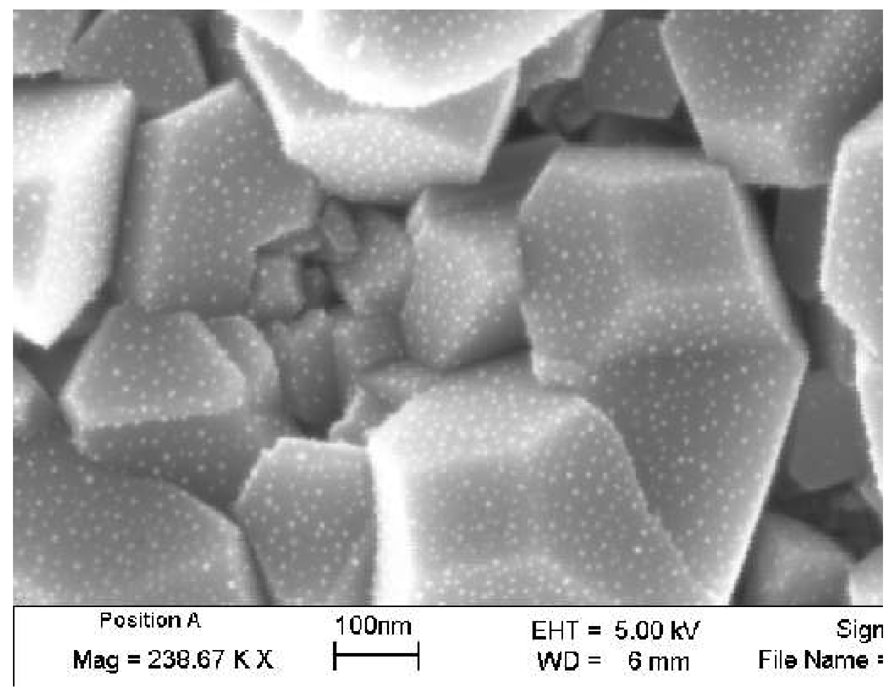


Electrocatalysis in BWRs





20 nm scale



OnLine NobleChem™ yields 1 - 3 nm Pt clusters on all wetted surfaces in a simple process during plant operation.

SCC of Boilers – Origin of ASME Boiler Codes

In the 1850s, over 50,000 people died & >2,000,000 injured in one year in the U.S. from boiler explosions (population ~23 million). This may be one of the first widespread & major industrial issues related to environmentally assisted cracking.

It helped drive the ASME Boiler and Pressure Vessel Codes, which first came out in 1914, developed by mechanical engineers to improve design margins against overload and fatigue design.

The Codes have still not addressed the original issue, and account for environmental effects simply as a correction or offset to the fatigue response. The Codes merely insist that "SCC be avoided".

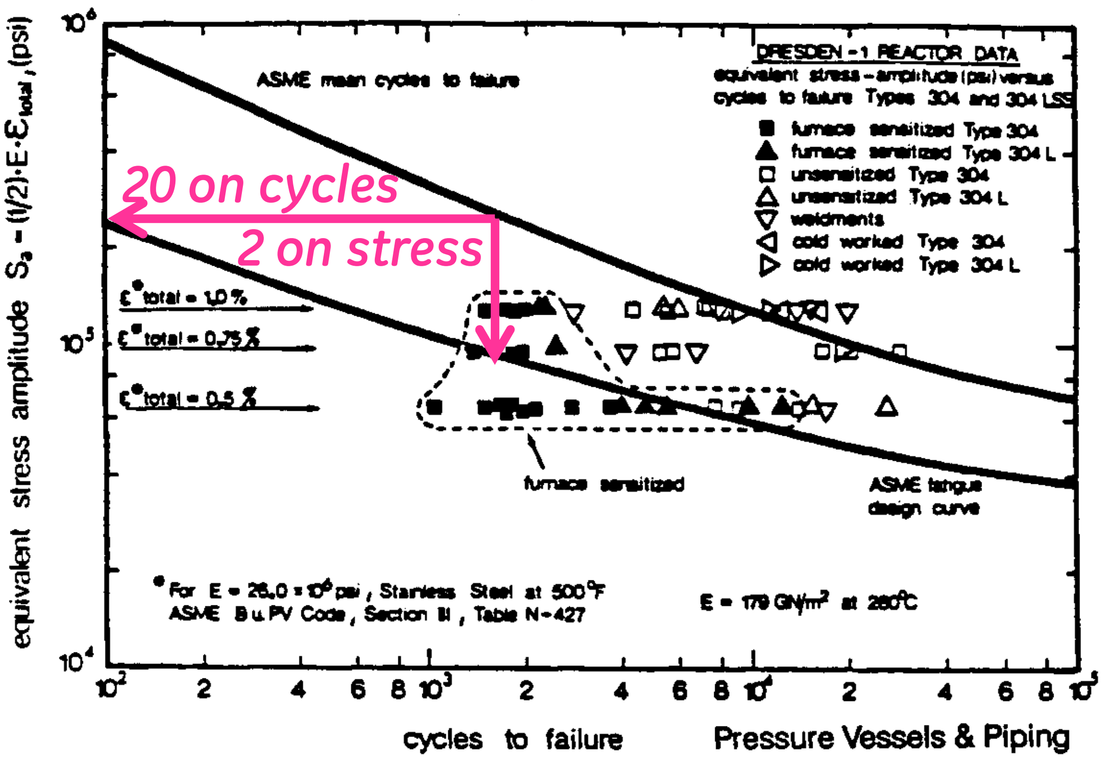
Most designers consider their <u>only objective</u> is to satisfy the design code. It should be viewed as a <u>first step</u>, a beginning.

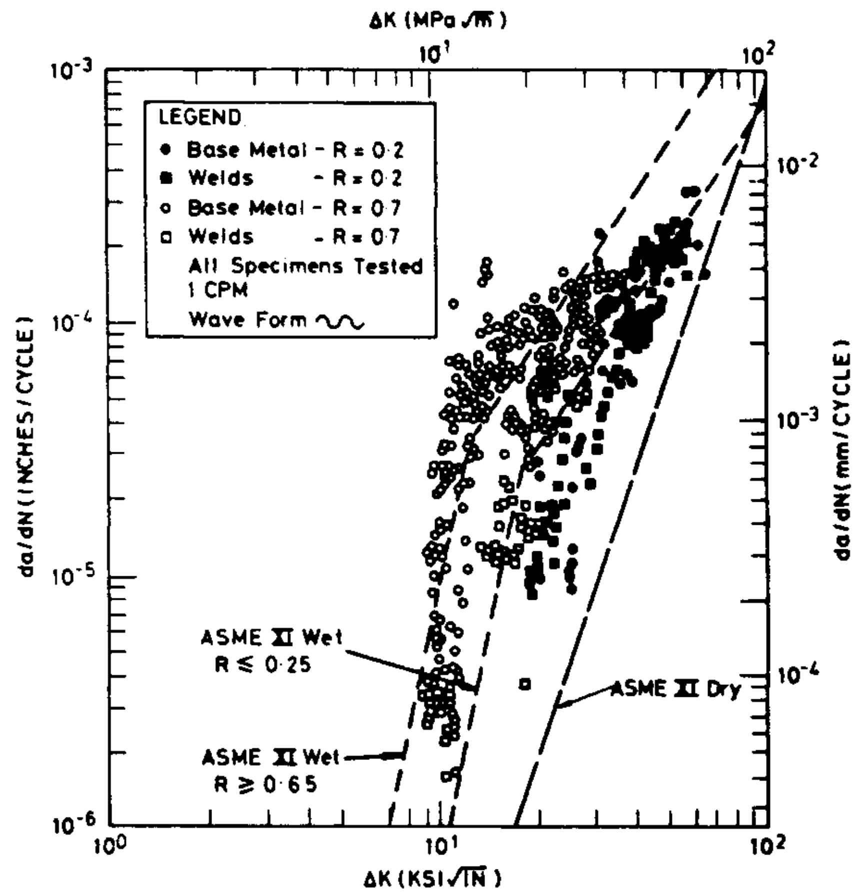
Corrosion Fatigue

Crack initiation (ASME Section III Design Curves)
- to prevent cracks -

Crack growth (ASME Section XI Life Evaluation Curves
- when cracks are detected -

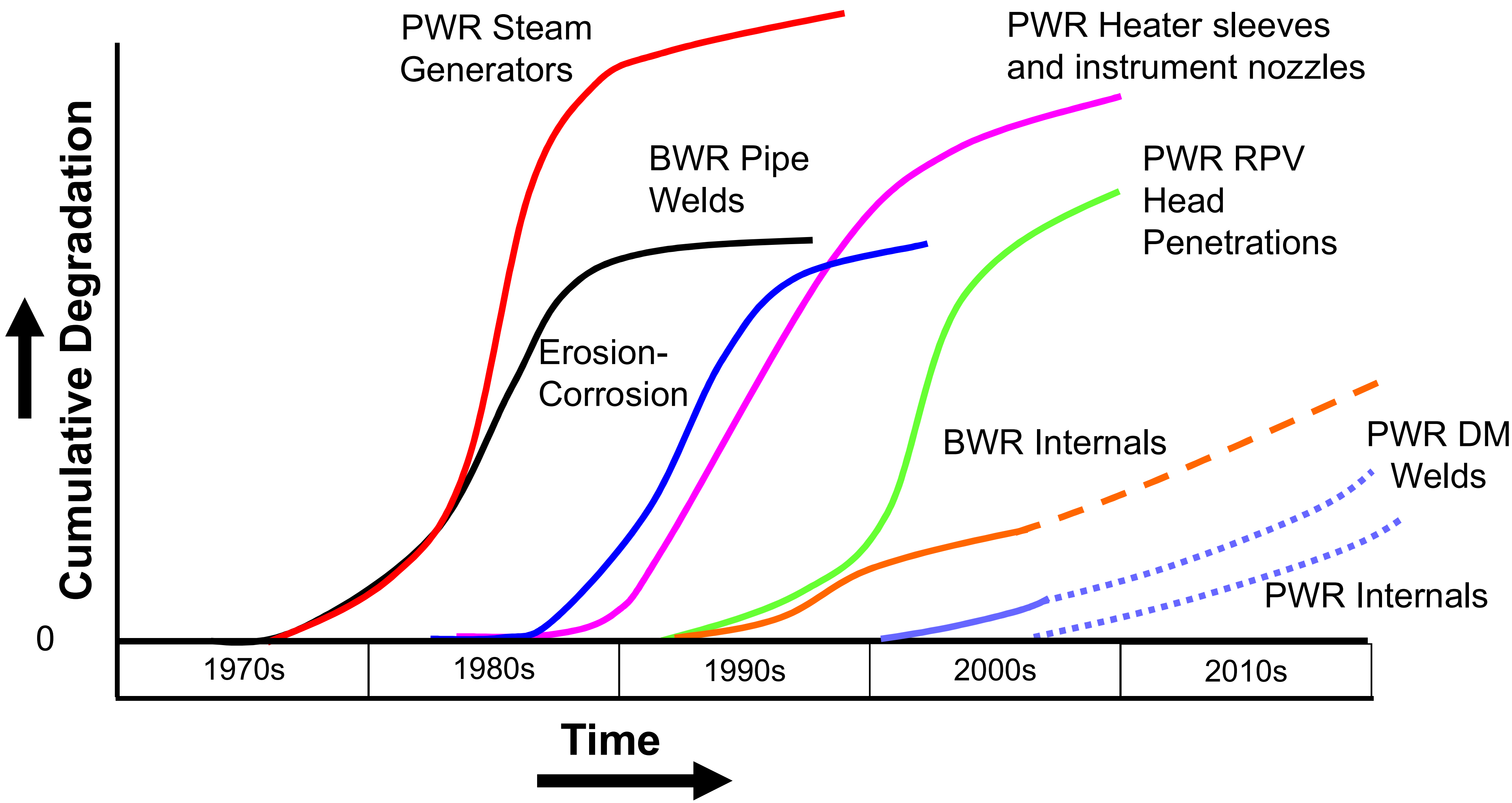
2-and-20 is for scatter, surface finish & size effects





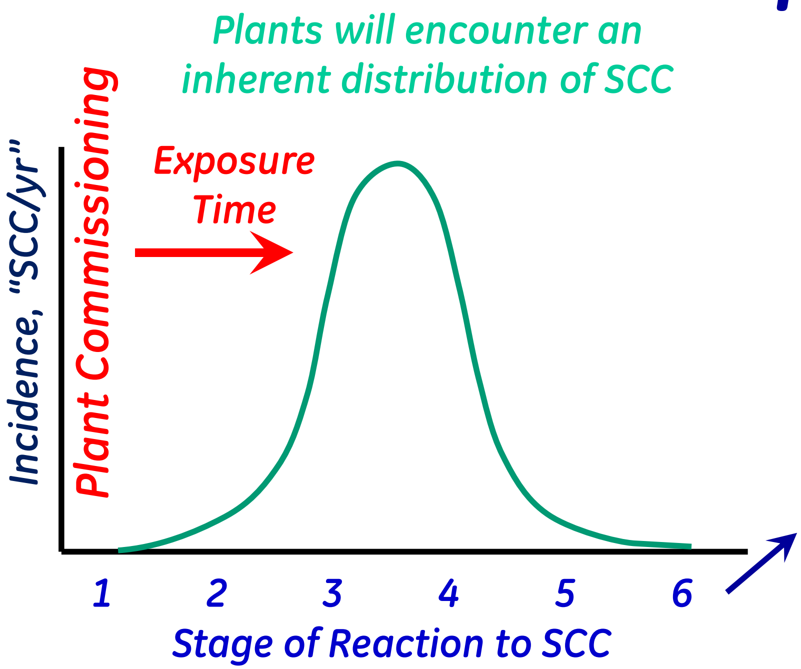
If the Section III Design Code was sufficient, the Section XI Life Evaluation (for how cracks grow) would not be needed!

Continuing Evolution of Materials Degradation



Not linear vs. time. Continuing, new degradation

Resolving vs. Re-solving SCC



The oft-repeated sequence to SCC occurrence:

1 – Design optimism: "immunity"

2 – First occurrence: unique, dismissed/explained

3 – Concern as SCC incidence rises

4 – High priority programs to explain / mitigate

5 – Implementation of mitigation / replacement

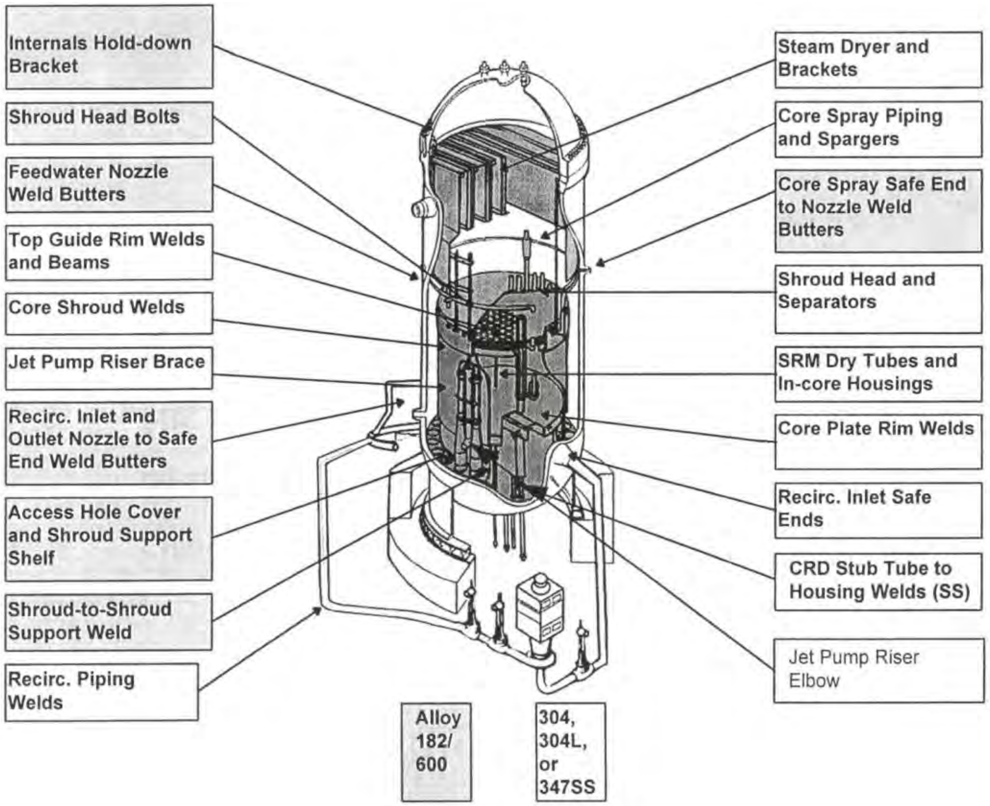
6 – Possible discovery of shortcomings, oversights

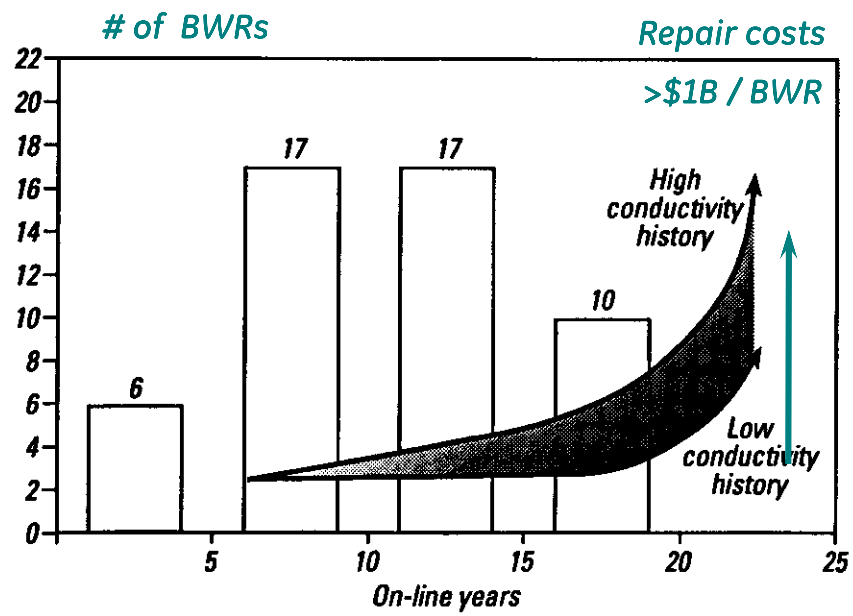
- BWR examples: cold work, crevices, furnace sens, weld sens, IASCC, unsens SS, Alloy 182, creviced 600….
- PWR examples: MA 600, TT 600, 600/182 upper head, lower head, RPV nozzle, SG nozzle, pressurizer, SS baffle bolts….

➢ Outdated ASME design codes avoid SCC and rely on "immunity".

➢ Can we rely on initiation in a 10 μm skin of a complex, welded part?

SCC in BWR Sens. SS Piping → Core Components





Operating BWRs in ~2010

	N. America	Europe	Asia	Total
GE	36	4	11	51
Non-GE	0	16	21	38

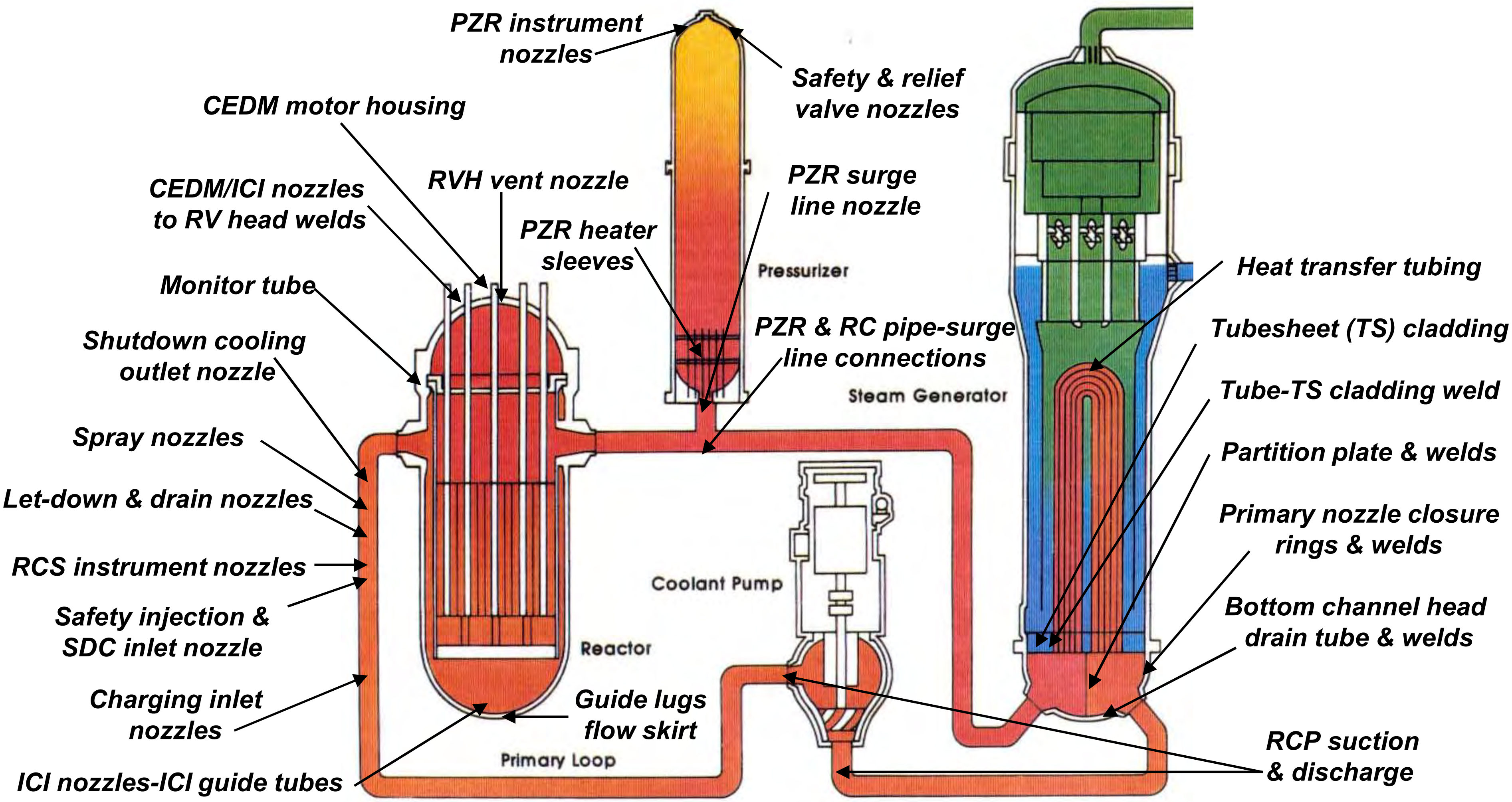
80,000 MWe installed; 7,400 MWe in construction

Stress Corrosion Cracking History

- 1969 1st detected in sensitized SS
- 1970s Stainless steel welded piping
- 1980s BWR internals
- 1990s Low stress BWR internals

→ NobleChem™ SCC mitigation

PWR Design (Shows A600/82/182 Use)



SS failures in many areas: seals, check valves, heater sleevers, irradiated SS… – recent cracking in weld HAZs

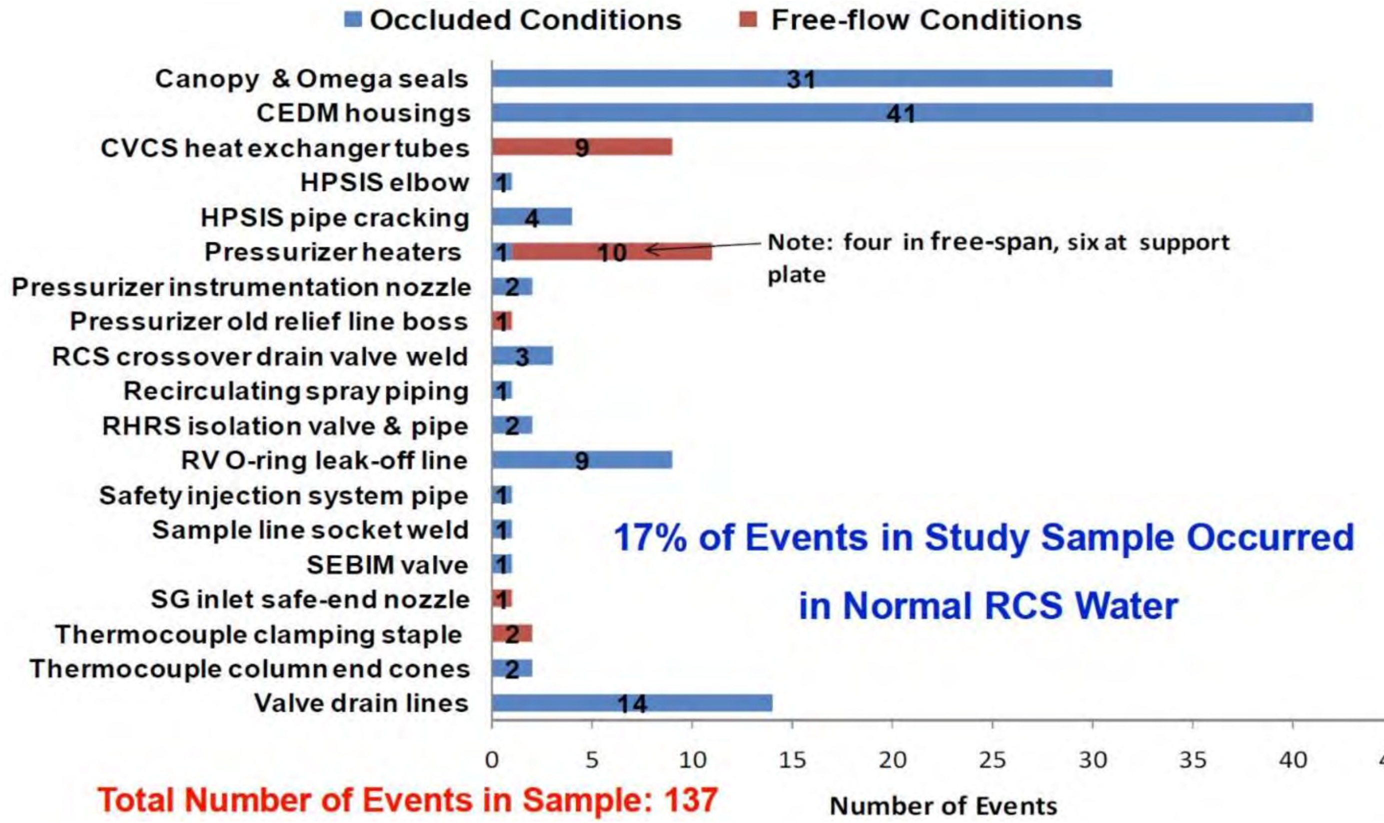
SCC of Stainless Steel in PWRs

- Optimism about SCC resistance of SS in PWR primary water.

- SCC increasing observed, including in the last six months in 8 PWRs in France: ~6 mm deep SCC in 300 mm diameter safety injection lines.

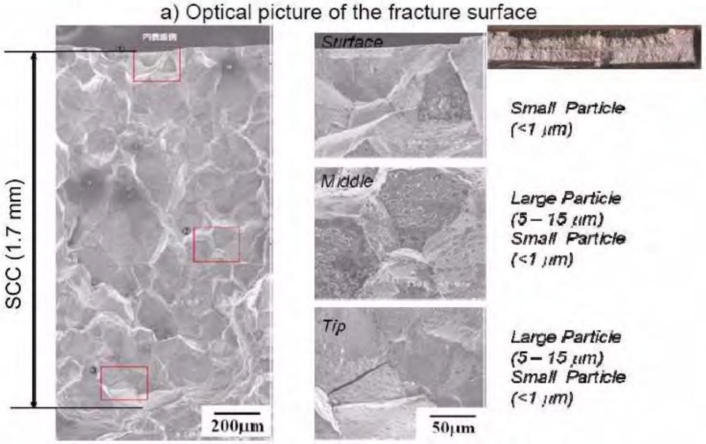
- SCC of SSs is now a generic issue in PWRs given:
  - Extensive SCC in elbows in Daya Bay PWR
  - SCC in Mihama-2 steam generator nozzle weld HAZ
  - Ohi-3 pressurizer spray line

SCC of SS in PWR Primary Water

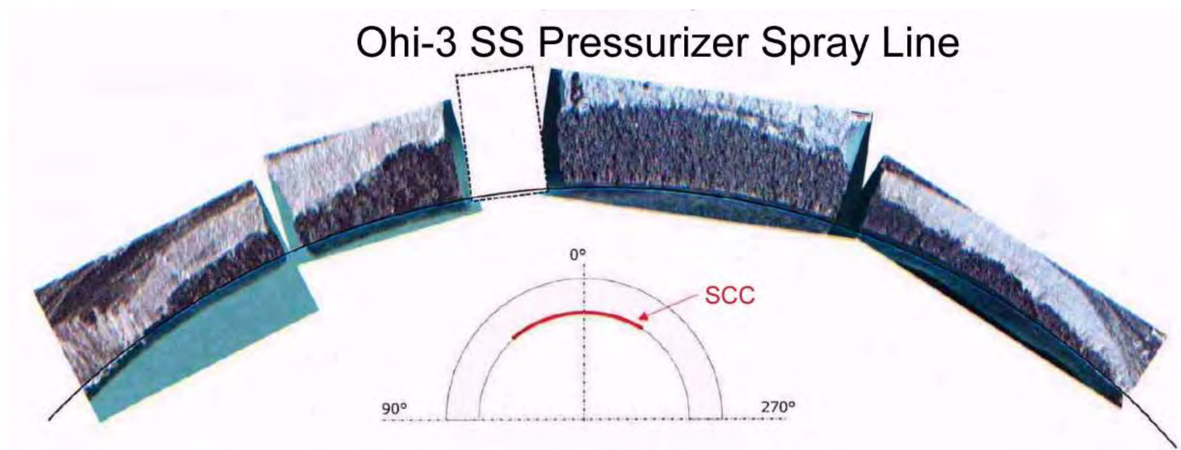


Mihama-2 SG HAZ

a) Optical picture of the fracture surface



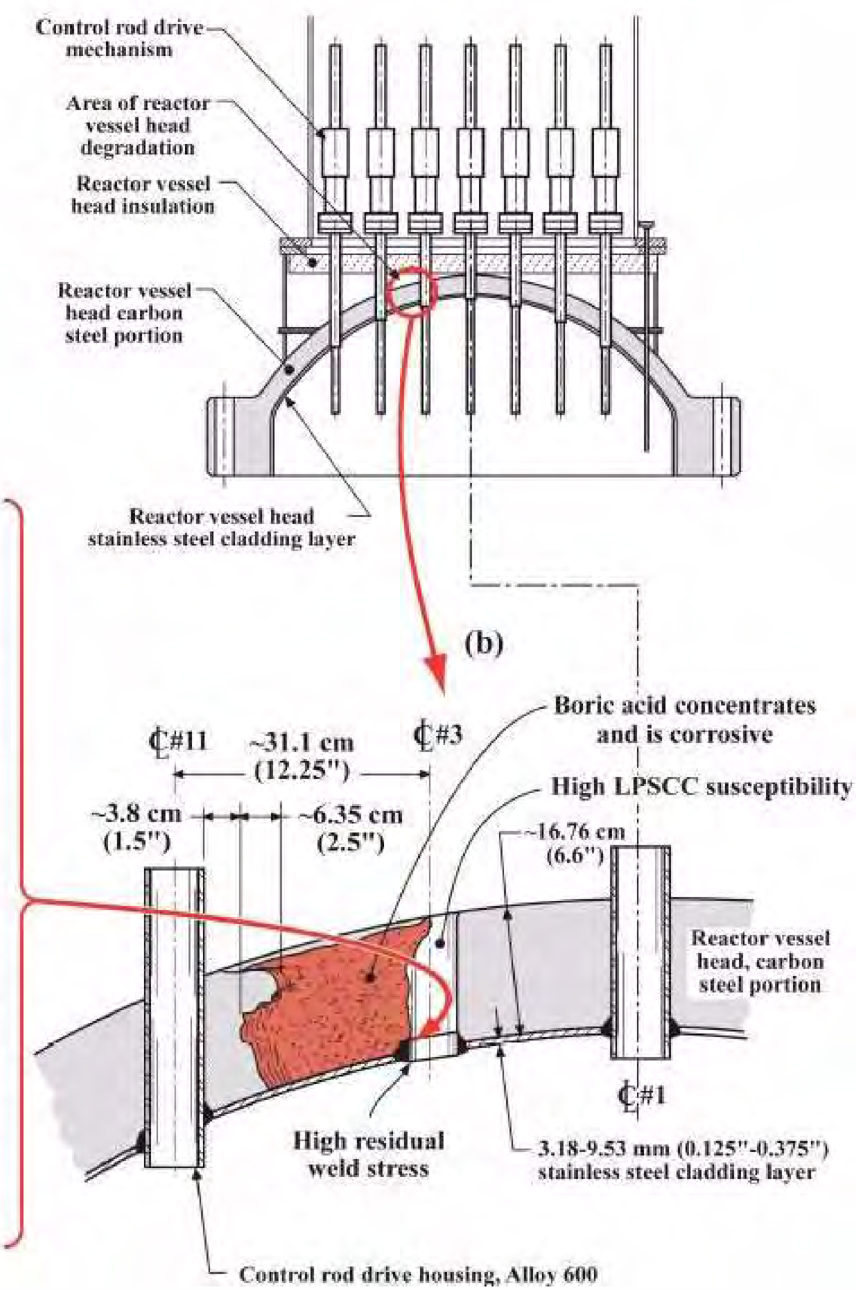
Ohi-3 Pressurizer Spray Line



Davis-Besse CRDM

SCC at Alloy 600 control rod drive housing in Davis Besse PWR plant. SCC perforated tube wall and allowed primary water to exit and the boric acid to accumulate.

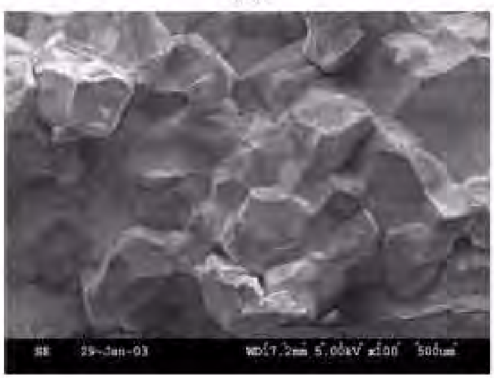
(a)



(c)

Dual etch 100X

(d)



SE 100X

(e)

Nozzle #3 with insulation removed and shielding installed 03-16-02

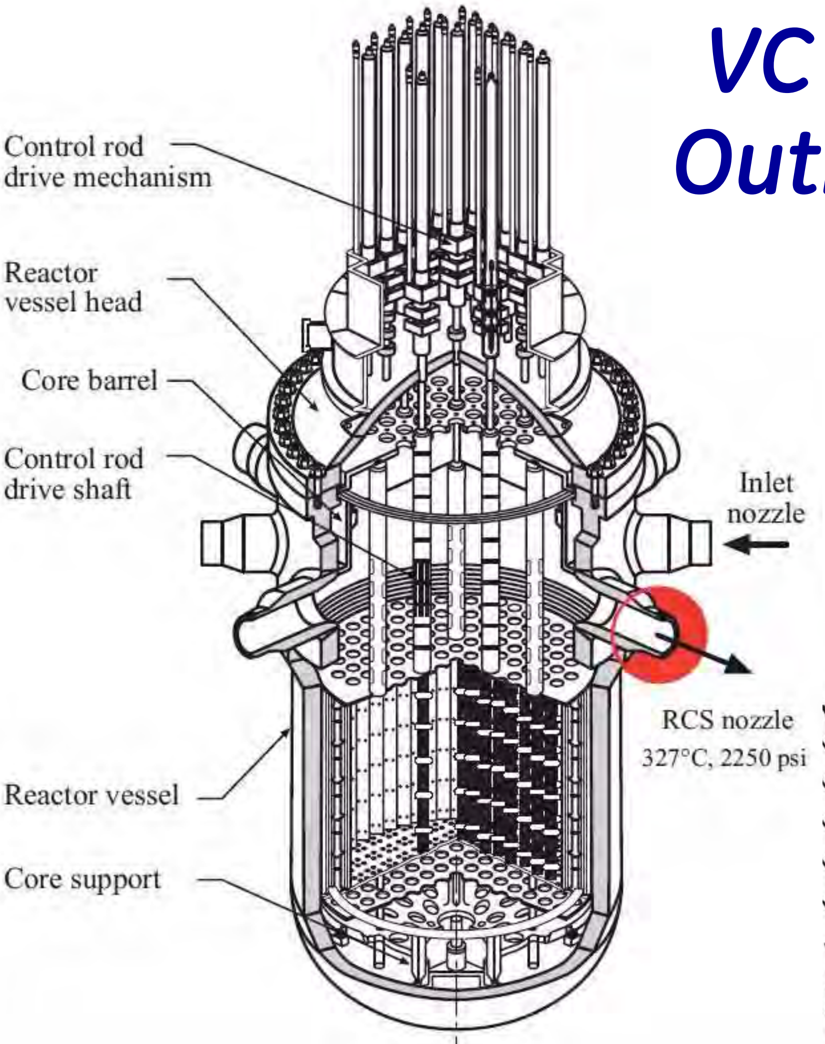
(f)

Nozzle #3 cleaned

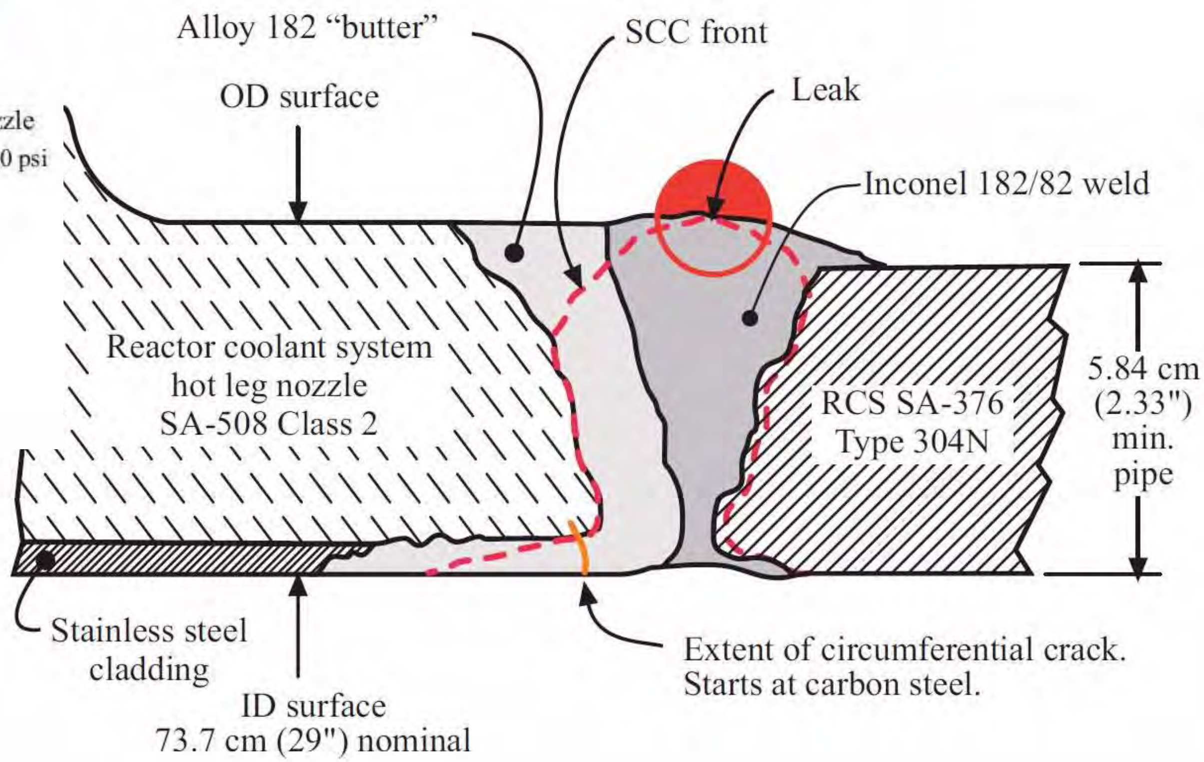
(g)

LPSCC crack in cladding

SCC in LWRs

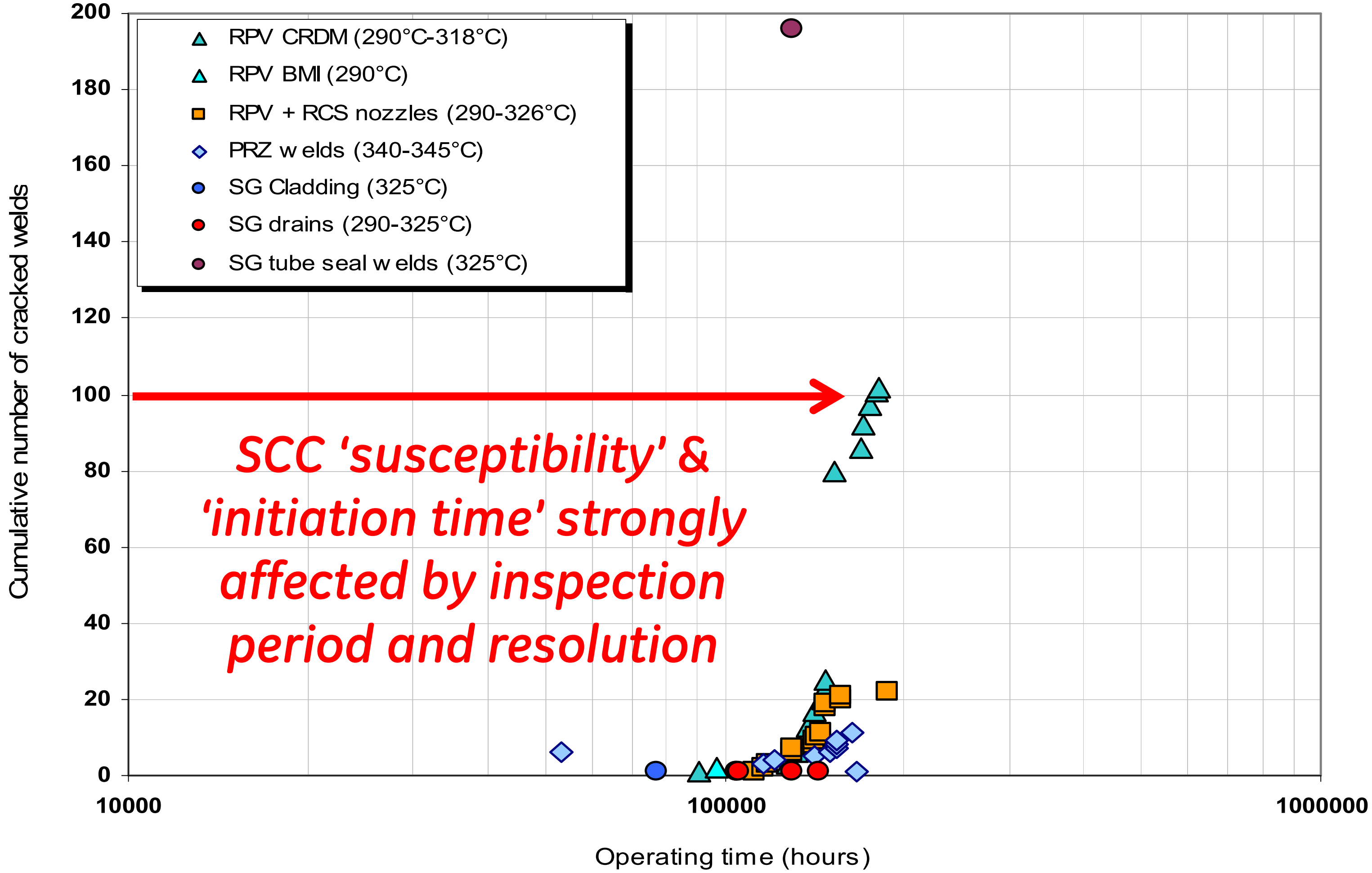


VC Summer Outlet Nozzle



Most first-of-a-kind SCC is found by leakage.

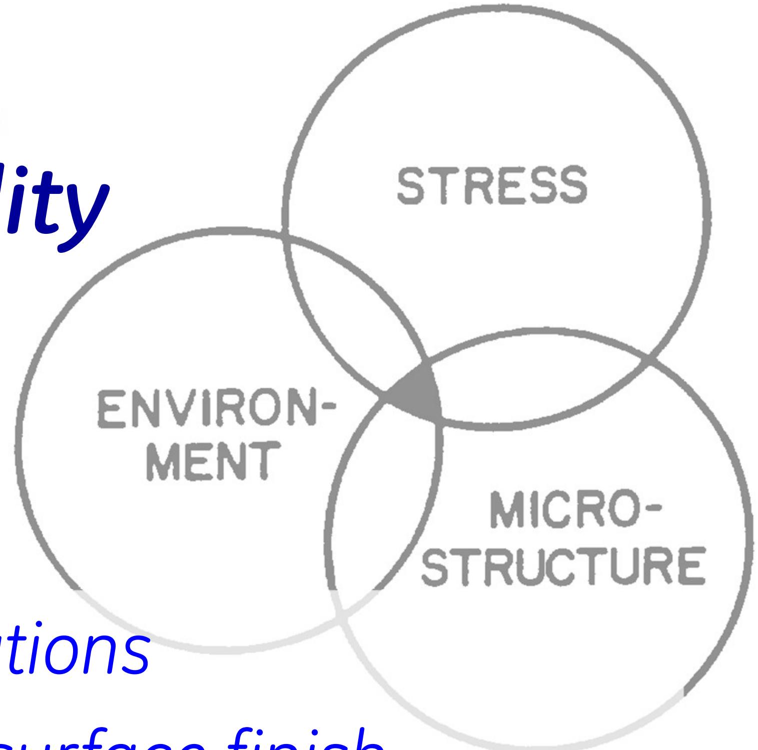
Operating Times to Alloy 182 Weld Cracking

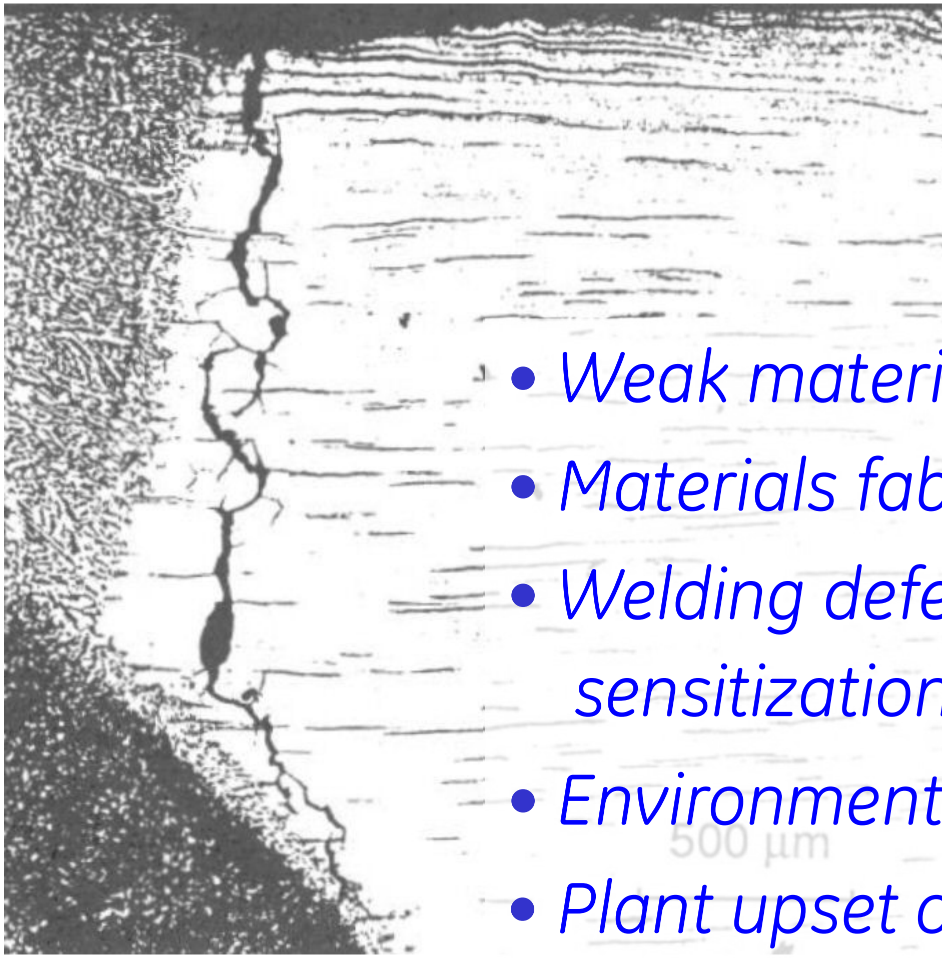


Sir Francis Bacon: "Hope is a good breakfast, but it is a bad supper."

"They are ill discoverers that think there is no land, when they see nothing but sea." (land=SCC, sea=no problems to date).

Key Sources of SCC Vulnerability





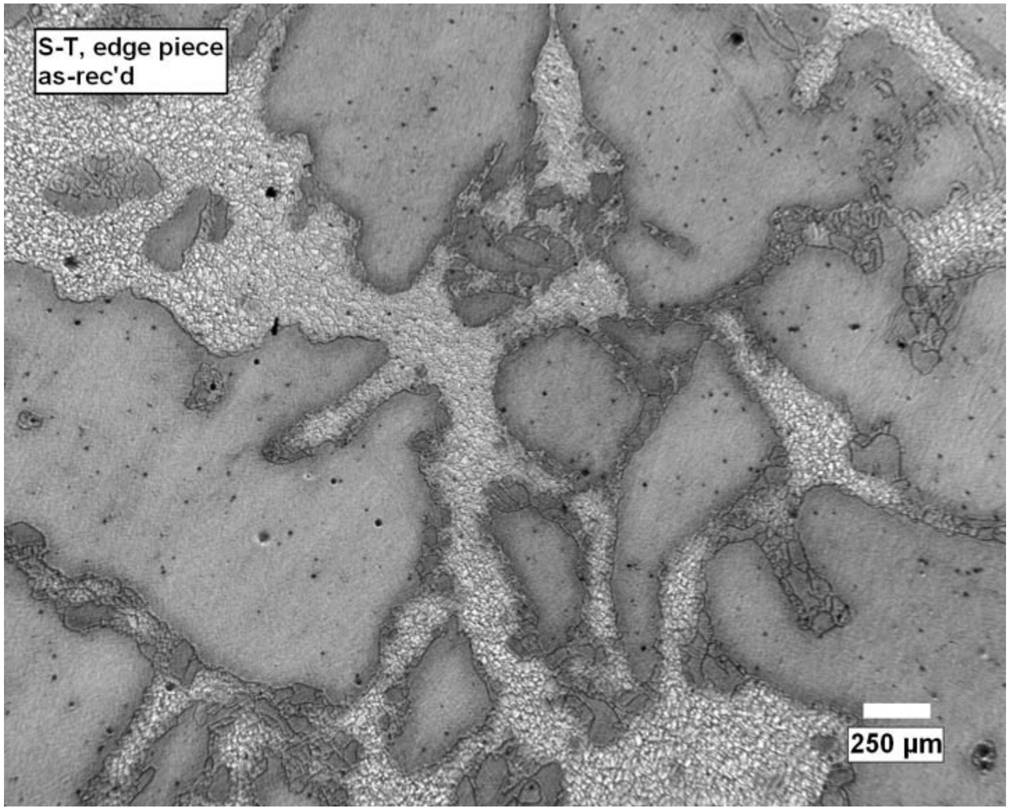
- Weak material specifications
- Materials fabrication & surface finish
- Welding defects, residual stress/strain, sensitization, grinding, sharp corners…
- Environment – boiling, crevices, O_2, Pb…
- Plant upset operation & operating changes

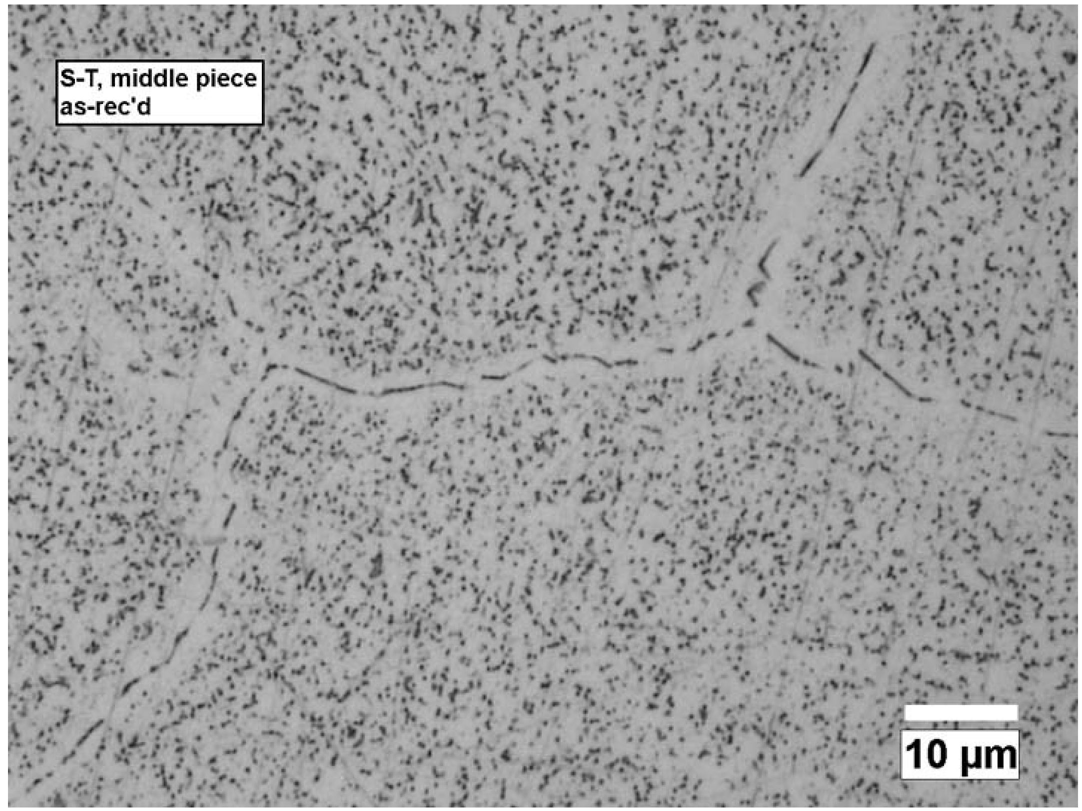
Modern View: "It's too difficult to change anything"…

Sir Francis Bacon: "Things alter for the worse spontaneously, if they be not altered for the better designedly."

Alloy 600 Core Support Leg from EPRI

From a canceled PWR

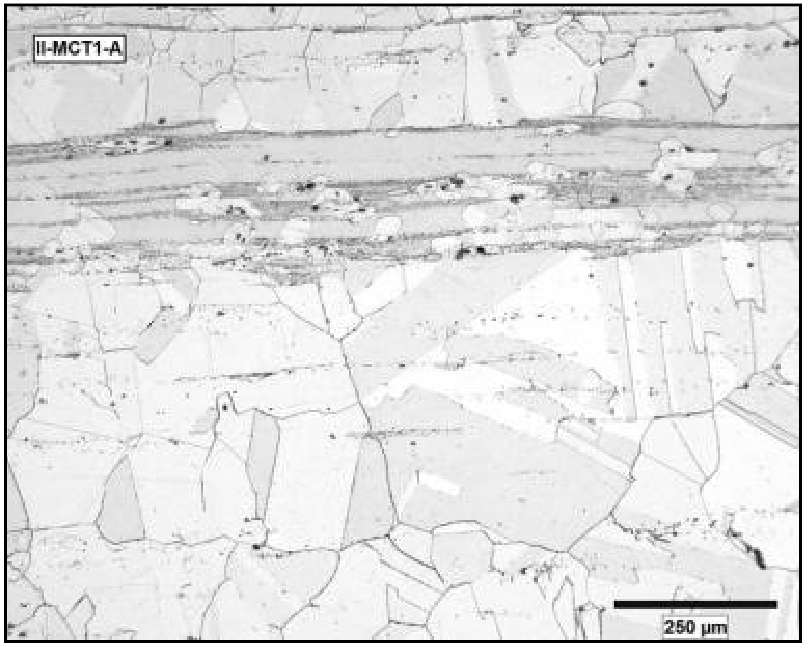


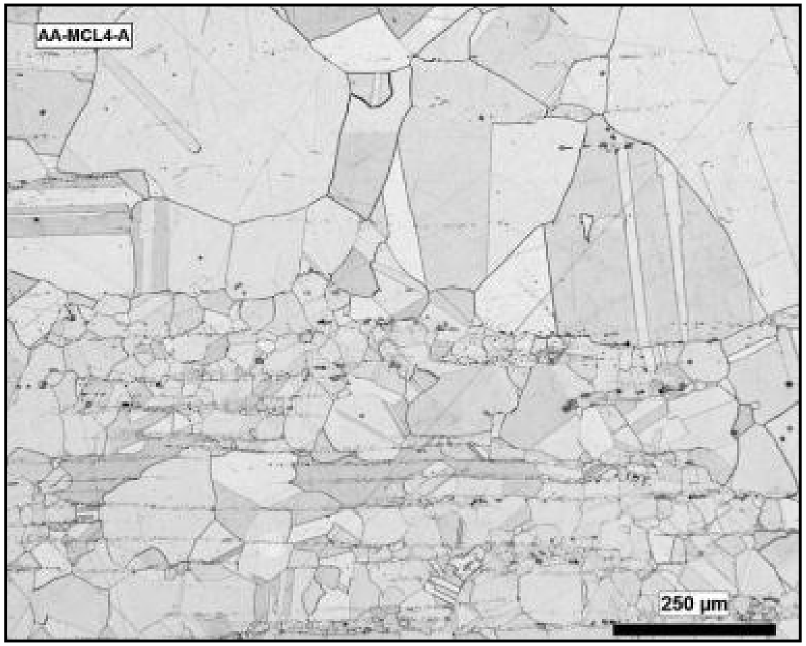


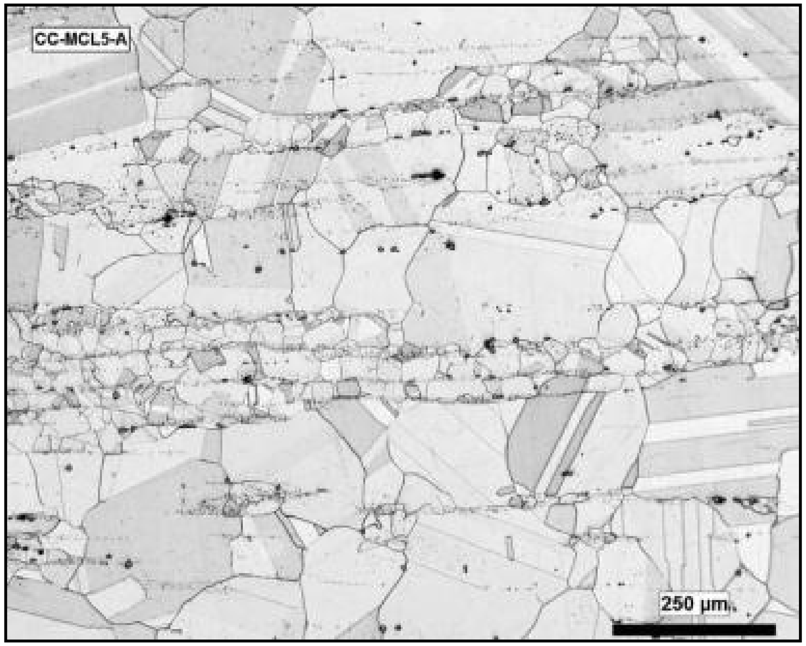
Unrecrystallized microstructure with duplex grain size and high particulate density, with denuded region along grain boundaries.

Alloy X-750 BWR Shroud Support Bracket

Significant banding, including large carbide stringers. Fracture toughness can be halved in banded structures.

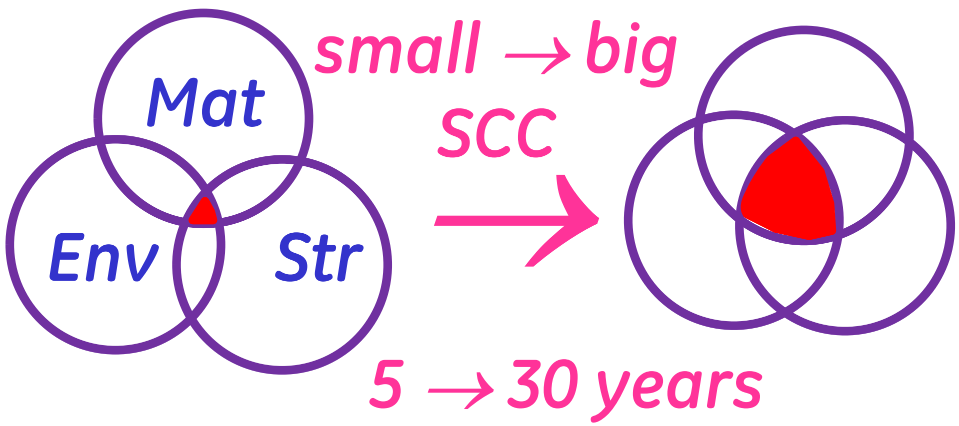






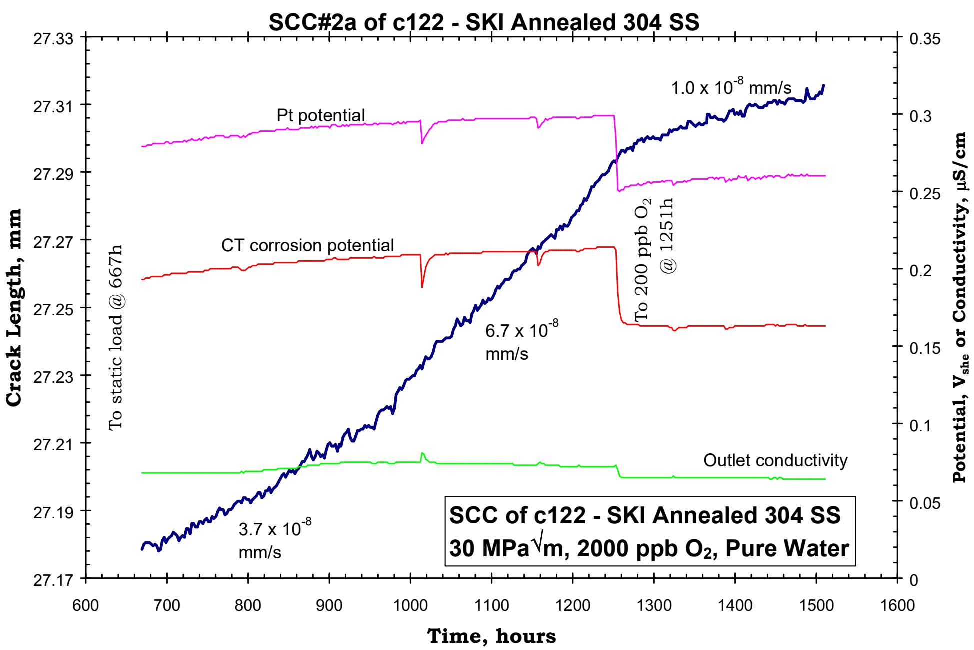
Why Did Surprises Occur in Nuclear?

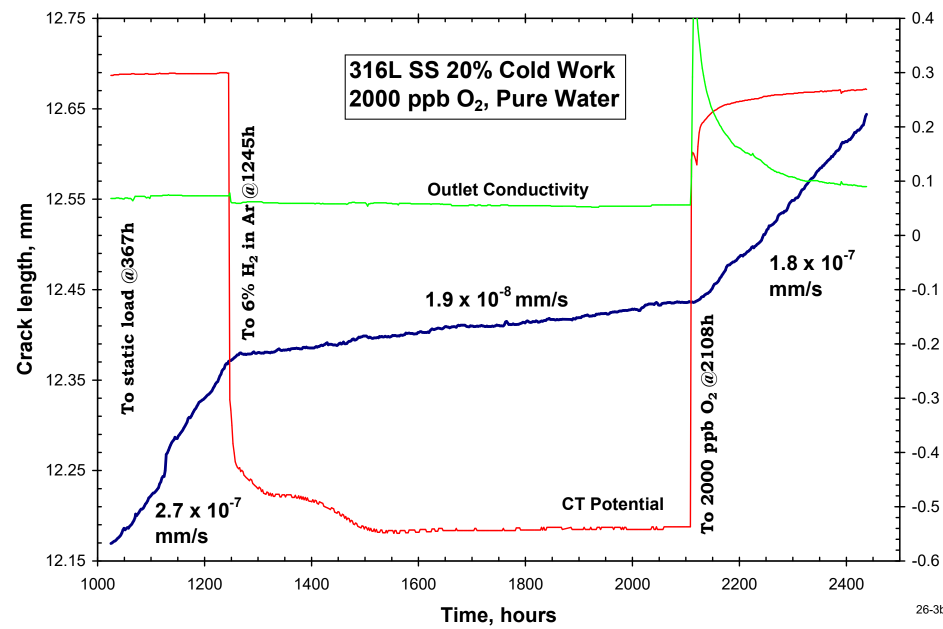
- *ASME Design Codes ignore complexity and importance of SCC by simply mandating that the designer ensure SCC won't occur.*
- *Immunity and thresholds based on simple tests; 'time' ignored. Should focus on vulnerabilities and continuum in response.*
- *Lore: historical opinions accepted, not challenged.*
- *Weak experiments: not reproducible, relevant, accurate… Emphasis on curiosities — not correlation, not causality.*
- *Over-emphasis on crack initiation over crack growth.*
- *Time evolution of processes:*



Immunity and Thresholds in SCC

There is no crack growth rate threshold (immunity) in Corrosion Potential, Water Purity, Sensitization Level, Neutron Fluence, Temperature…



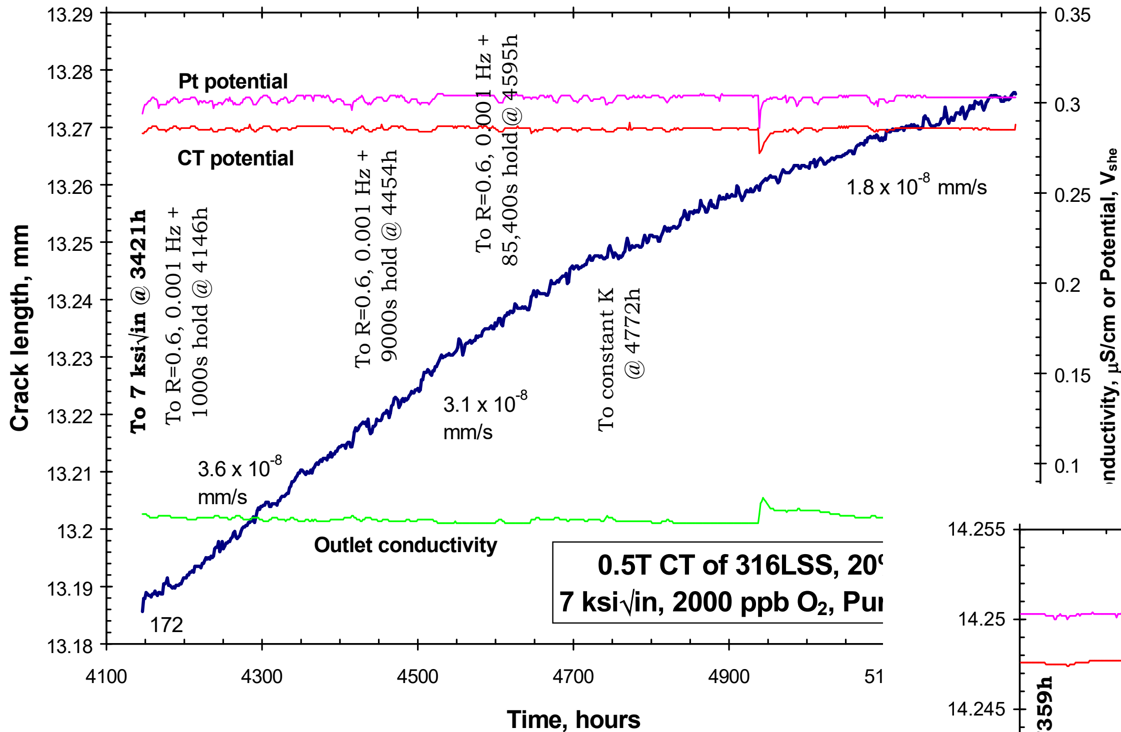


Annealed SS, high potential

Cold worked SS

both in ultra high purity water (<1 ppb impurities in outlet)

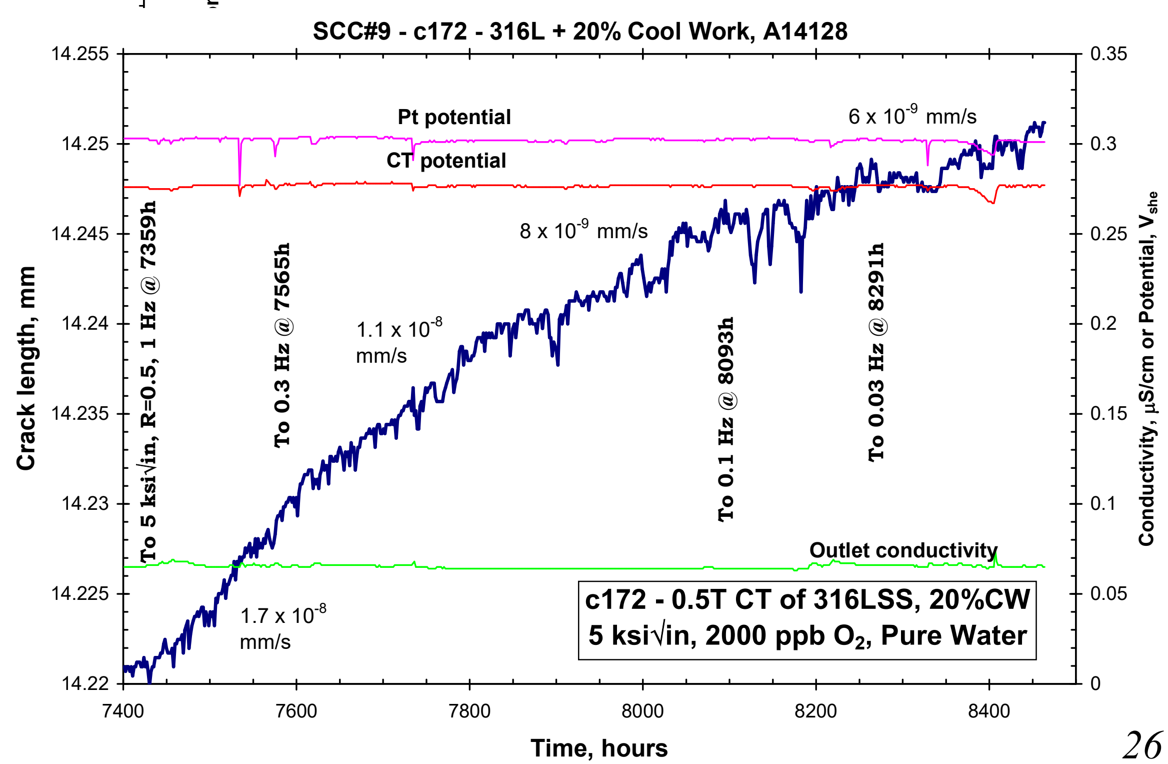
K_{ISCC} ? 316L SS +20%CW in Pure Water



$K \propto \sigma\sqrt{a}$

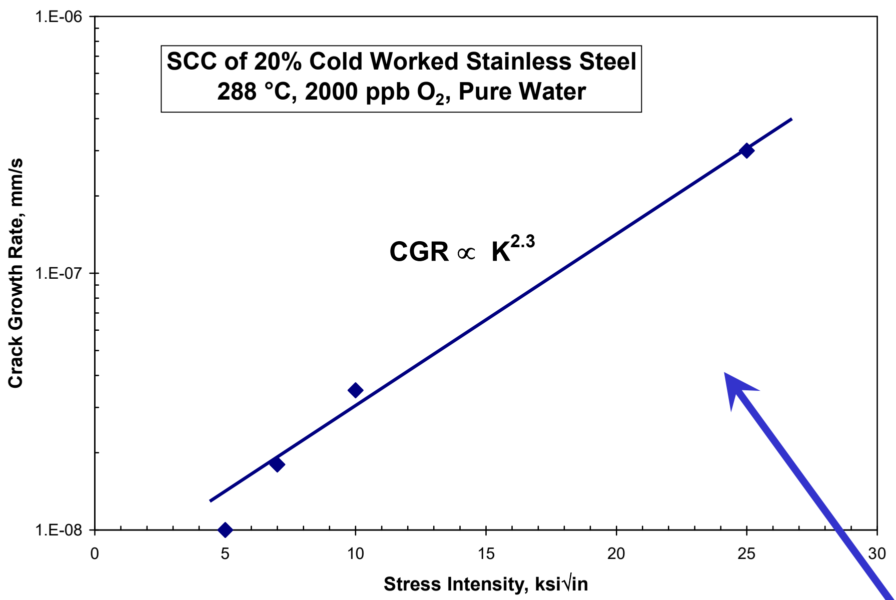
$\propto$ stress $\sqrt{\text{crack-depth}}$

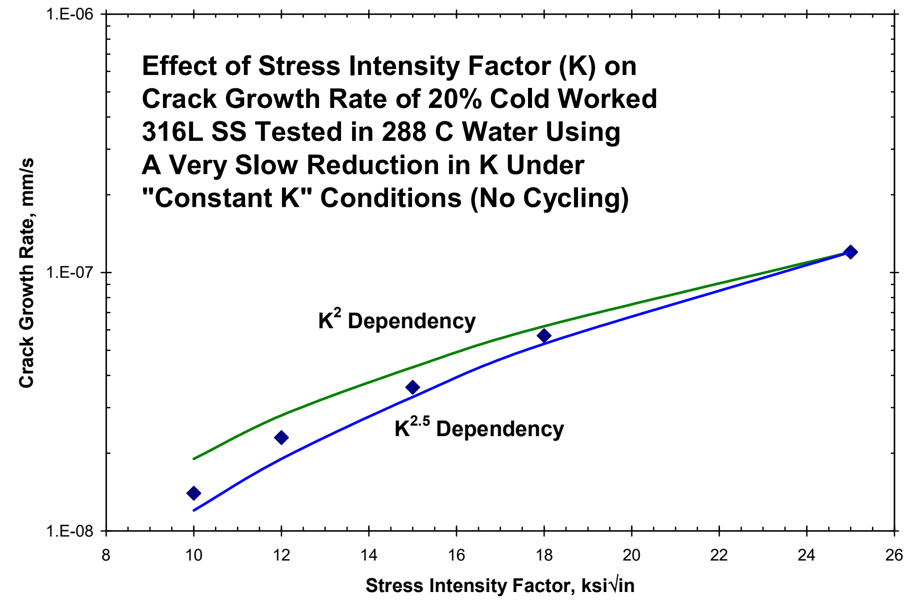
K_{iscc} is an outmoded concept. Cracks have grown in the 'low K regime' in thousands of components.

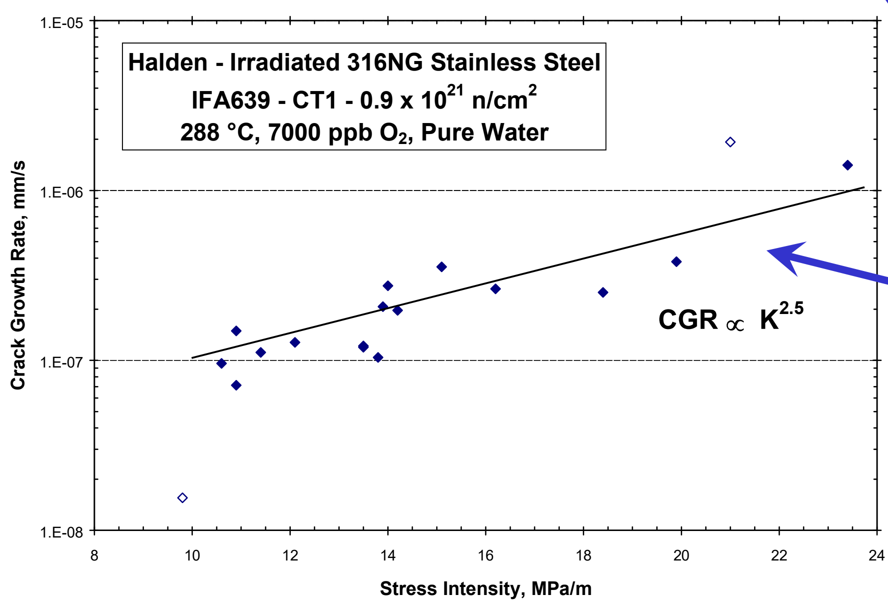


No Evidence of Threshold Stress Intensity Factor K

for austenitic materials







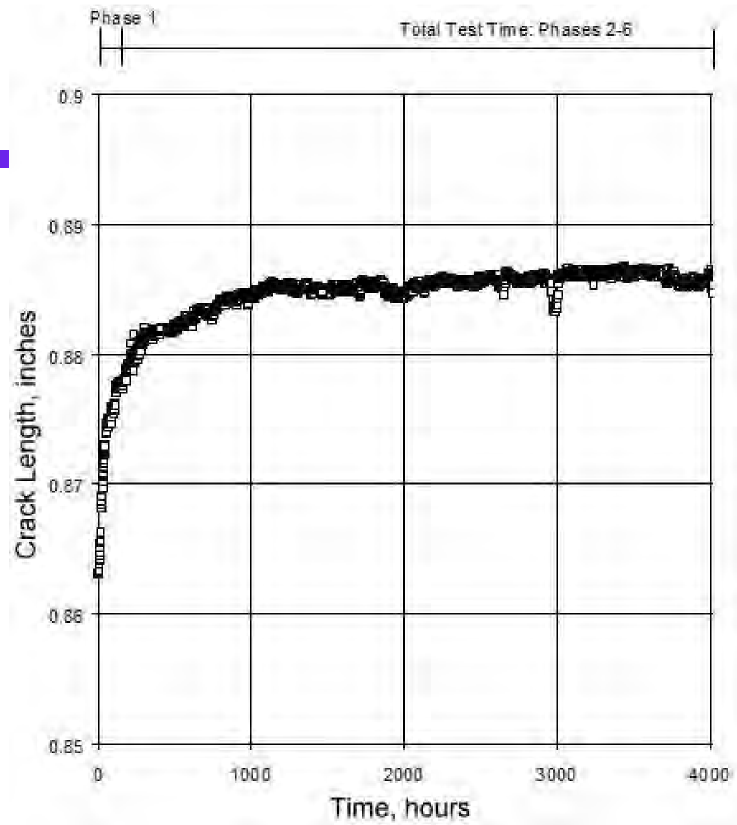
Varying-K Tests, –dK/da

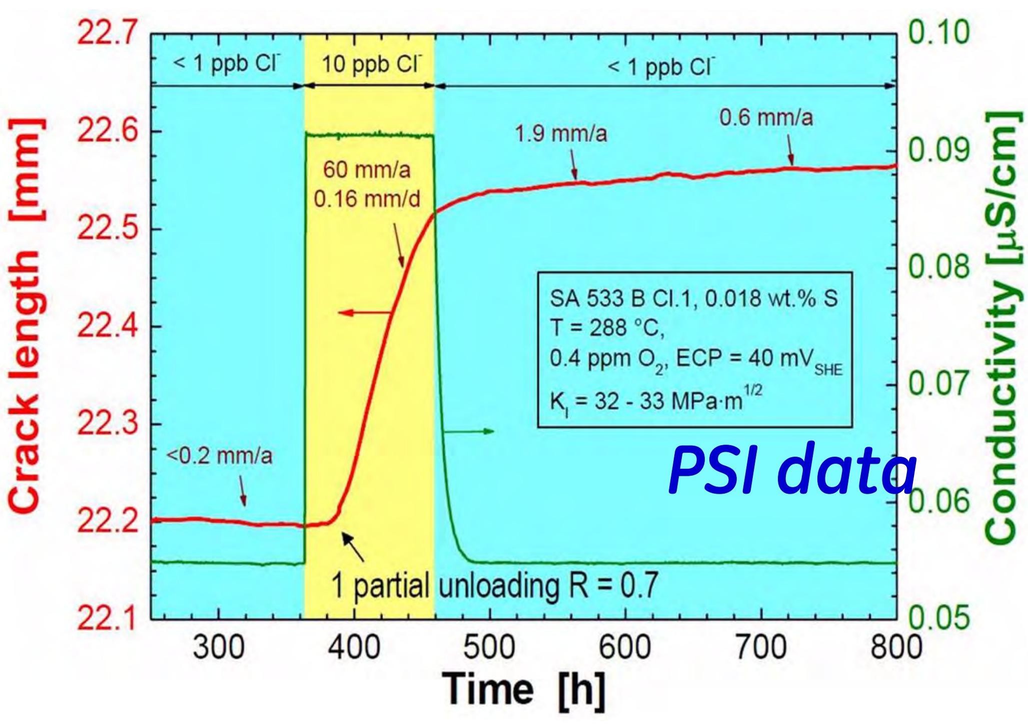
Constant K Tests

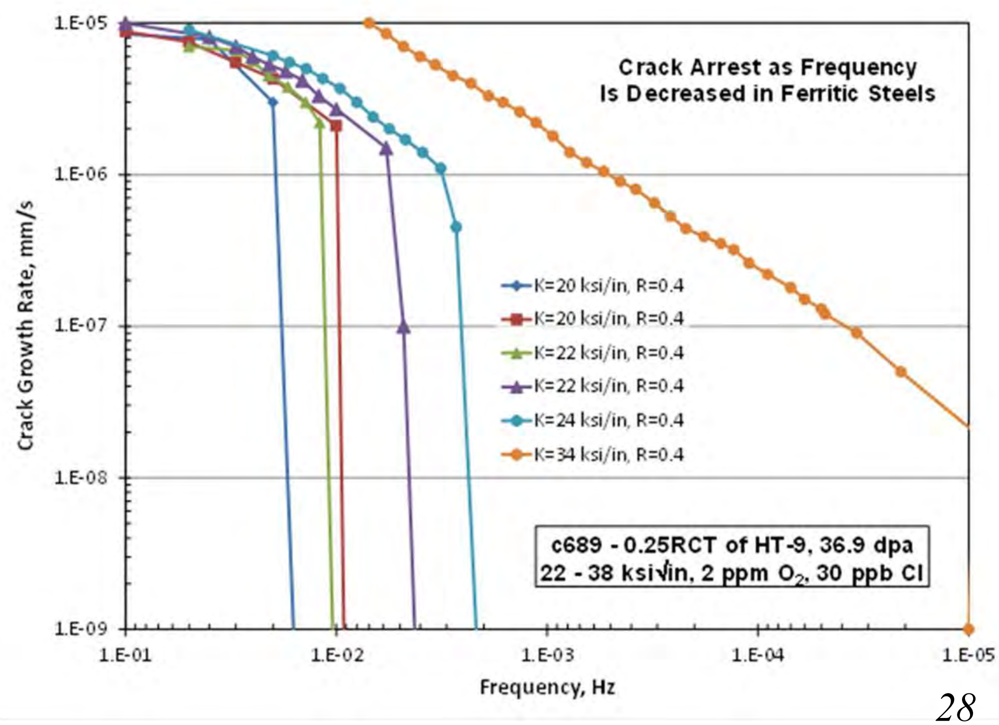
Constant K Tests on
Irradiated 316 SS

Ferritic Steels

In good water chemistry and at lower K, crack arrest is often observed in ferritic steels but Cl and high-K can sustain SCC.





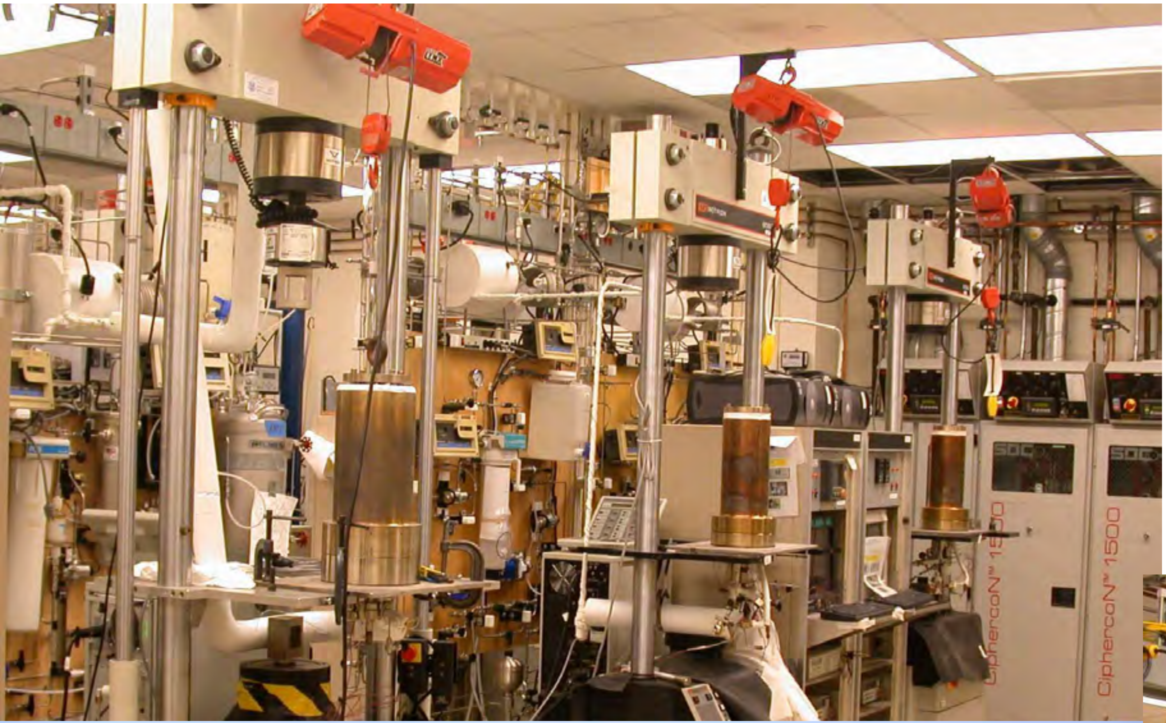


SCC Quantification – Why Crack Growth?

- SCC growth experiments provide much more definitive data:
  - thousands of crack length vs. time data, • on-the-fly changes,
  - sampling of extensive microstructure,
  - ~1 μm level sensitivity, • highly representative of components,
  - data and systems held to a much higher standard….
- SCC initiation experiments are generally:
  - crude and simplistic (U-bend , crevice bent-beam, SSRT….),
  - sample small areas of microstructure,
  - one-point per specimen, • few replicates,
  - no continuous detection of cracking, • rapid ↑in net stress,
  - plant component surfaces and loading are poorly known,
  - performed on a short time scale relative to plant life, etc.

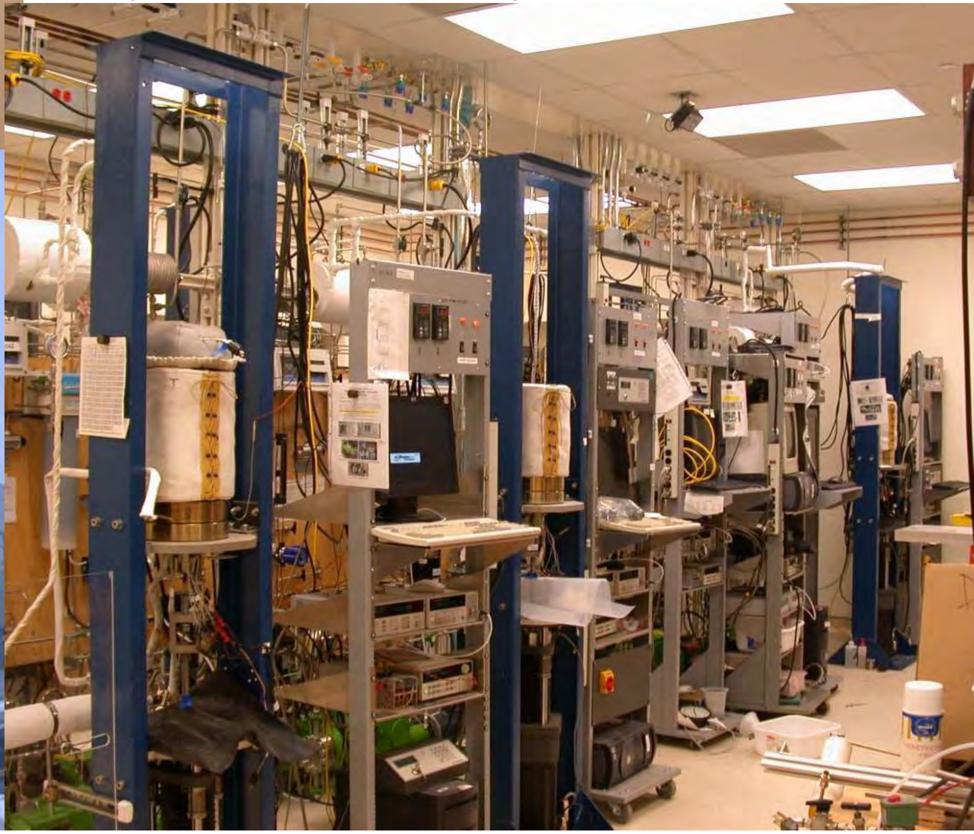
Need resistance to both initiation and growth

SCC Lab at GE Research / Lucideon



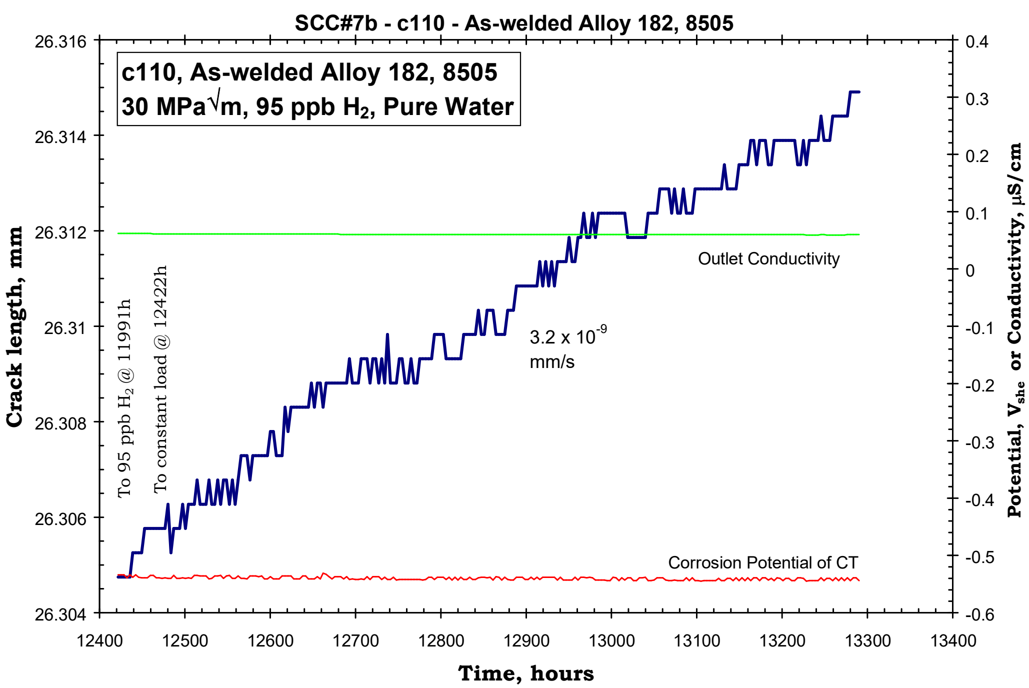
43 fully instrumented high temp. water BWR/PWR SCC crack growth rate systems.

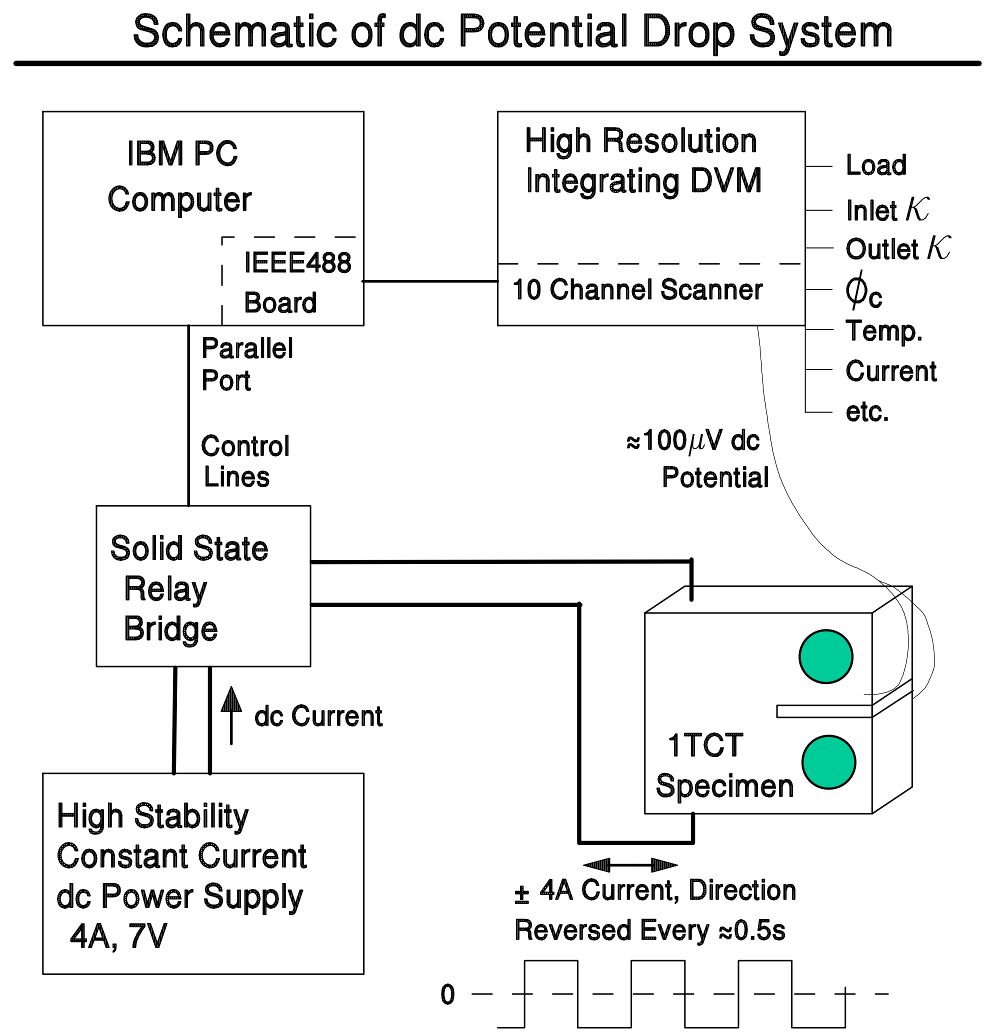
~18 other autoclave systems for electrochemistry, high flow rate studies, rotating cylinder, Kelvin probe, Zircaloy corrosion....



DC Potential Drop Measurement

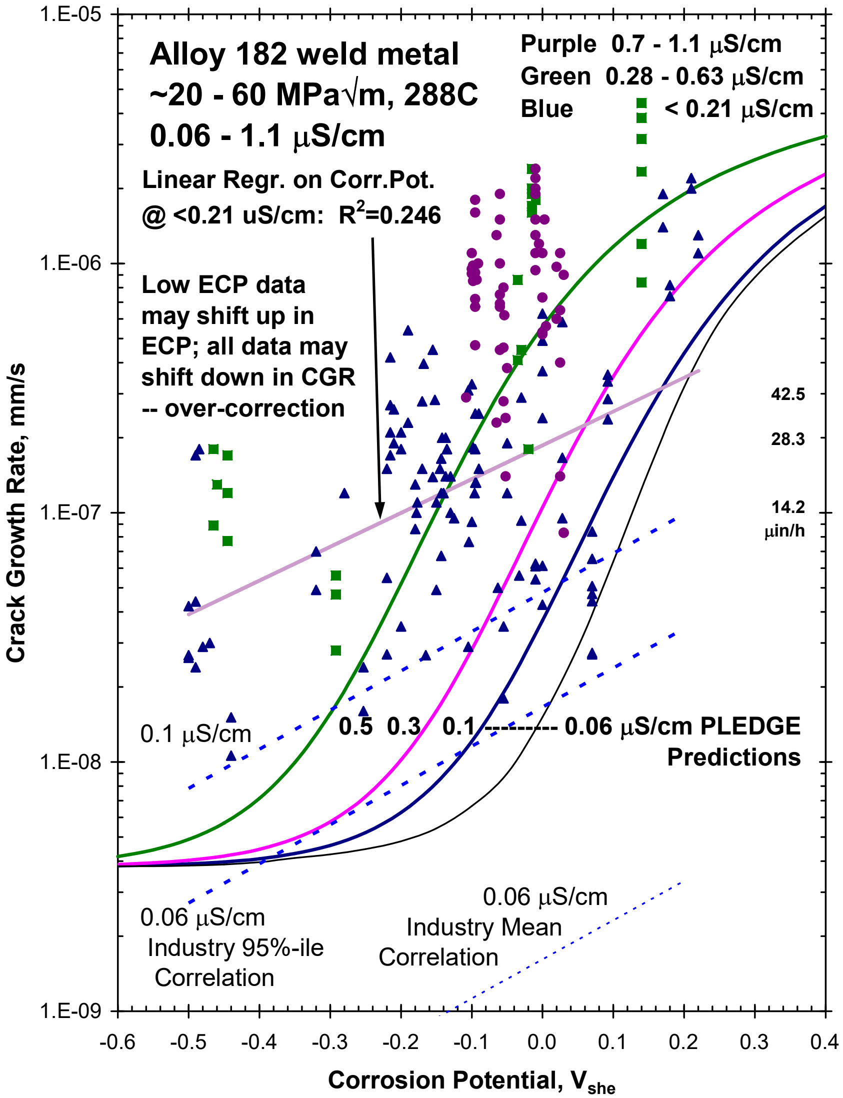
DCPD applies constant current and measures ≈100 μV ΔV on the specimen with a sensitivity of ~2 nV (~1 μm crack advance)



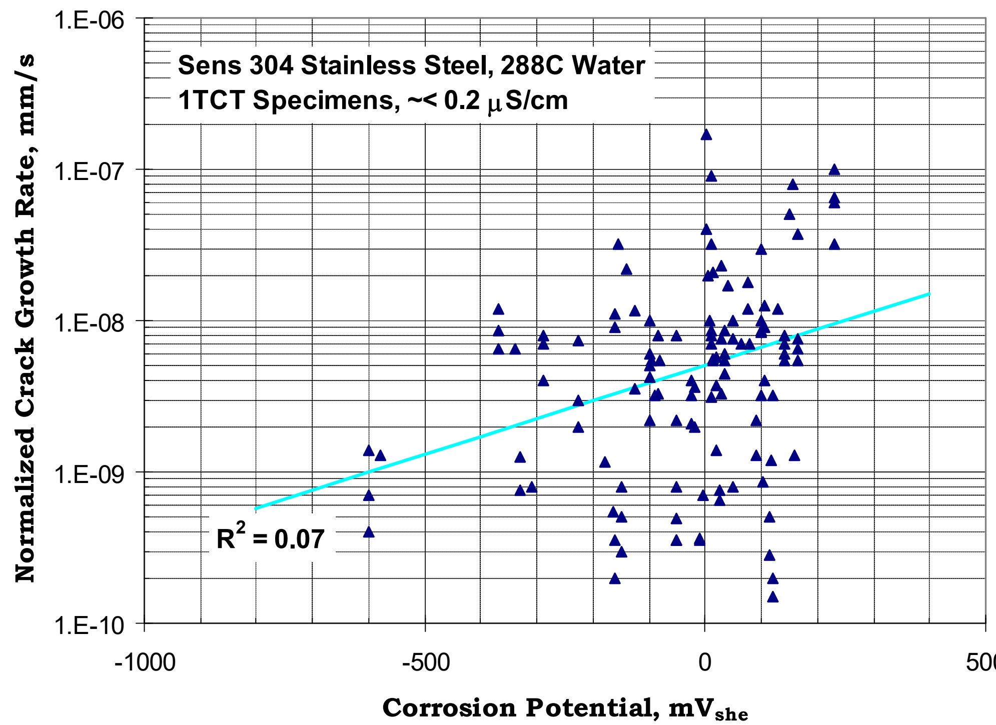


$$V = I \times R$$

SCC Testing & Data Base Issues

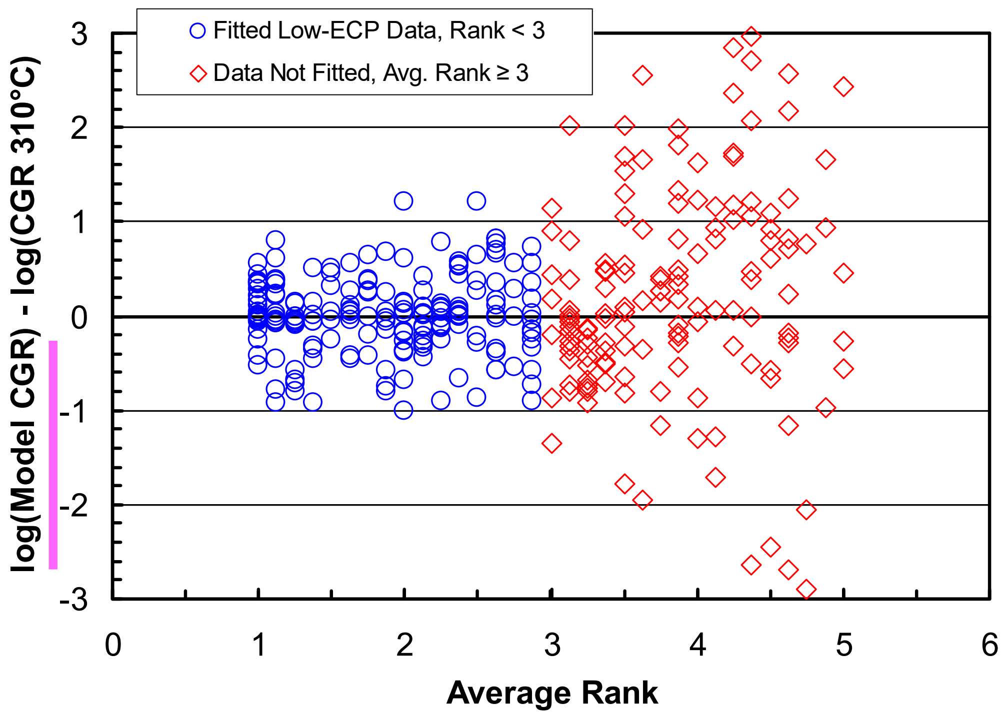


Scatter is related to testing problems, so the "mean" of the data ≠ the mean SCC response. *Statistics can't overcome bad experiments (R^2<0.07)*



1000X Scatter Can Support Any Concept or Model

SCC Scatter vs. Model after normalization by specimen (not heat)

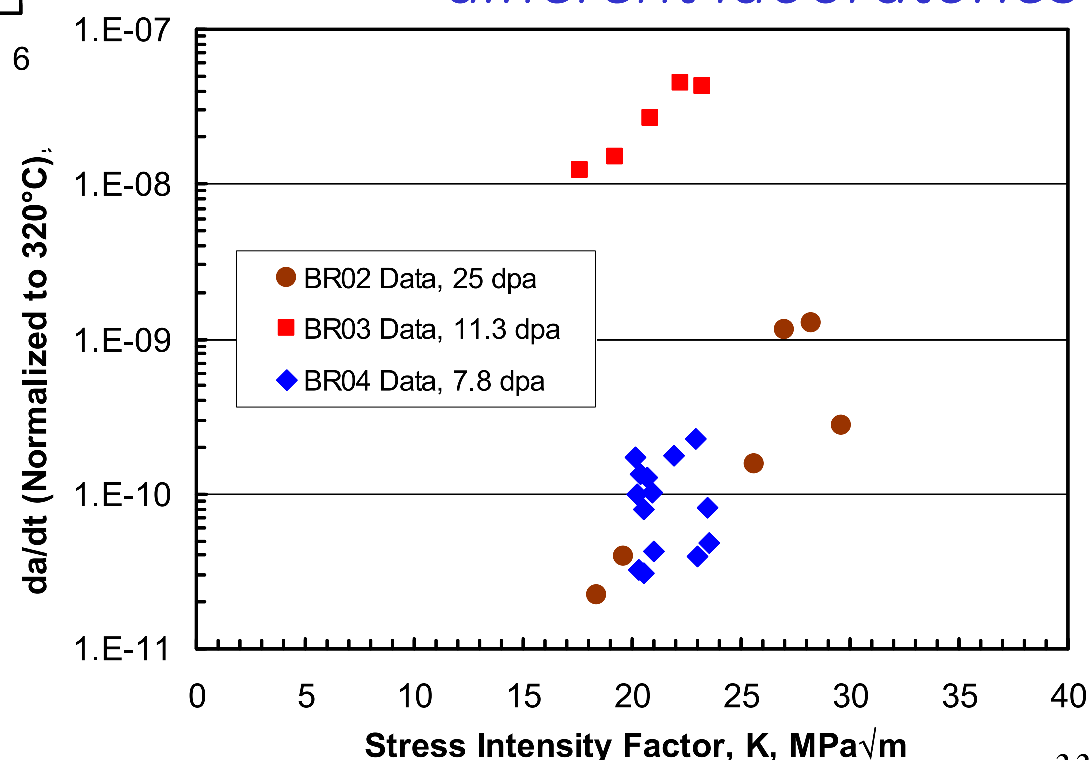


1,000,000X spread in data *after modeling* !

75th percentile model is used, but not 75%-confidence!

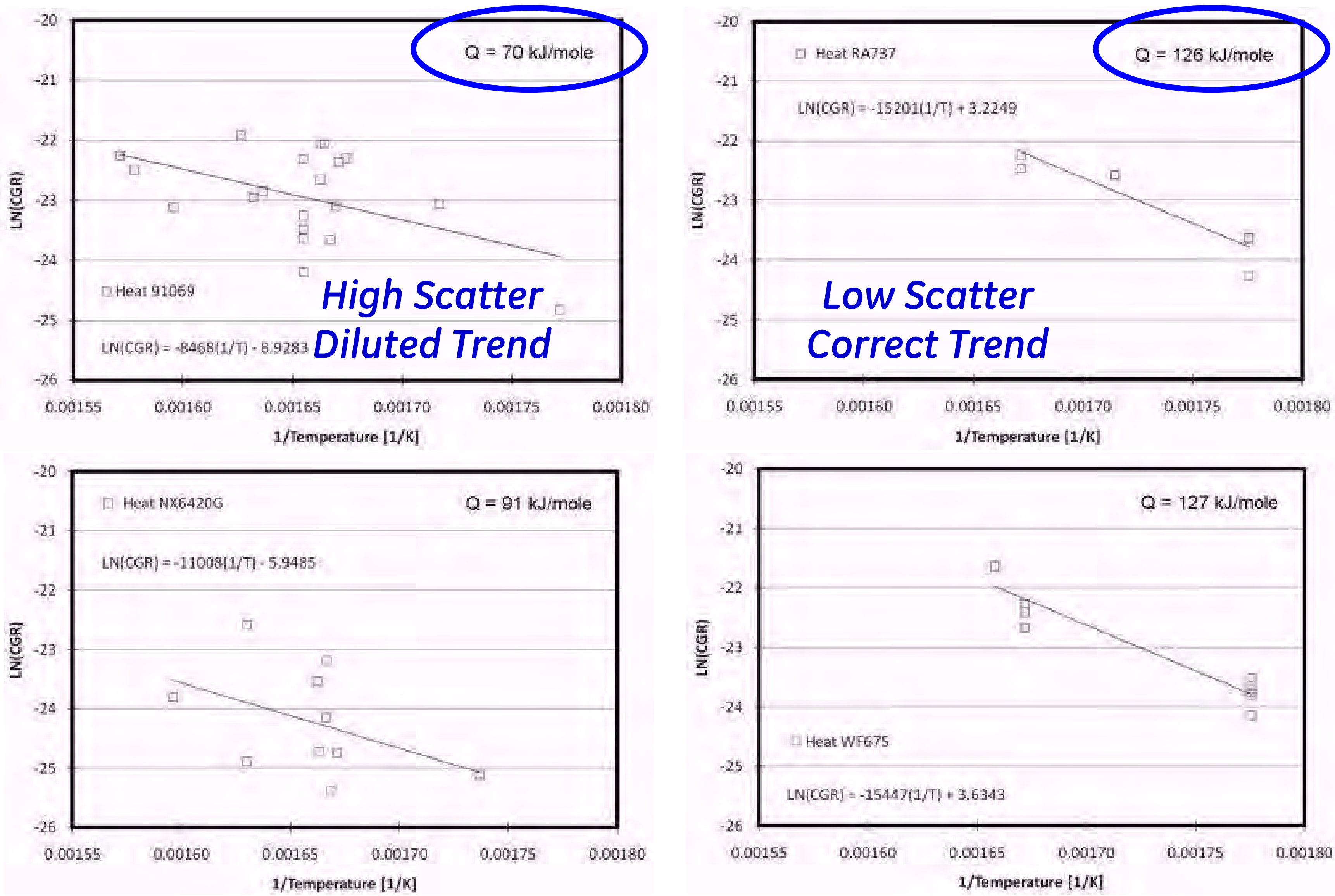
75th %-ile is ~3X above mean, but highest few points are 75X

Same heat tested in different laboratories



SCC Testing Issues

Scatter softens trends



Accepted value from best lab data is ~130 kJ/mole

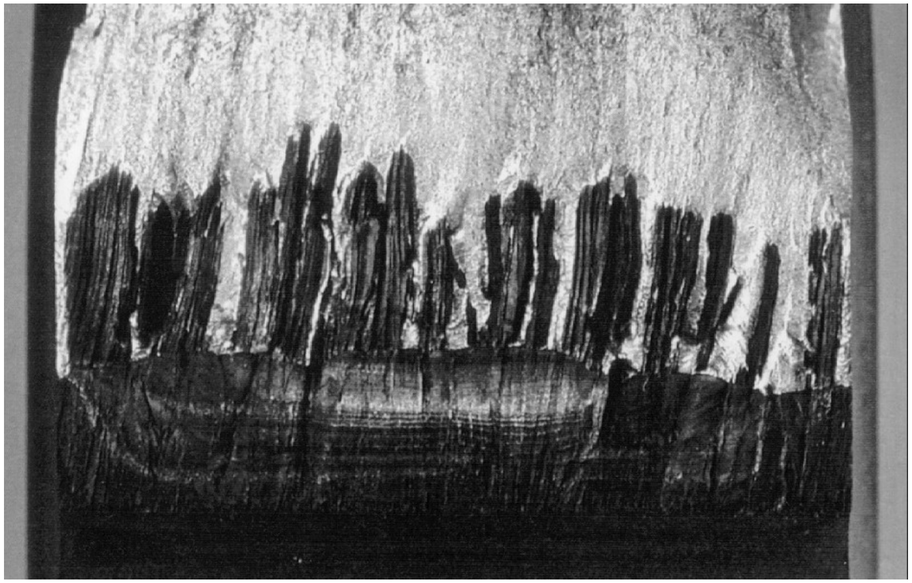
Effect of Temperature on the Crack Growth Rate of Ni Alloys

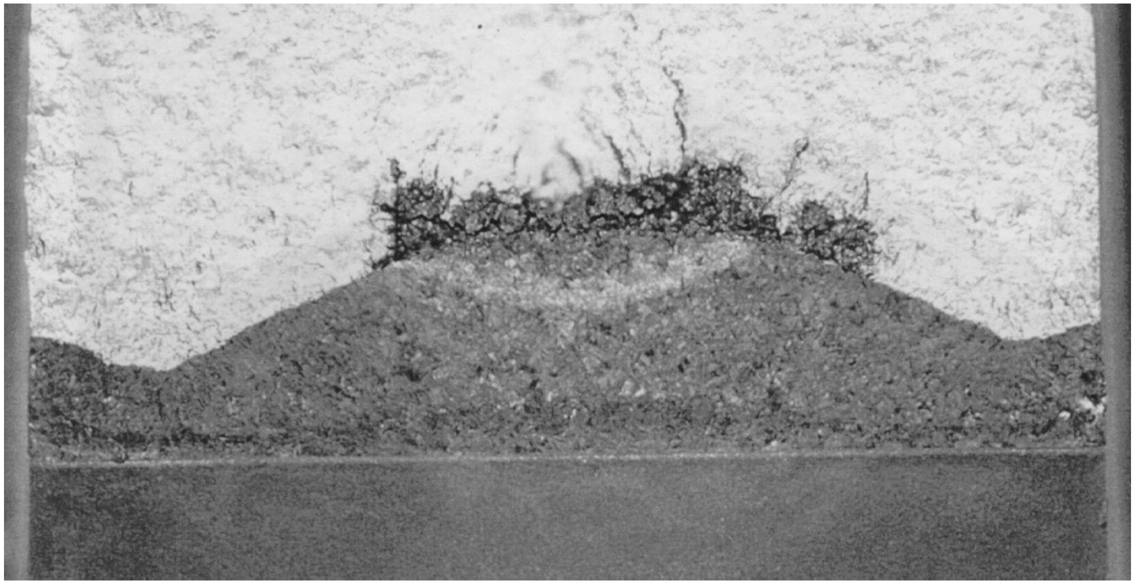
Transgranular Fatigue Precracking

TG fatigue cracks very poorly simulate lab or field IGSCC

Morphology change, plastic zone, crack front pinning issues

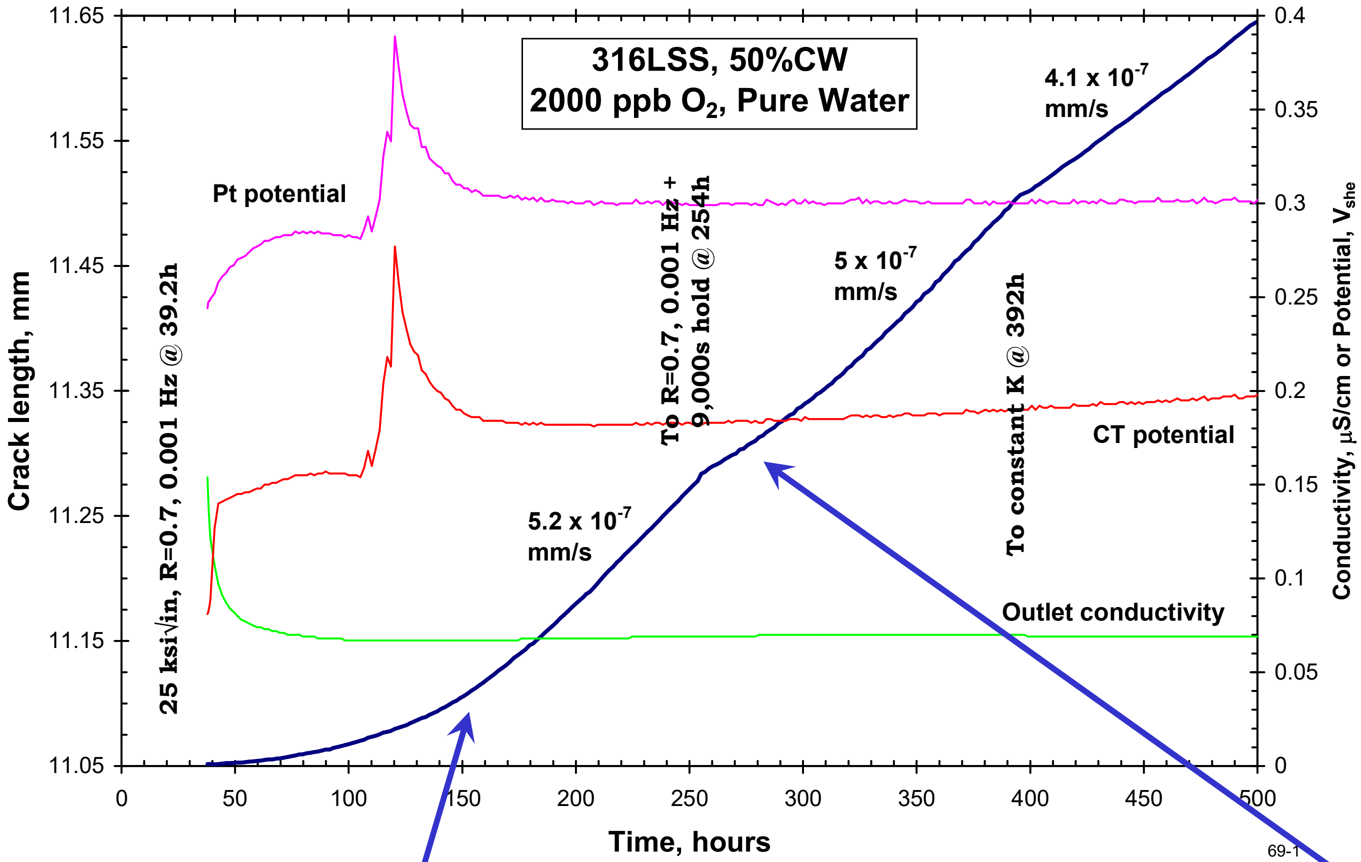
Transition needed to IG crack & "monotonic" plastic zone





What is K when load is mostly held at shortest part of the crack?
Crack monitoring is biased to the shortest part of the crack!

Typical SCC Crack Growth Data

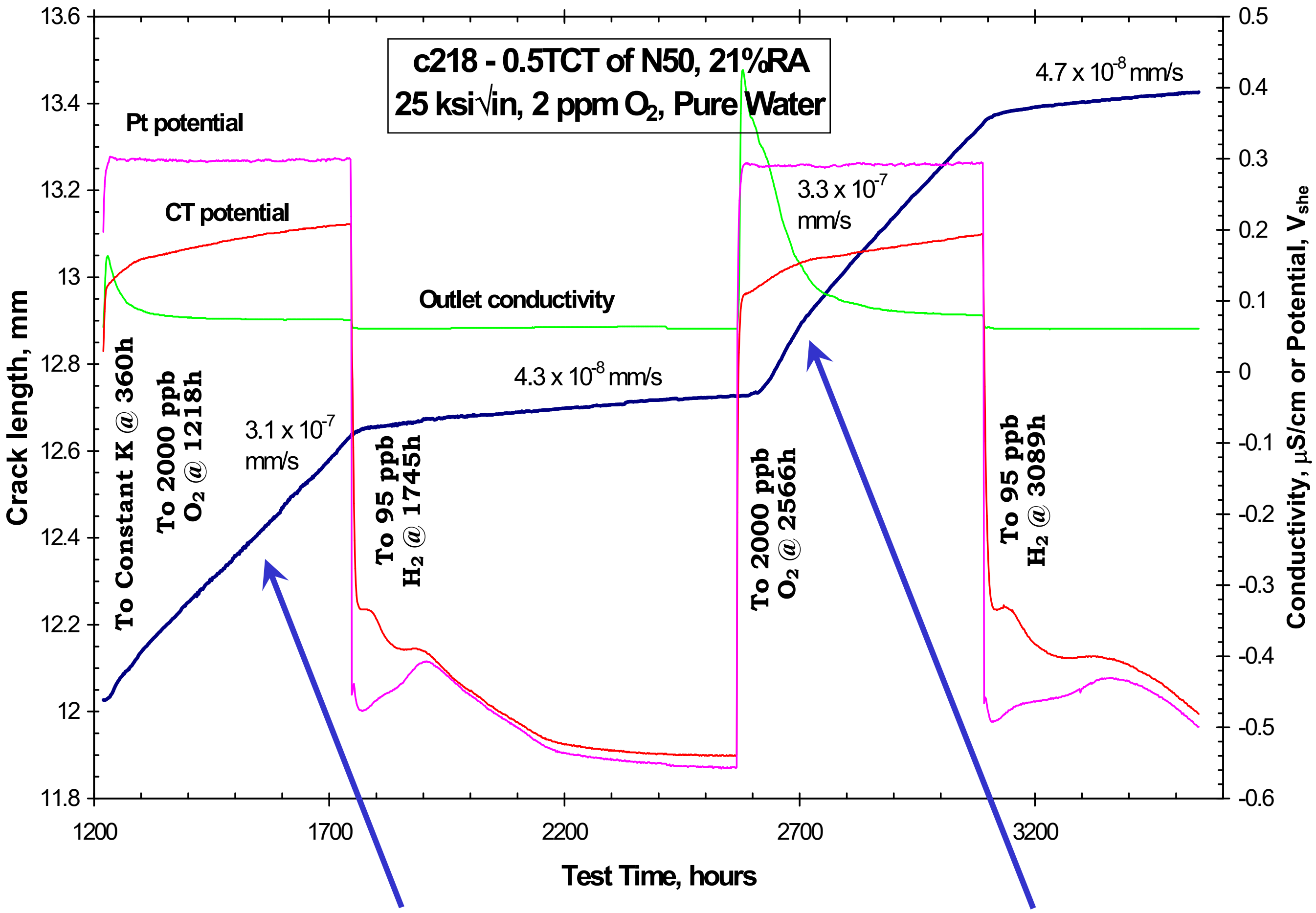


Crack starts transgranular from fatigue, and becomes intergranular like SCC

Transgranular fatigue pre-crack transitioned to IG SCC crack at constant K

The Crack Must Behaves Like It Was Always an SCC Crack

Example of Crack Growth Data



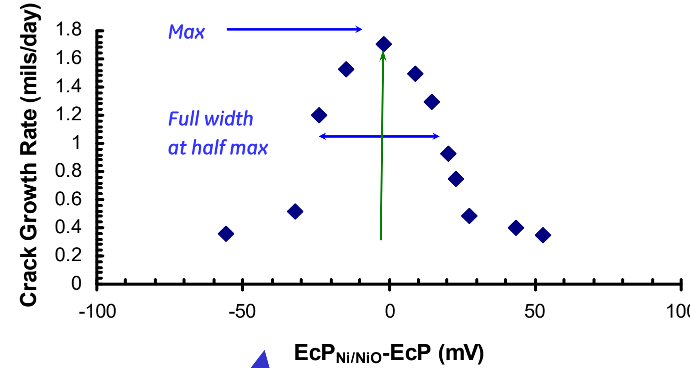
Compact tension (CT) specimen of annealed XM-19 (Nitronic 50) +20% cold work by cross-roll at +140C

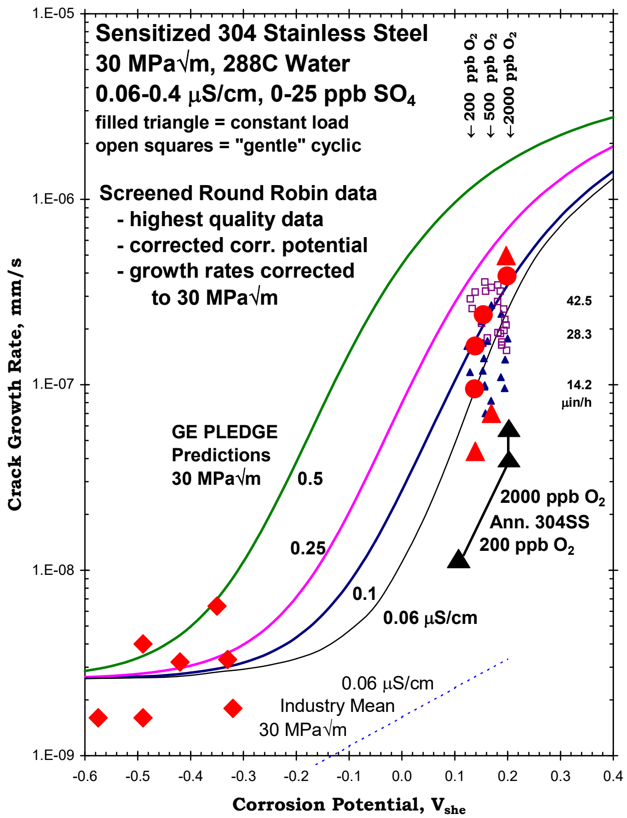
Usually acquire data by repeating the changes to demonstrate reproducibility, e.g., low ↔ high potential

Effect of Corrosion Potential & Cold Work of SS & Ni Alloys

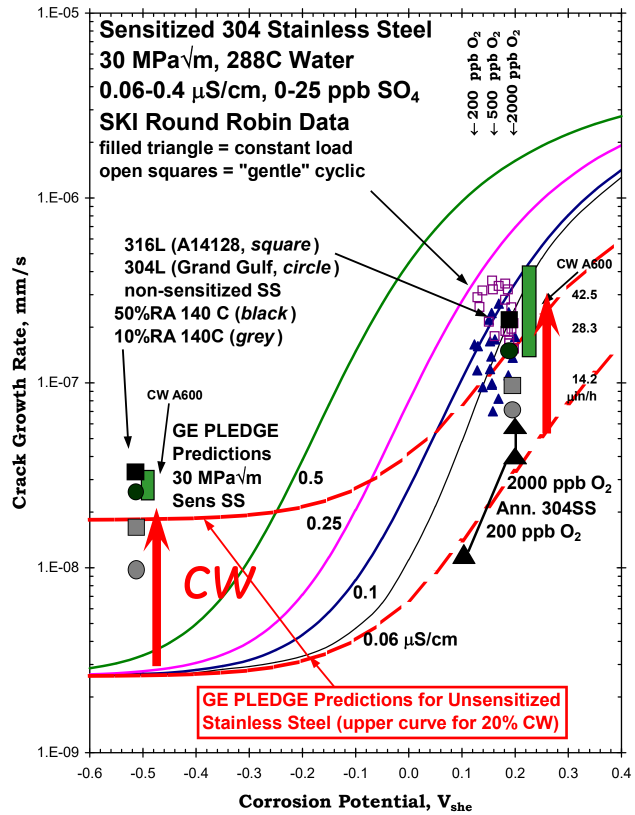
↑Yield strength produces ↑growth rate at both low and high potential

Higher H_2 Lower H_2

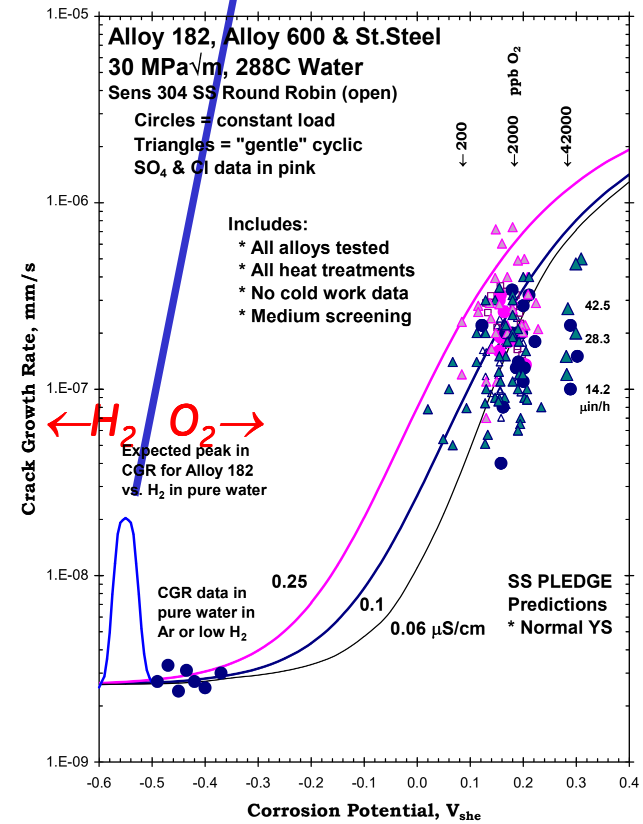




Sensitized SS



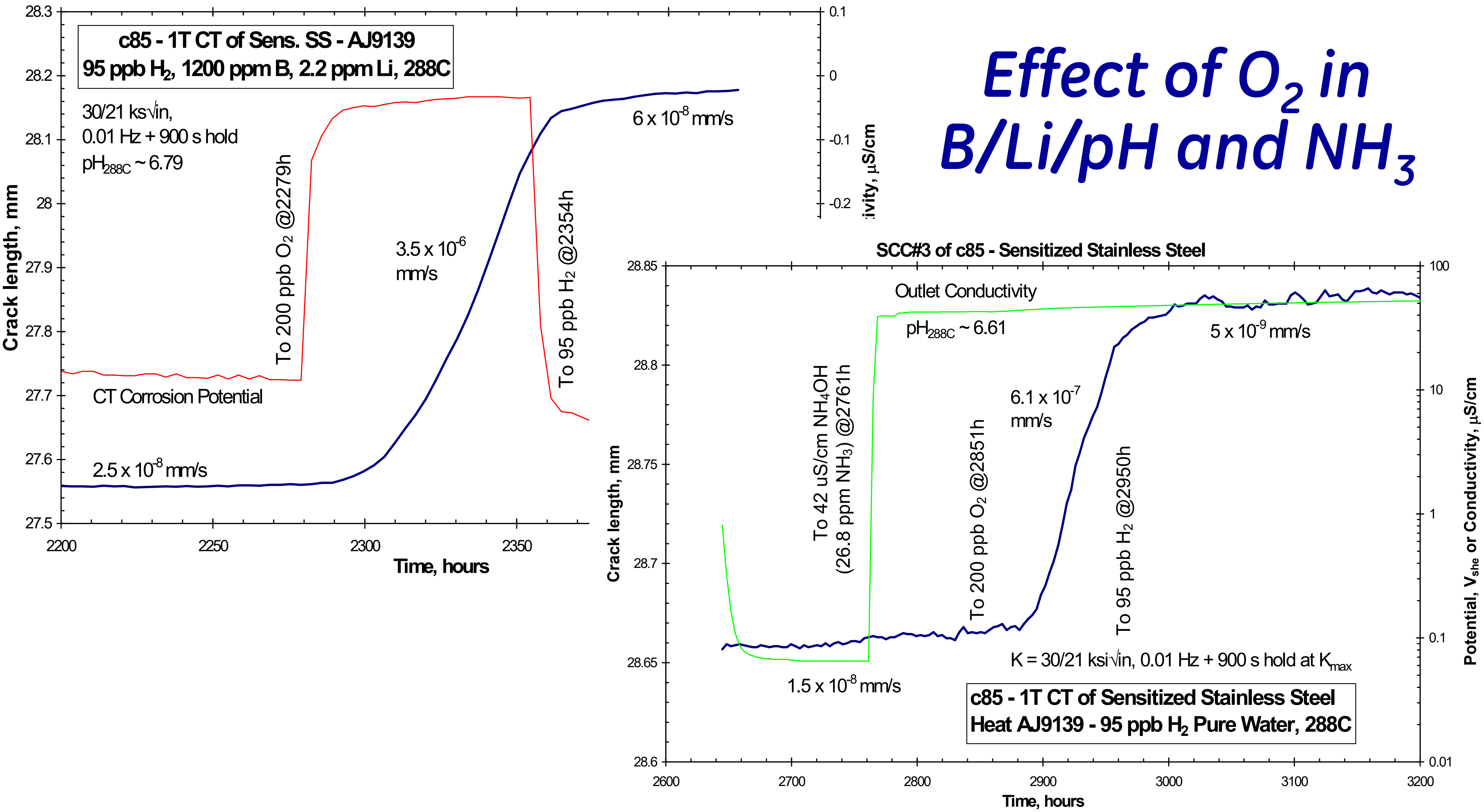
Cold worked SS/600



Ni alloys

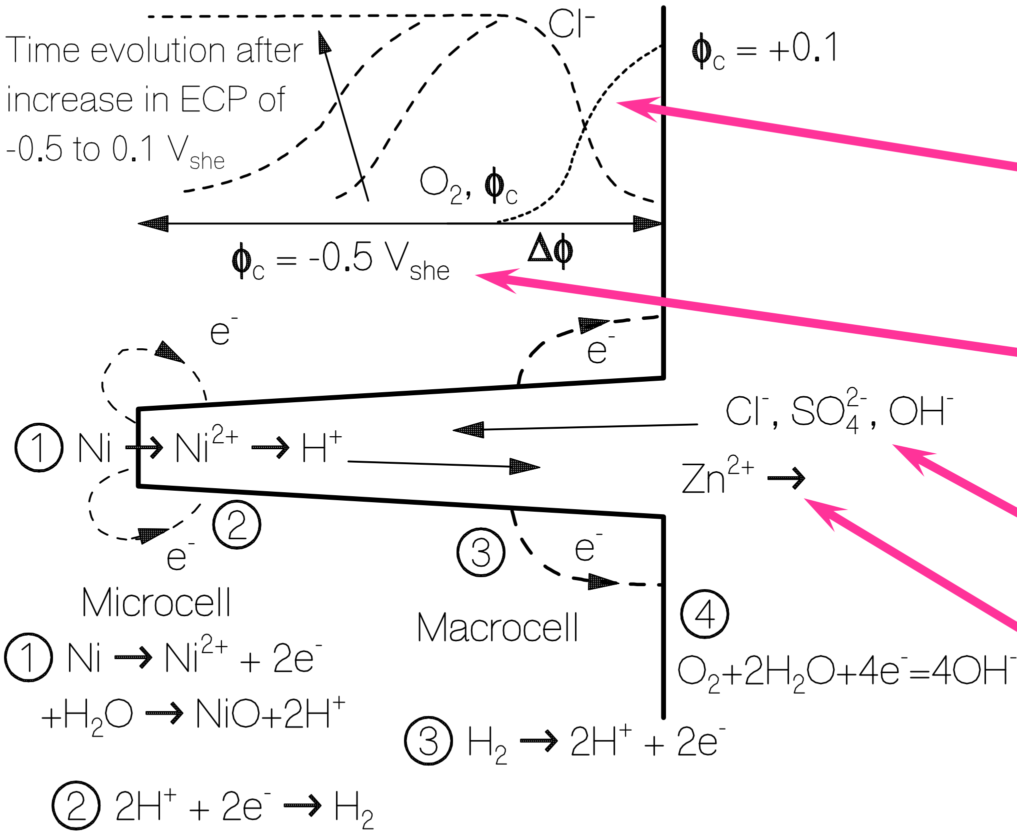
Strong effects of corrosion potential on SCC

Effect of O_2 in B/Li/pH and NH_3



Similar concerns for corrosion potential exist in PWRs as in BWRs

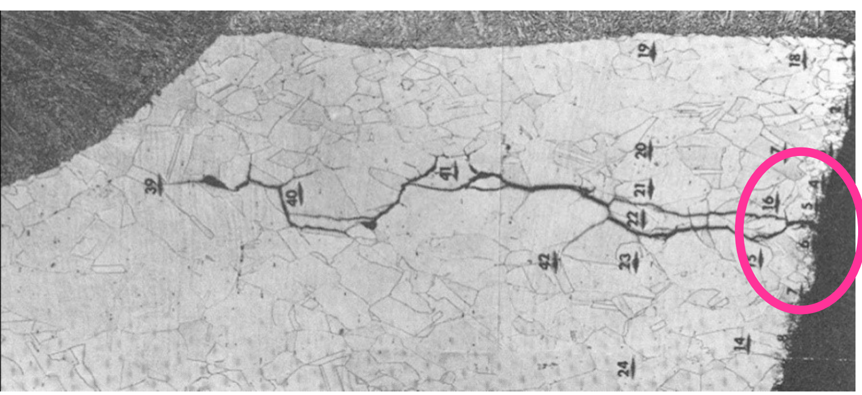
Crack Tip Chemistry



$$J_A = -D_A \Delta C_A - z\mu C_A F \Delta\phi + C_A V$$

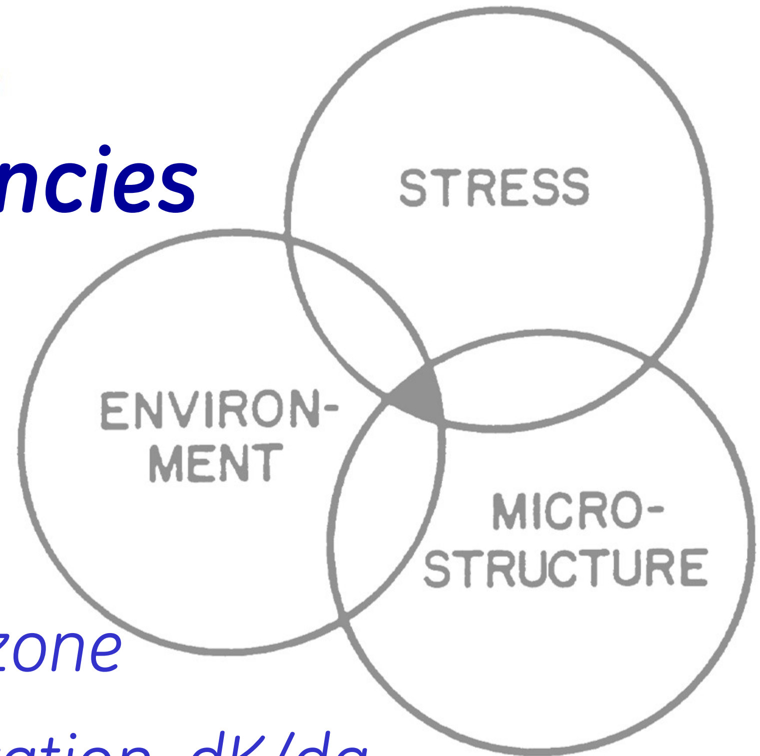
flux = diffusion + ϕ-driven + convection

- *Oxidants are consumed near crack mouth*
- *Crack tip is always deaerated (low potential)*
- *Anions (Cl^-) are drawn into the crack*
- *Cations (Zn^{+2}) are rejected from the crack*
- *Transient response predictable from transport*



Crack chemistry is defined primarily by O_2 consumption near the crack mouth, not by ionic coupling down a long, tight crack

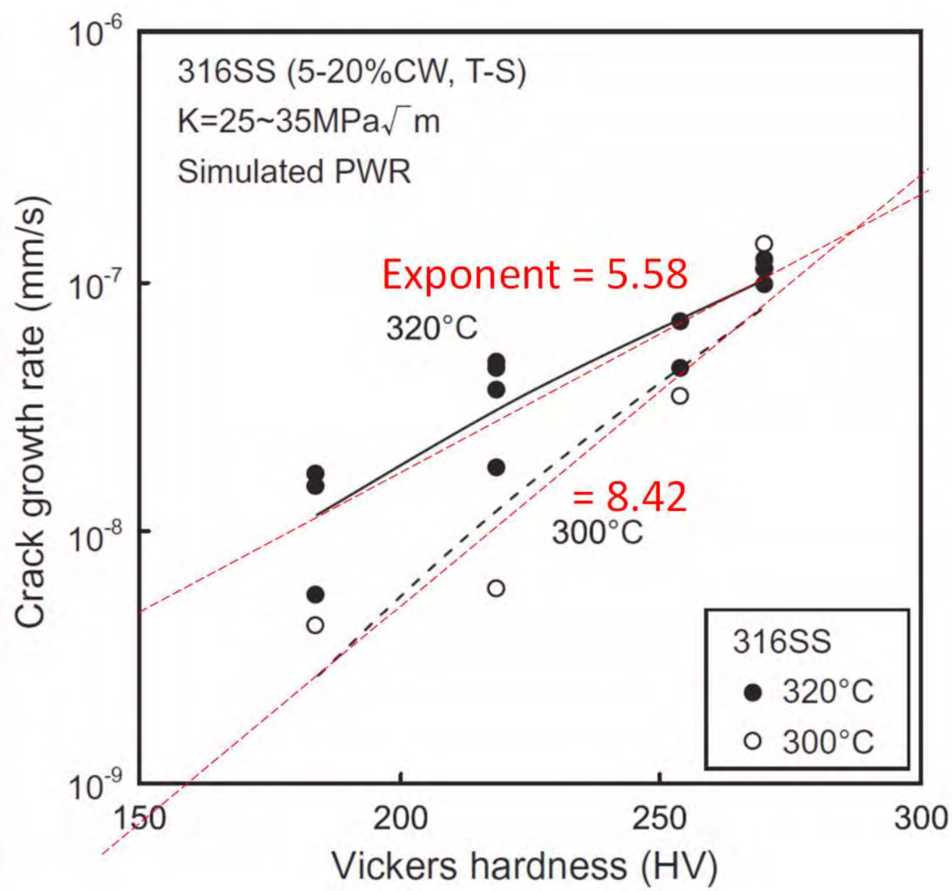
SCC Vulnerabilities & Dependencies

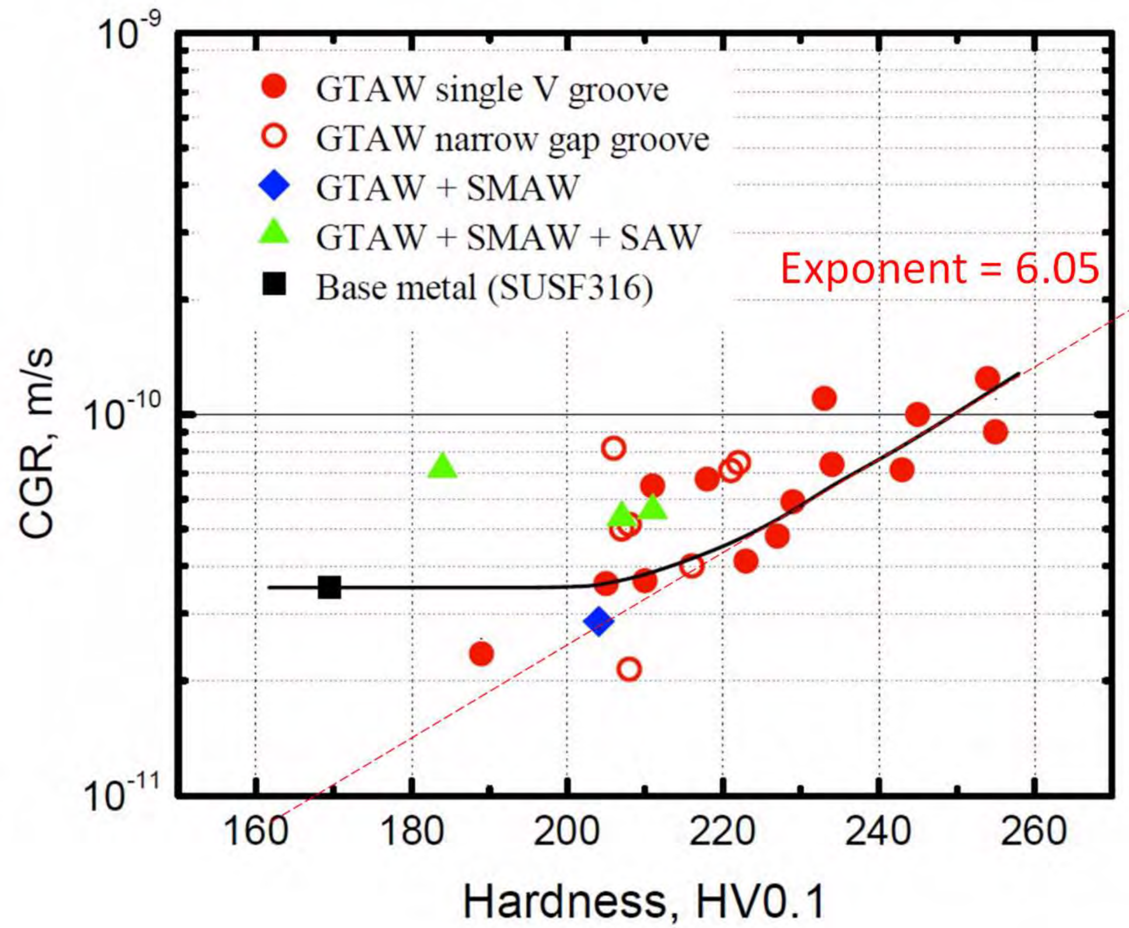


- Corrosion Potential & Boiling
- Water Purity – esp. Cl & SO_4
- Yield Strength / Cold Work in bulk, surface or weld heat affected zone
- Stress Intensity Factor – & cycling, vibration, dK/da
- Sensitization (grain boundary Cr depletion)
- Grain Boundary Carbides; Low Energy Boundaries
- Temperature
- Composition (Mo, Ti, Nb, low C, high N) not that important apart from decreasing sensitization

Interdependencies mean that empirical models require ~10^{20} exp'ts

Cold Work Effects on SCC of All Fe-Cr-Ni Alloys



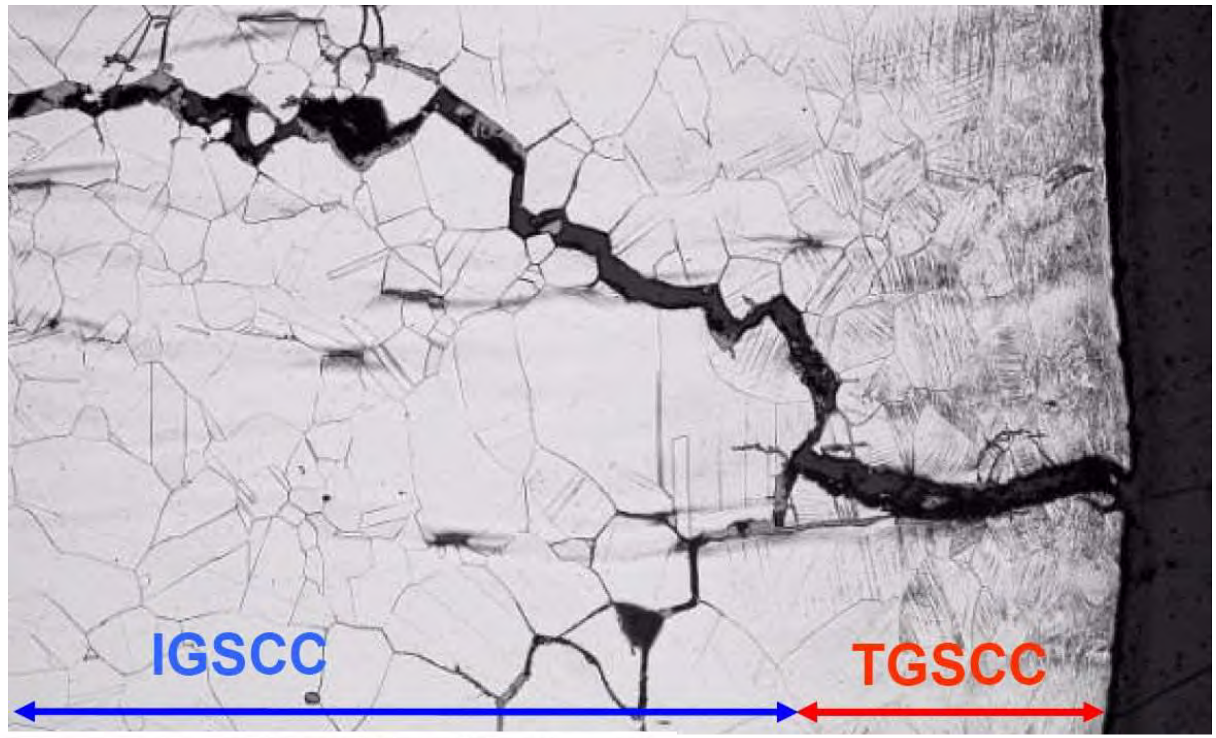


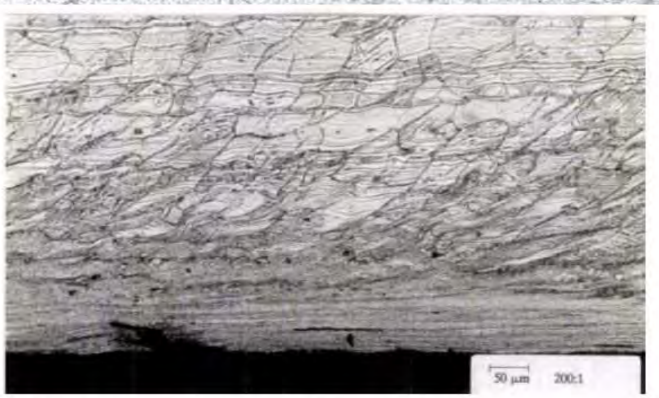
Pressure Vessel Codes limit bulk cold work, but 'deviations and exceptions' exist – including >30% CW at Daya Bay

Example of Effect of Surface Cold Work

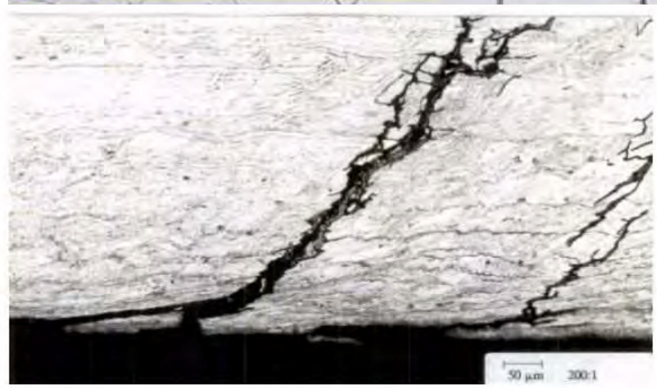
Alloy 600, BMI Surface Cold Work

TEPCO 316L Core Shroud





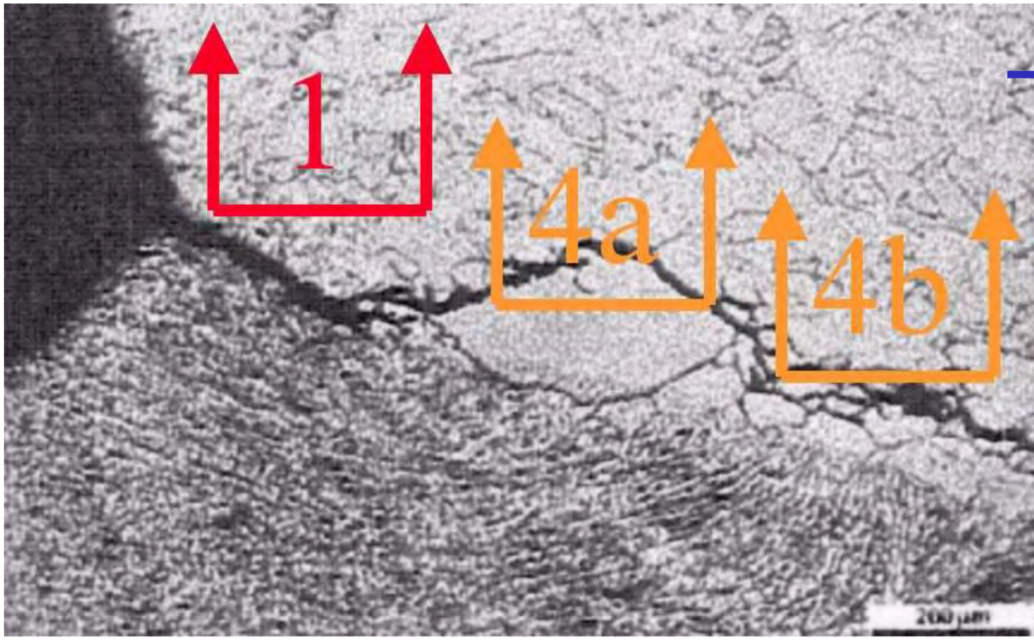
Mechanically induced defects in the cold worked area

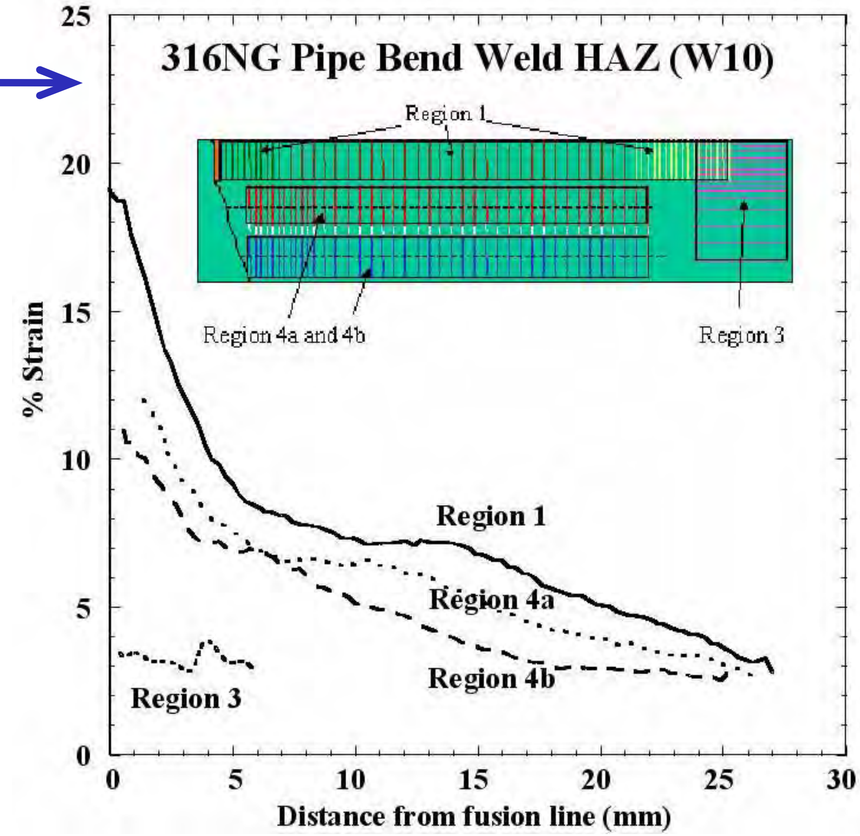


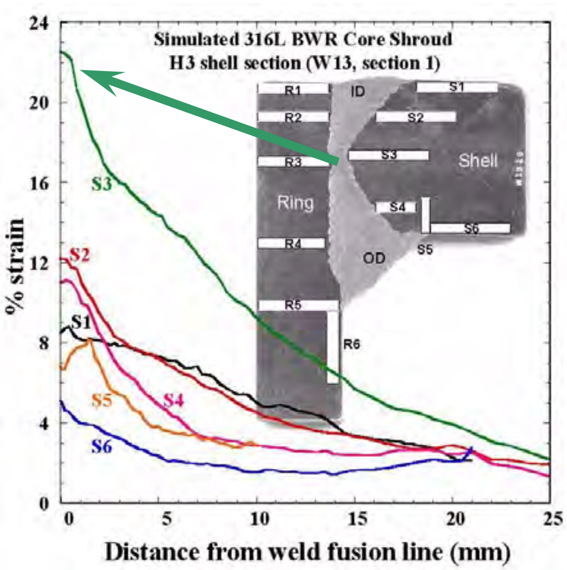
Overlapping, mechanical induced defects with further IGSCC propagation

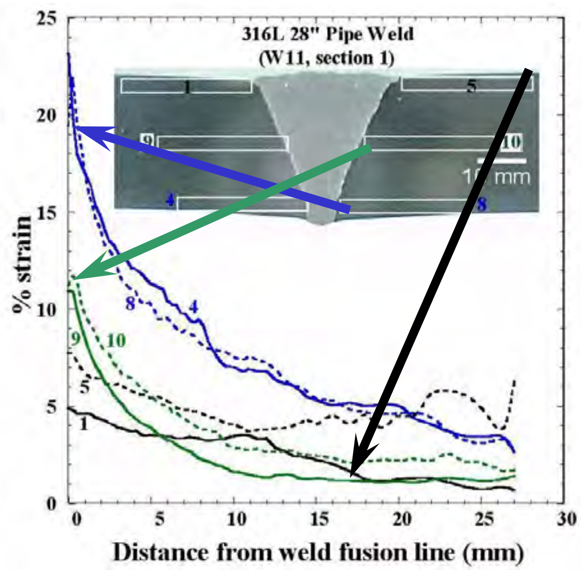
Surface cold work from machining, grinding, etc. enhances initiation and growth

Weld Residual Strain Effects on SCC



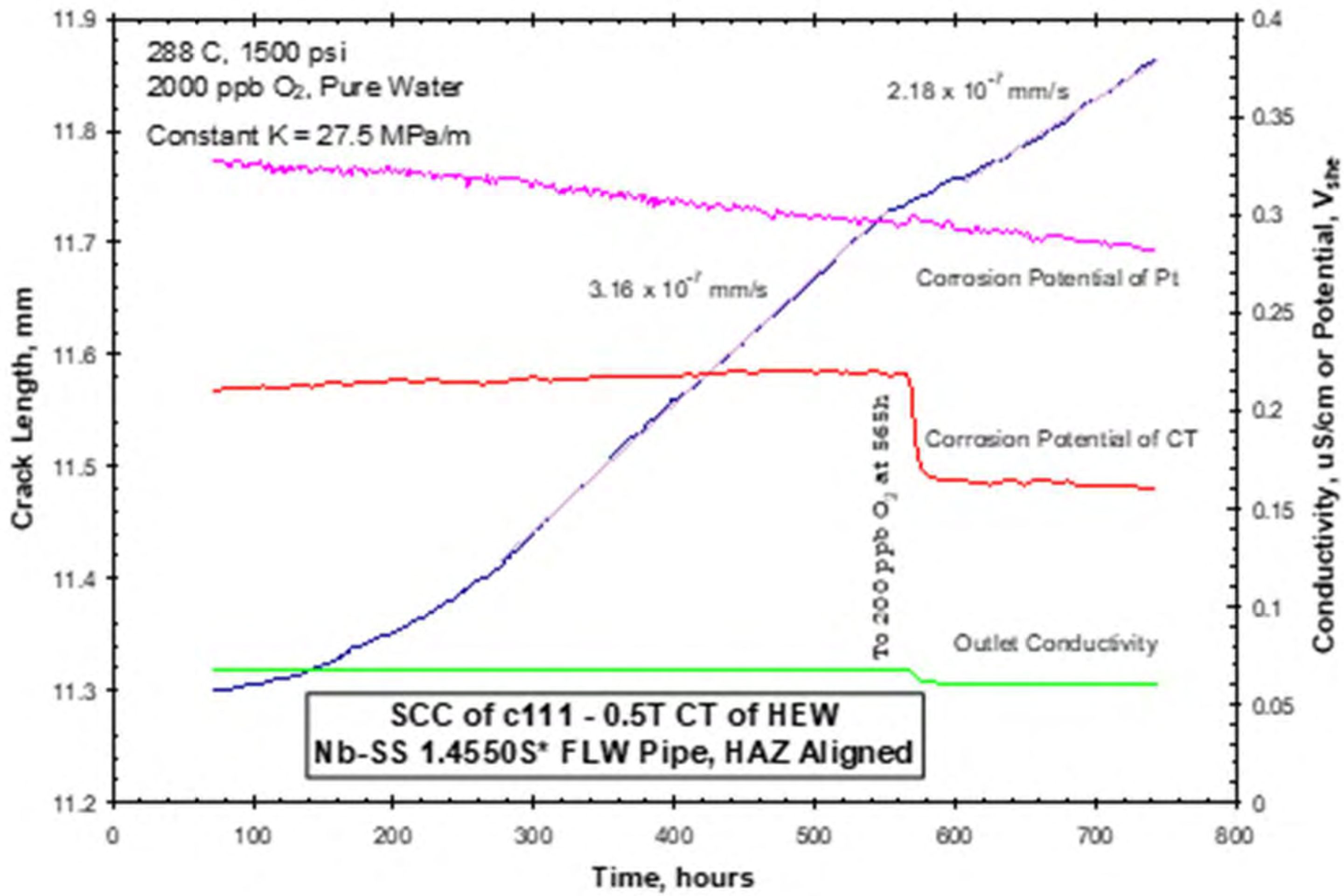






Residual strain at weld root typically peaks at >20% equivalent room temperature strain

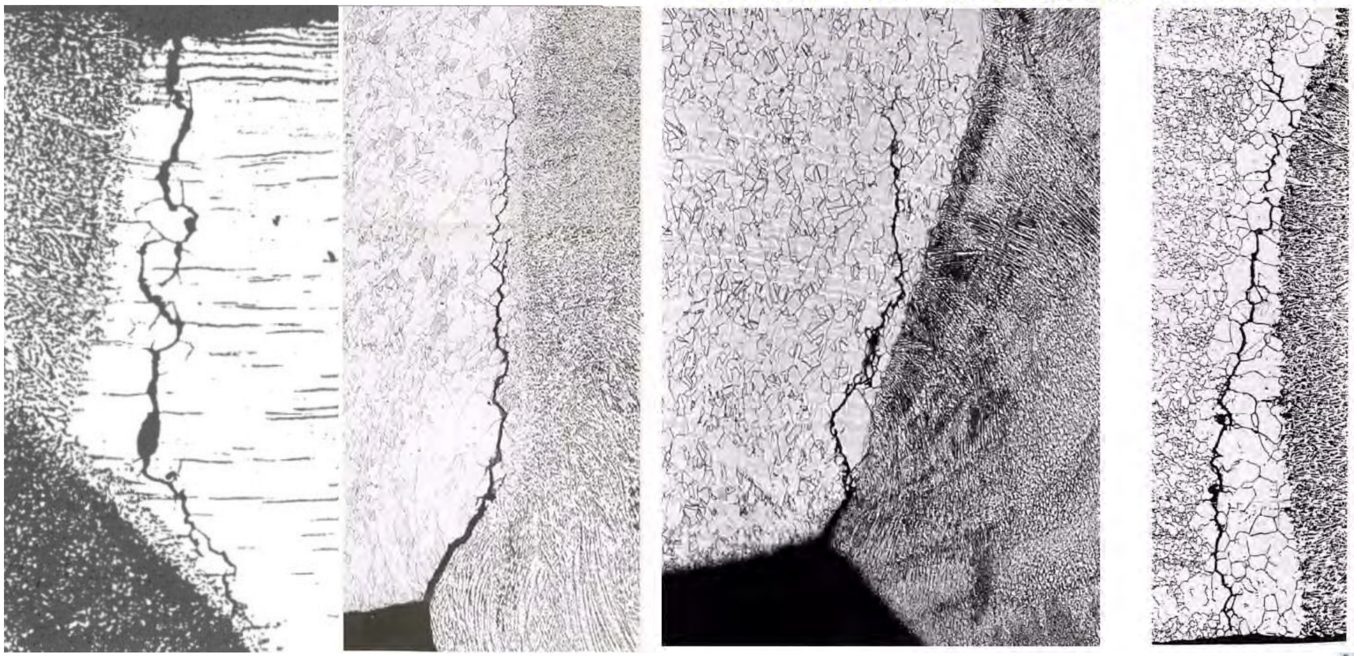
Crack Aligned in HAZ of SS Narrow Gap Weld



Annealed 348 stainless steels with narrow gap weld

Most SCC in SS in LWRs Occur in Weld HAZ

Stainless Steel - Unsensitized & Stabilized



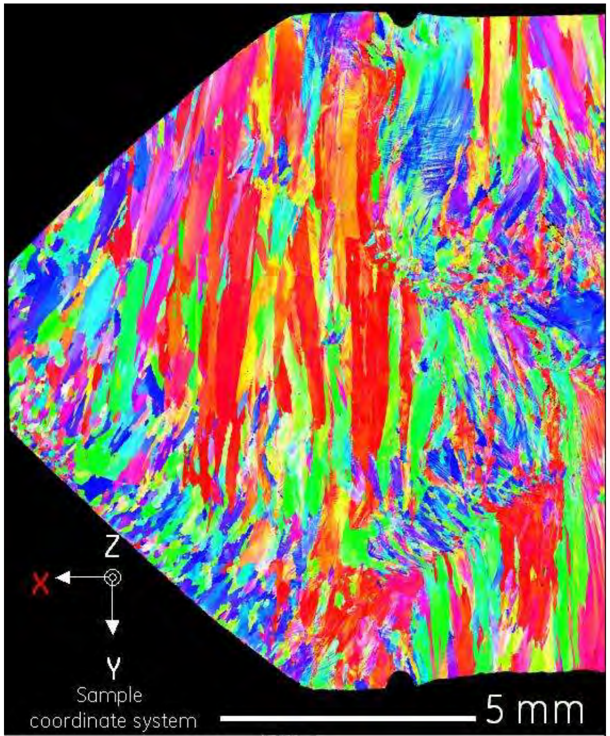
Ringhals 1, 304L SS

Crack path is strongly influenced by weld residual strain.

Weld residual stresses (+ applied and fit-up stresses) are spatially broader.

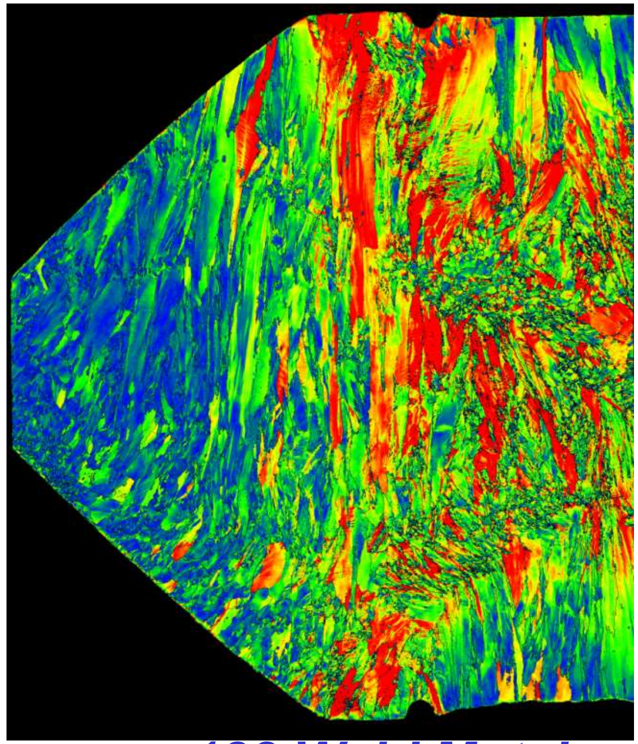
Inhomogeneity of Strain

Grain Orientation



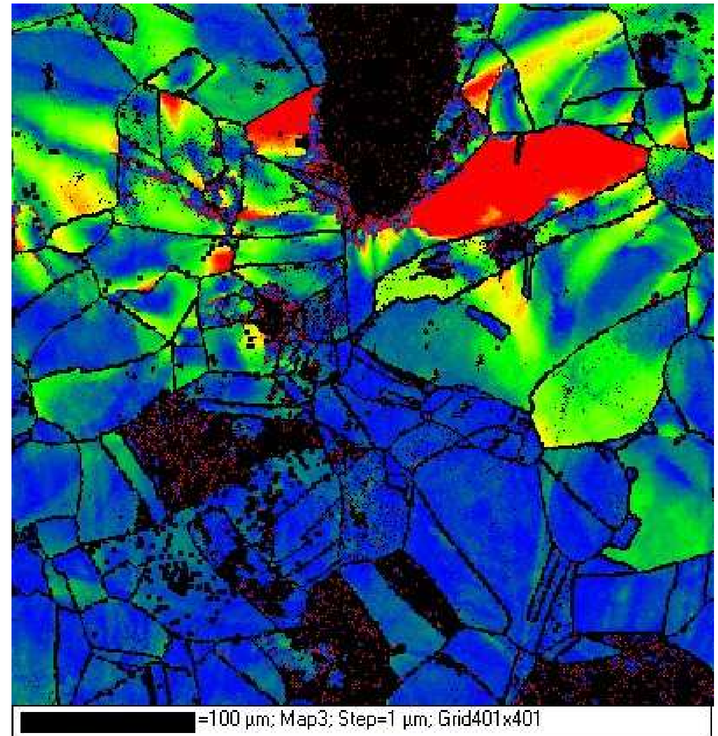
182 Weld Metal

Misorientation (Strain)

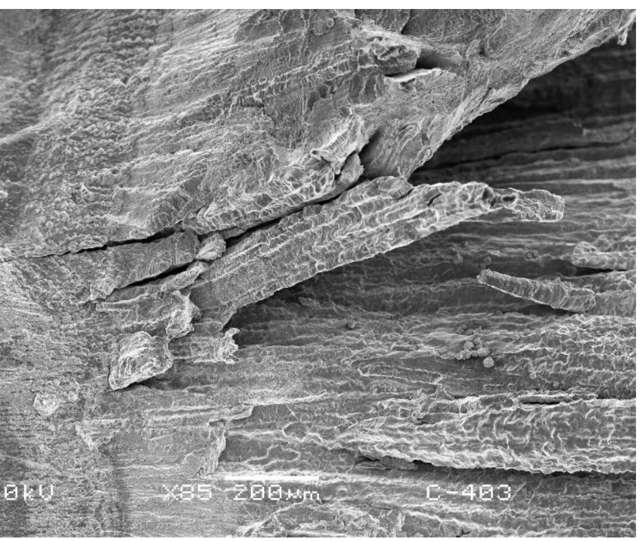


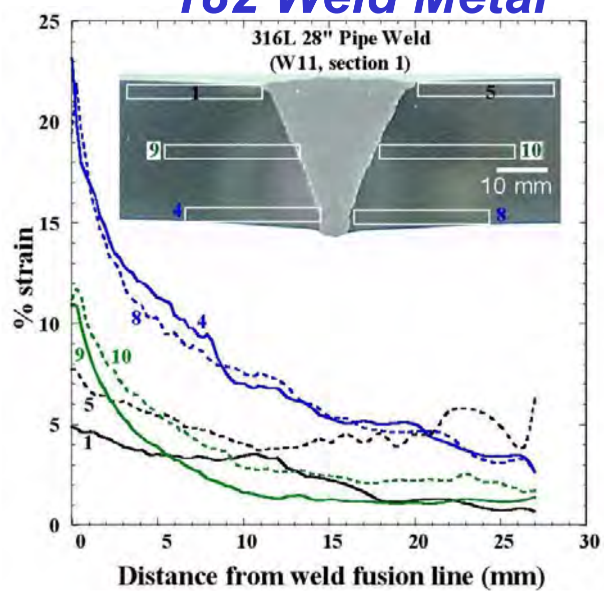
182 Weld Metal

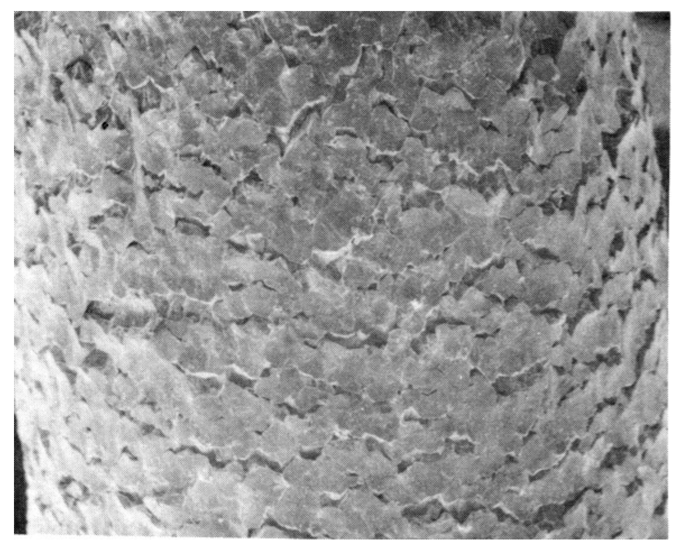
Strain Around Crack



Sensitized SS



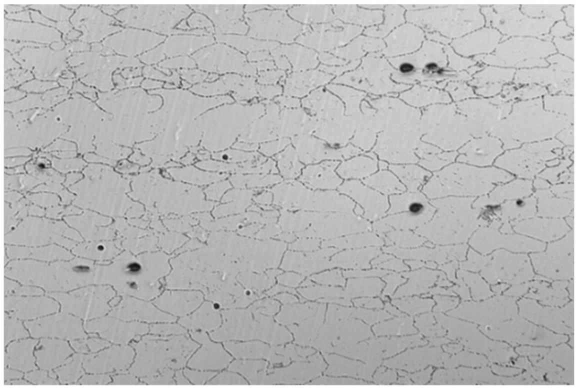




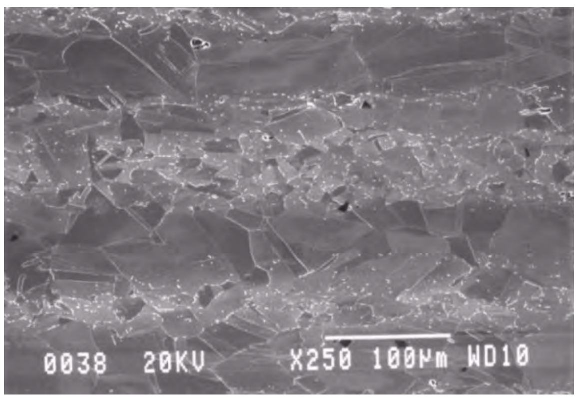
Effects of Microstructural Banding & Plane of CW

Specs are not keeping up with changes in metal processing

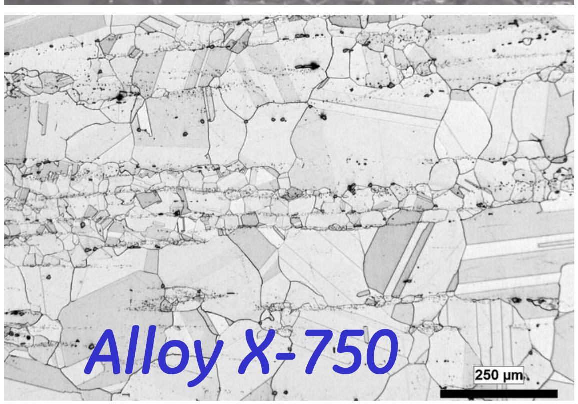
High growth rates in:



Alloy 690

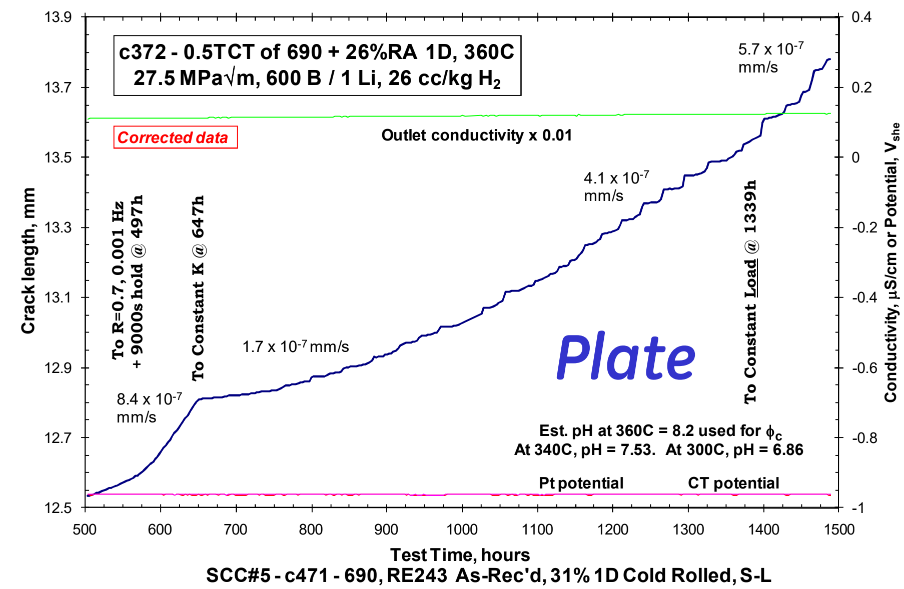


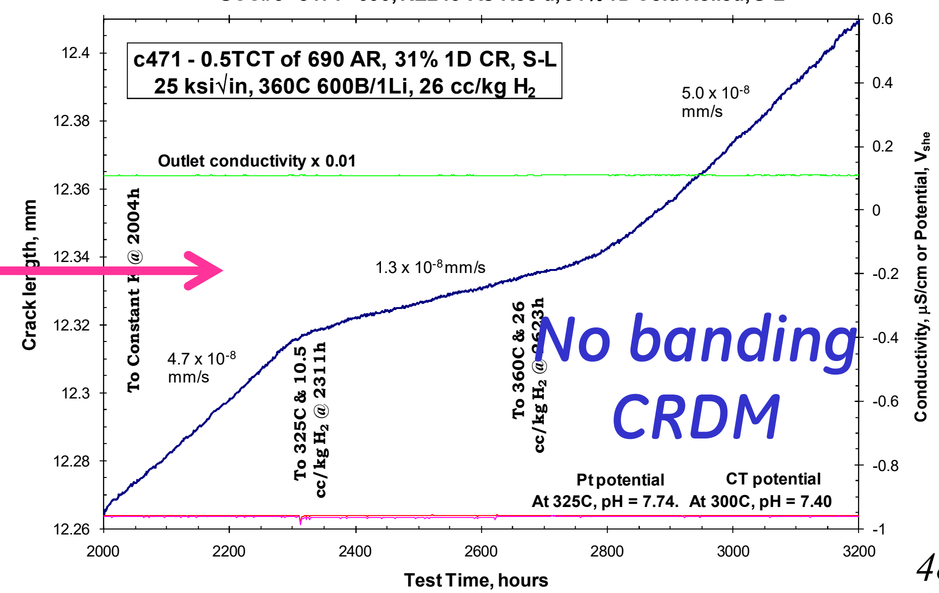
Alloy 690



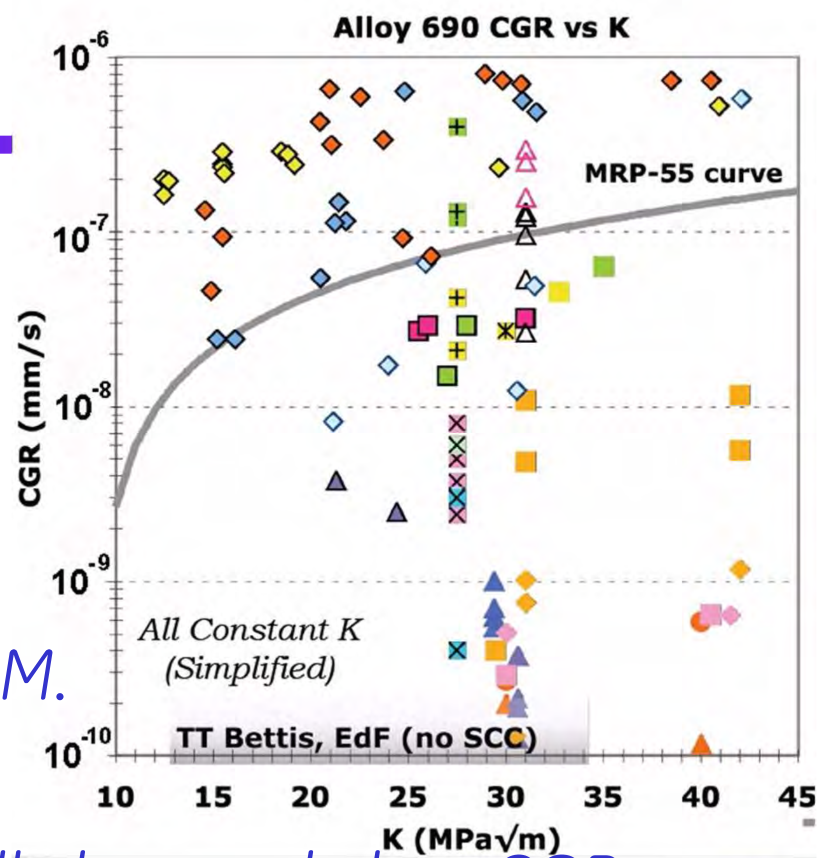
Alloy X-750

Alloy 690



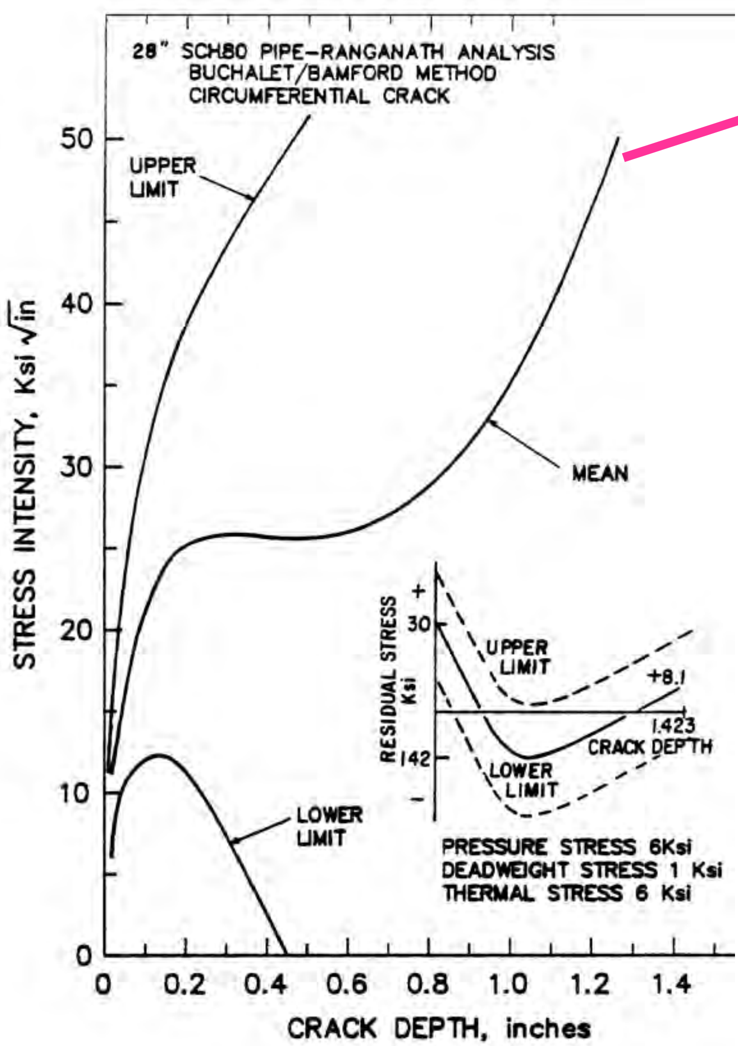


690 – Lore & Misconceptions

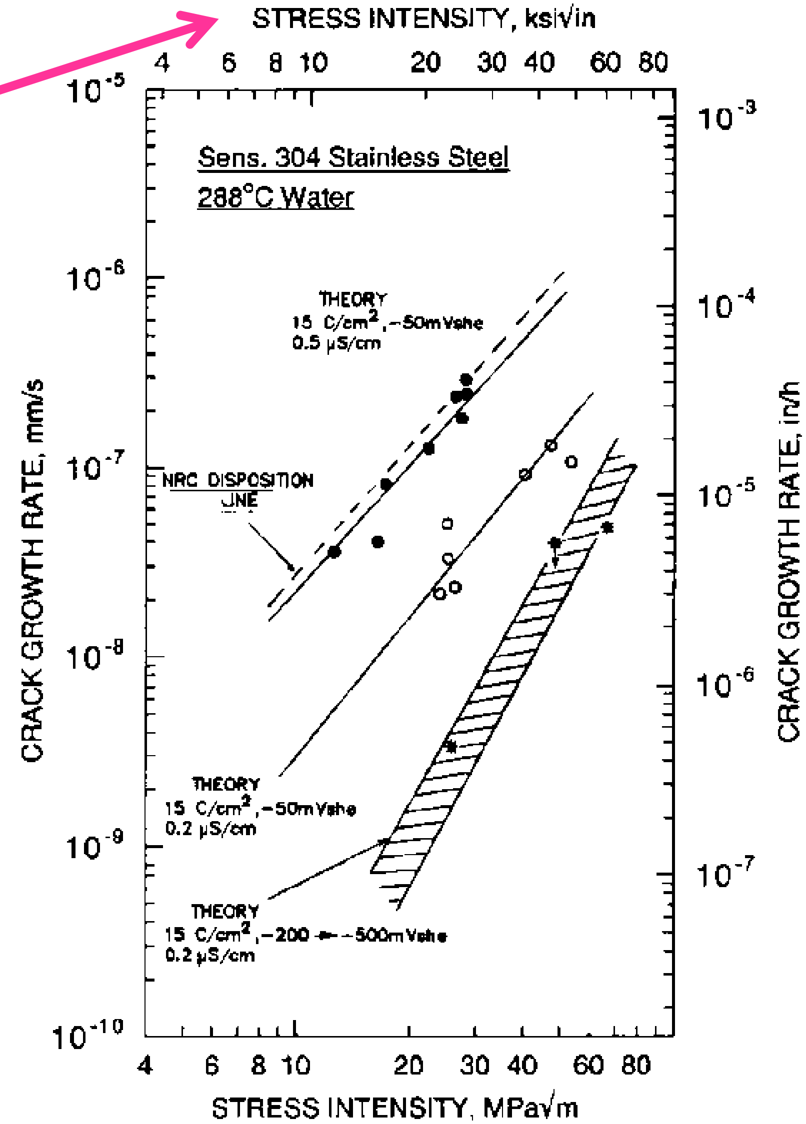


- Alloy 690 (30% Cr) is immune.
- Most Alloy 690 is homogeneous.
- Only plate forms are inhomogeneous.
- Only extruded material is used for CRDM.
- 1-D cold rolling is uniquely bad.
- Forged or tensile strained materials will show only low CGRs.
- CRDM forms, esp. if homogeneous, show only low CGRs.
- GB carbides are beneficial, and the more the better.
- EBSD is measuring artificial characteristics.
- Residual strains are always <10%.
- One or two "relevant" specimens (e.g., from mockups) provide clear evidence that there are no SCC concerns.

Crack Trajectory in Plant Components: Simple



K vs. Depth in Piping



SCC Growth Rate vs. K

Modeling Stress Corrosion Cracking

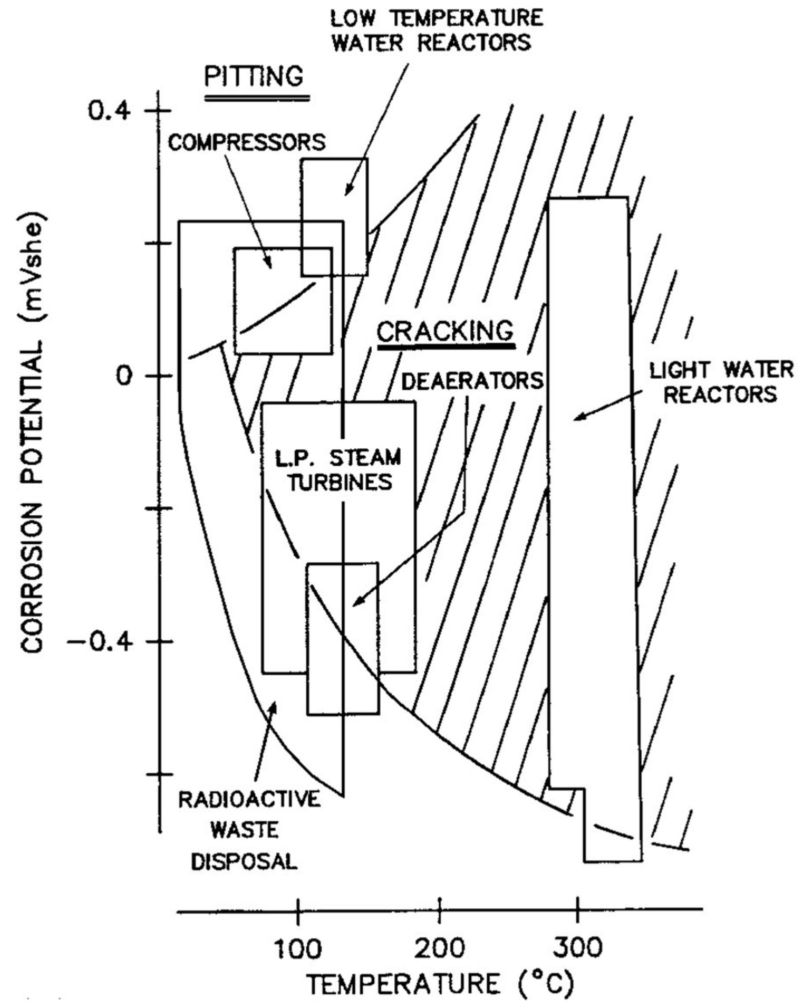
What are the key thermodynamic and kinetic processes in SCC?

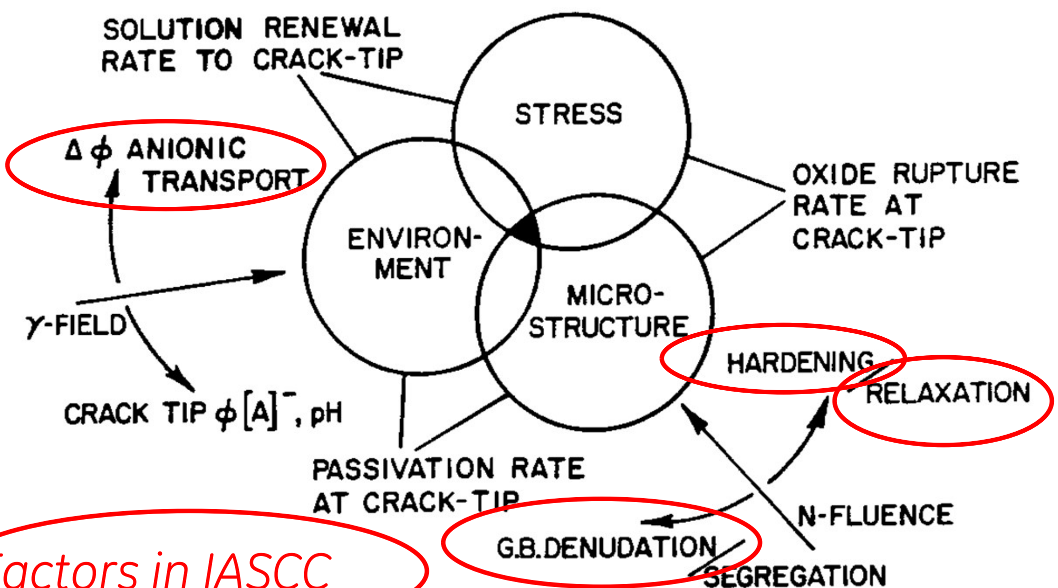
- *Liquid mass transport in crack?*
- *Cathodic reaction rates?*
- *Cathodic H formation?*
- *H adsorption kinetics?*
- *H diffusion kinetics?*
- *H trapping / embrittlement?*
- *Cr diffusion in GBs?*
- *O transport in GBs?*
- *Transport processes in films?*
- *Semi-conductivity of films?*
- *Diffusion of interstitials?*
- *H trapping sites?*
- *Film repassivation kinetics?*
- *GB creep?*
- *GB vacancy motion?*
- *GB void formation?*
- *Creep crack growth?*
- *Atomically sharp cracks?*
- *Adsorbed species?*
- *Surface mobility?*
- *Oxide solubility*
- *Metal oxidation kinetics*
- *Film ductility?*
- *Grain boundary sliding?*

Unified View of SCC Growth

Unified perspective of SCC in hot water:

- *the crack tip system*
- *localized (crack tip) deformation*
  - → *disruption of passivity*
  - → *corrosion*
  - → *repassivation*





Factors in IASCC

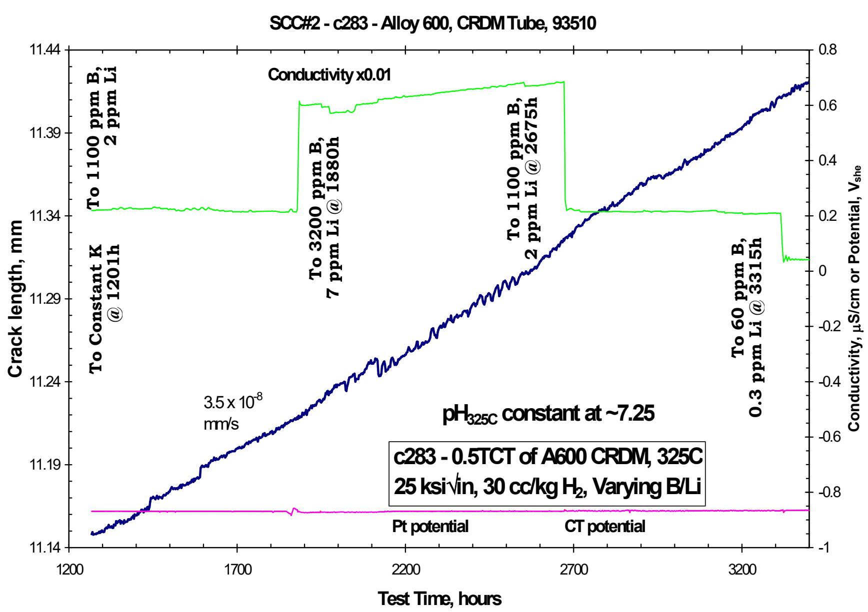
Many similar vulnerabilities:

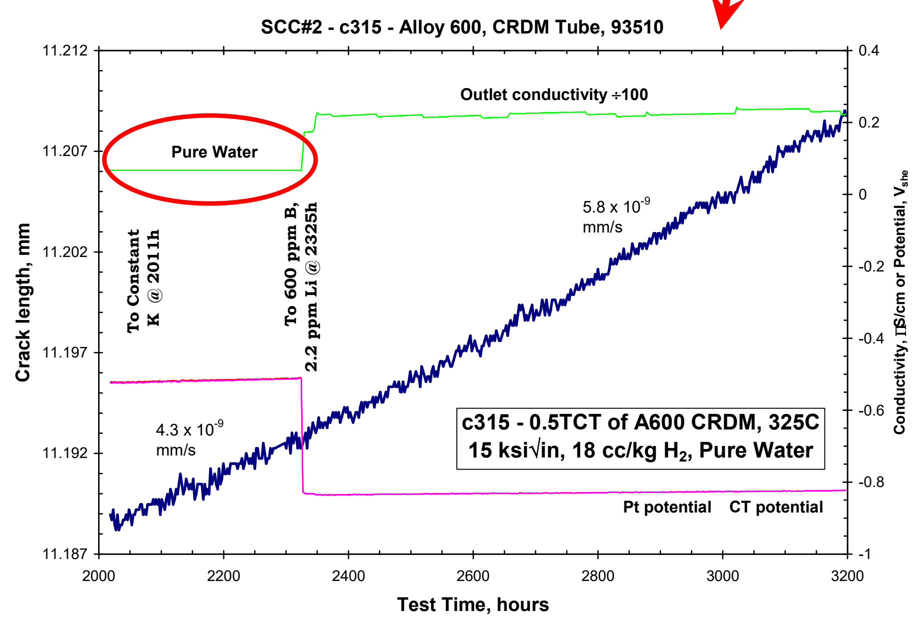
- *Range of Fe- & Ni- alloys*
- *BWR & BWR water*
- *SCC & Corrosion Fatigue*

BWR & PWR SCC in Hot Water

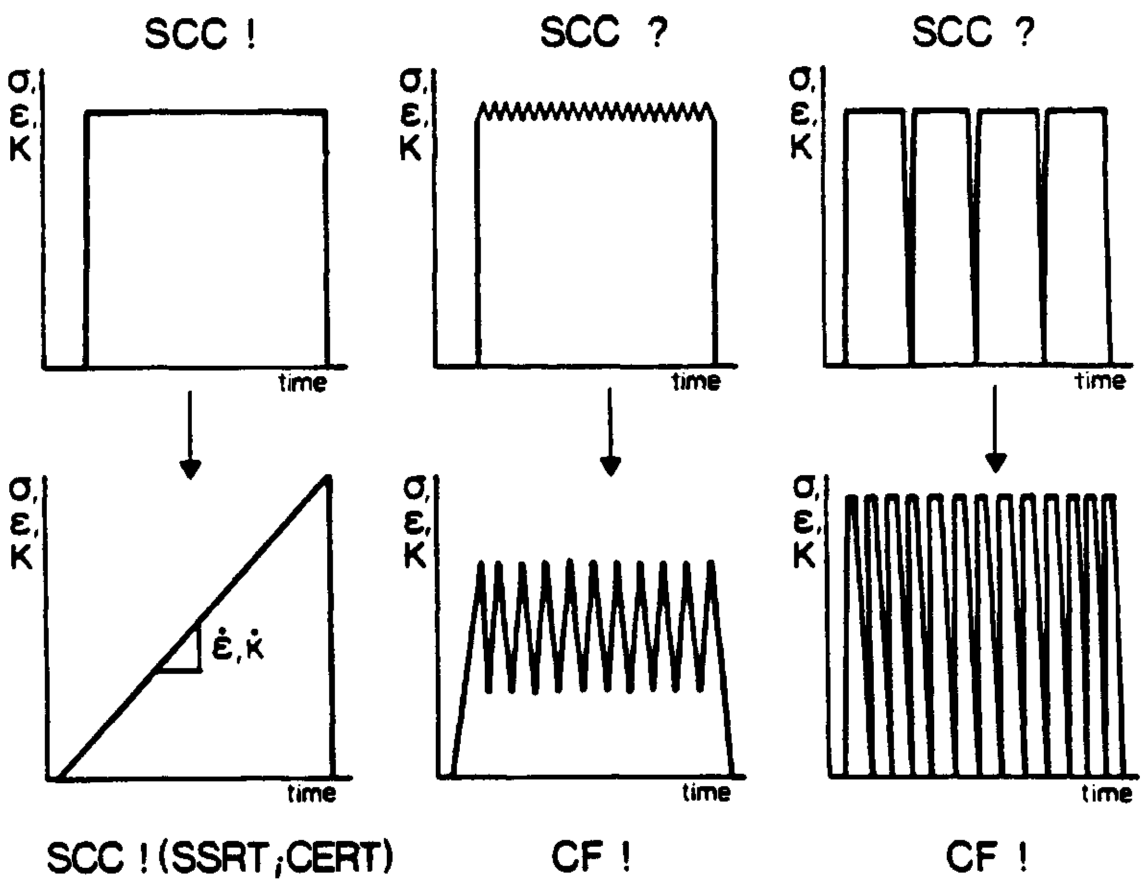
1 – PWR and BWR chemistries are not that different:
- the crack tip is always deaerated & at low potential especially as BWRs adopt low potential / NobleChem™

2 – The primary differences BWR vs. PWR are:
- temperature: 274/288C vs. 286/323/343C
- pH: 5.65 = neutral vs. 7.0 – 7.4 with B/Li
- H_2 fugacity: 0.02 – 0.1 ppm vs. ~3 ppm H_2





Continuum in Response from Cyclic to Static Load



In Fatigue, reversed slip causes crack advance, so dynamic strain is a multiple (~100 – 200X) of the inert fatigue CGR.

In Slow Strain Rate, dynamic strain is a multiple of the applied $\dot{\varepsilon}$.

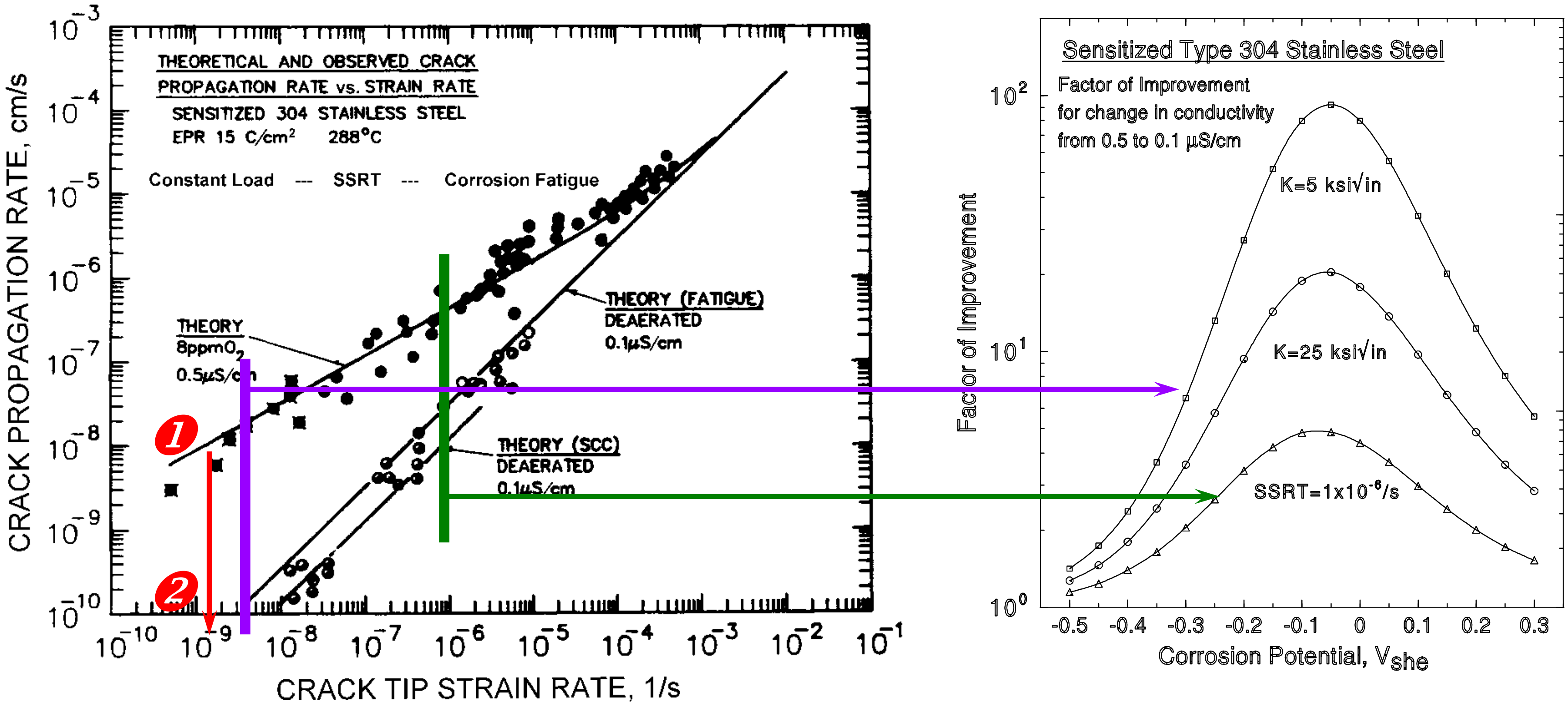
At Constant K, dynamic strain results from crack advance and strain field redistribution.

Formulations for dynamic strain at crack tip but fundamental basis is weaker when moving from fatigue → SCC.

SCC Processes, Dependencies & Modeling

The simplicity of slip oxidation $V \propto (\dot{\varepsilon}_{ct})^n$ belies complexities:

- *large inter-dependencies in all SCC parameters, e.g.:*
  - *– ECP vs. water purity*
  - *– sensitization vs. water chem*
  - *– K vs. water chemistry*
  - *– temperature vs. water chem*



Benefit of ❶→❷ depends on loading (crack tip strain rate)

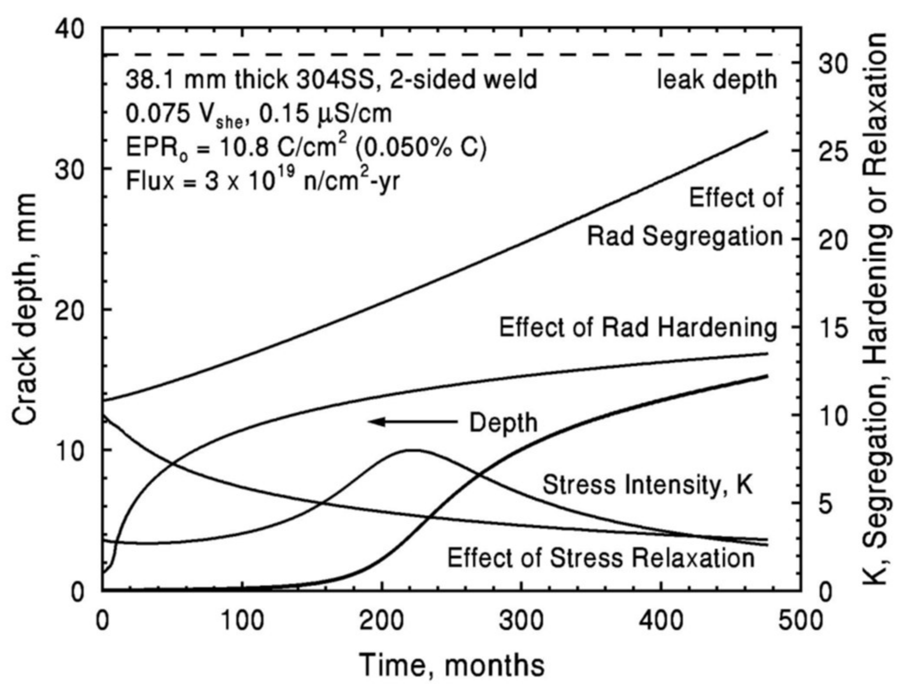
SCC Predictions Integrate Time- & Depth Variations

Time-varying phenomena:

- neutron fluence & dependencies
  - → radiation segregation
  - → residual stress profiles
  - → plasticity/YS effects
- solution conductivity / impurities
- corrosion potential (HWC)

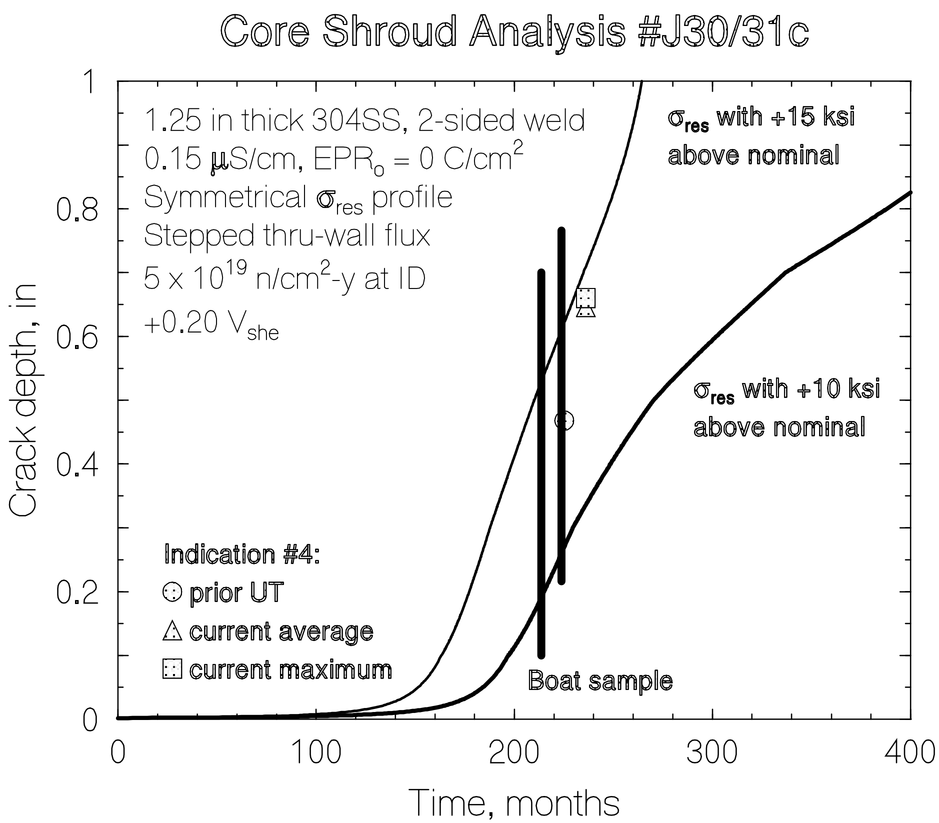
Crack depth-varying phenomena:

- residual stress thru-wall
  - → relaxation from fluence
- stress intensity
- thermal sensitization thru-wall
- surface cold work
- chemistry in very small cracks

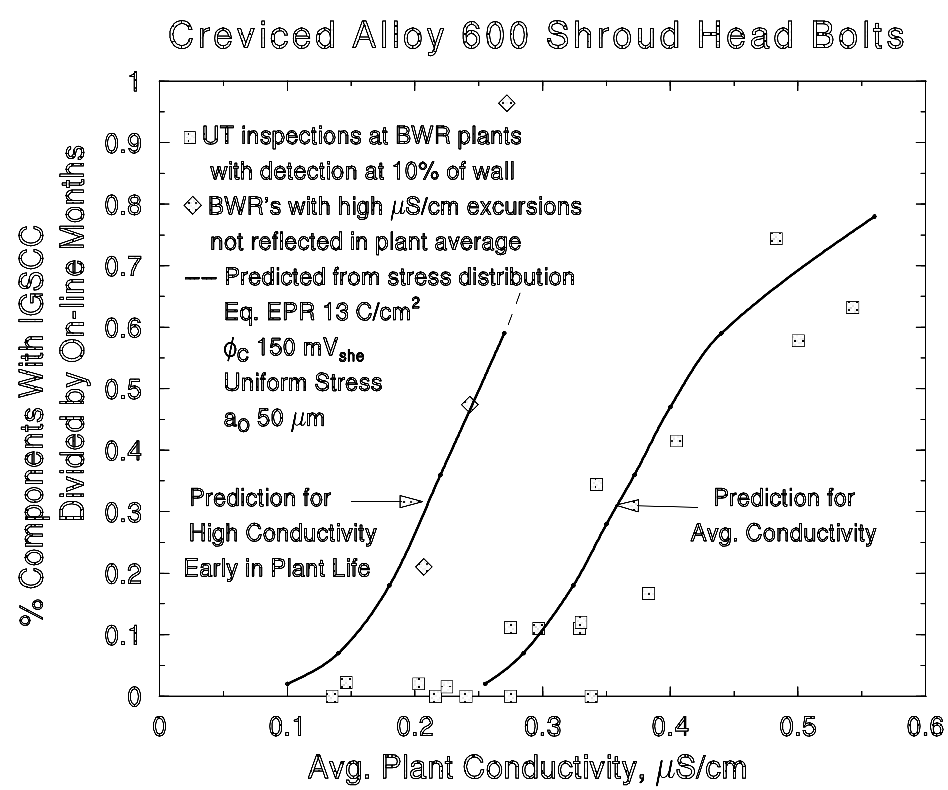


Example of complex crack depth- and time-varying relationships in SCC in BWR core shrouds

SCC Life Prediction



Prediction of SCC in BWR Core Shrouds (5 years before first observation)



Prediction of SCC in A600 BWR Shroud Head Bolts

Material Degradation Matrix

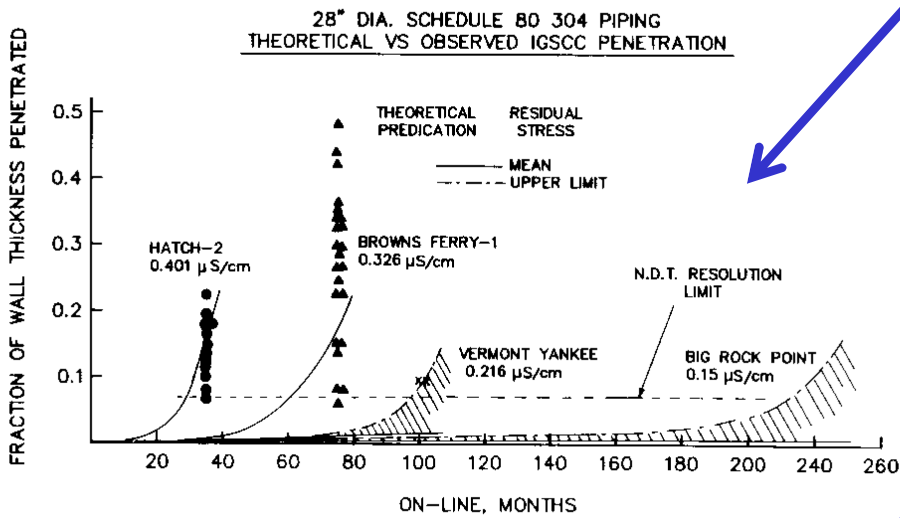
www.epri.com

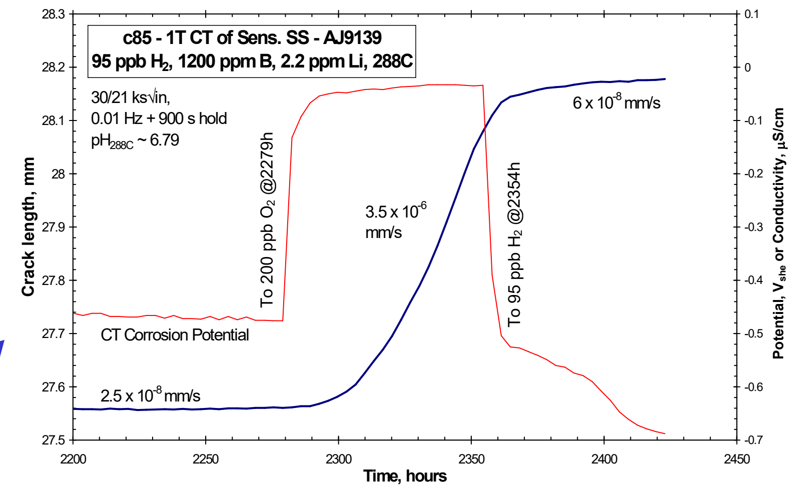
BWR Component	Material	SCC SCC				Corrosion/Wear C & W				Fatigue Fat			Reduction in Toughness RiT					
													Aging	Irradiation				
	?Subdivision→	IG	IA	TG	LTCP	Wstg	Pit	Wear	FAC	HC	LC/Th	Env	Th	Emb	VS	SR	Th	Fl
BWR Pressure Vessel (Including stainless steel and Ni-base penetrations)	C&LAS	? e096	? e097	Y e098	N	Y e099	Y e099	N	N	N	Y e100	Y e101	Y e102	Y e009	N	N	N	Y e010
	C&LAS Welds	? e096	? e097	Y e098	N	Y e099	Y e099	N	N	N	Y e100	Y e101	Y e102	Y e009	N	N	N	Y e010
	Wrought SS	Y e103	N	Y e104	? e013	N	N	N	N	Y e032	Y e105	Y e007	N	N	N	N	N	N
	SS Welds & Clad	Y e106	Y e107	Y e108	? e013	N	N	N	N	Y e032	Y e109	Y e109	Y e022	Y e022	N	N	N	N
	Wrought Ni Alloys	Y e110	Y e050	N	Y e031	N	N	N	N	Y e032	N	Y e053	Y e057	Y e057	N	N	N	Y e057
	Ni-base Welds & Clad	Y e110	Y e050	N	Y e031	N	N	N	N	Y e032	N	Y e053	Y e057	Y e057	N	N	N	Y e057
BWR Reactor Internals e135	Wrought SS	Y e103	Y e045	Y e111 e104	? e013	? e112	N	Y e113	N	Y e114	N	Y e014	N	Y e045	N	Y e115	Y e116	? e117
	SS Welds & Clad	Y e103	Y e045	Y e111 e104	? e013	? e112	N	Y e113	N	Y e114	N	Y e014	Y e118	Y e045	N	Y e115	Y e116	? e117
	CASS	Y e119	Y e045	N	? e013	N	N	N	N	N	N	N	Y e057	Y e045	N	N	N	N
	Ni-base Welds & Clad	Y e120	Y e045	N	Y e031	N	N	N	N	Y e121	N	Y e040	? e045	Y e122	N	Y e123	N	N
	Wrought Ni Alloys	Y e124	Y e053	N	Y e051	N	N	N	N	Y e040	N	Y e040	? e045	Y e122	N	Y e123	N	N

Green means degradation, but perhaps adequately understood.
Yellow, orange and blue are increasingly severe problem areas.
These will be surprises, since little R&D is done to address them.

Disconnects Between Past & Future Degradation

1. Absence of Inspection – first of a kind cracks cause leaks.
2. The Non-Linear Effect of Time – cracks grow non-linearly.

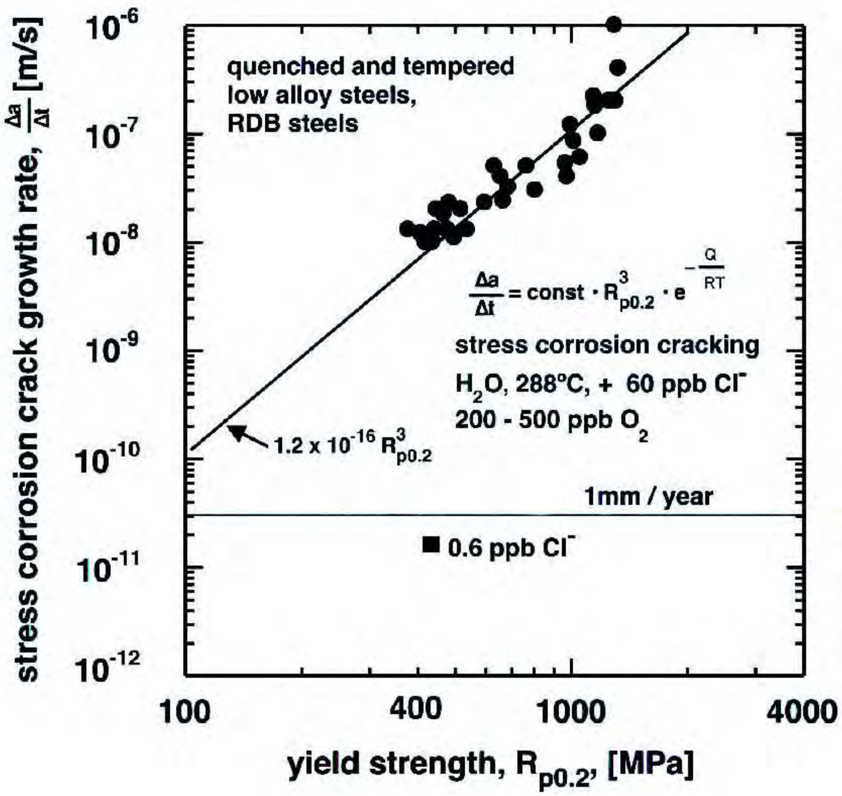




3. Changes in Plant Operation – O_2, low leakage core…
4. Aging: Single Variable Changes – fluence, thermal aging…
5. Aging Synergies – RPV radiation ↓K_{IC}, ↑YS → ↑SCC.
6. Staged or Sequential Phenomena – 182 on RPV.
7. Emerging Issues – lots we don't yet know.

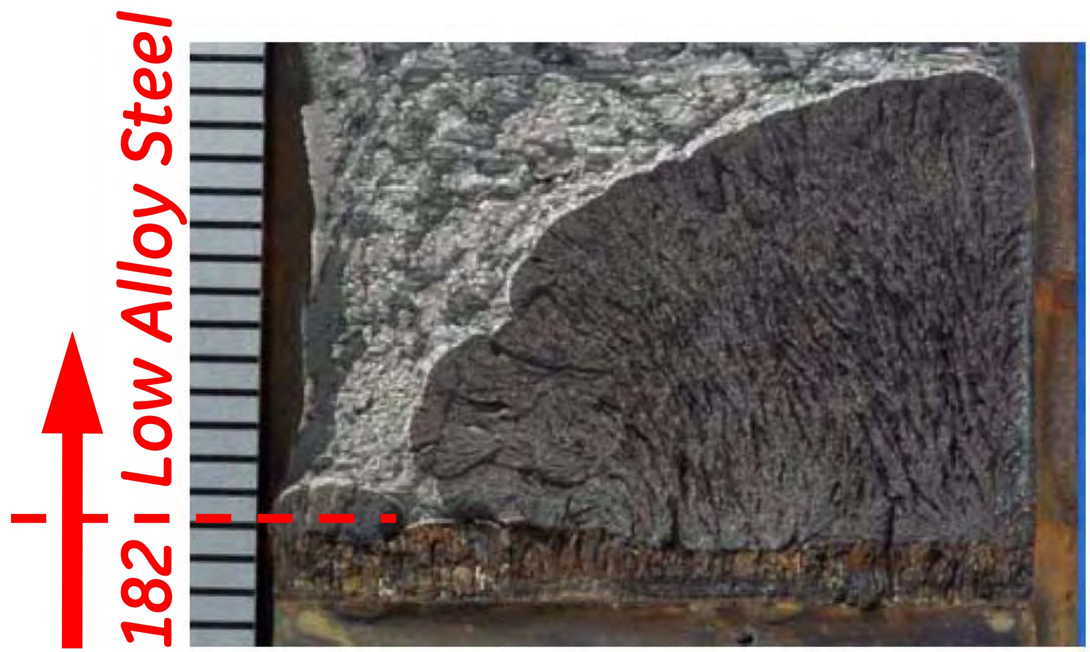
Aging Synergies

In RPV embrittlement, the yield strength is ↑by >30%. Data show that ↑YS increases SCC susceptibility & growth.



Sequential Phenomena

SCC in Alloy 182 attachment pads must first occur before they can intersect the underlying RPV. SCC can cross the interface.

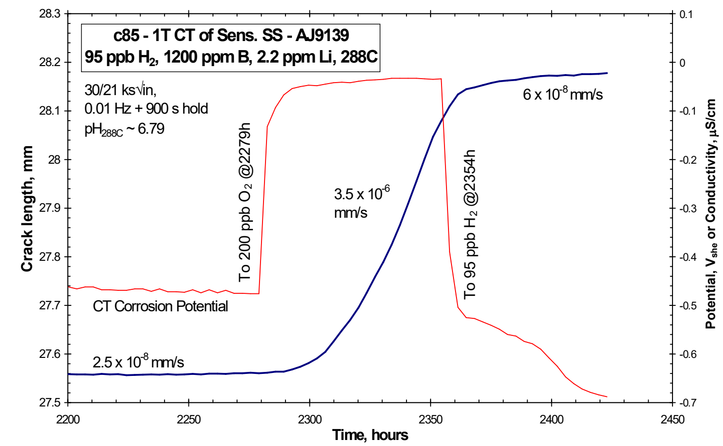


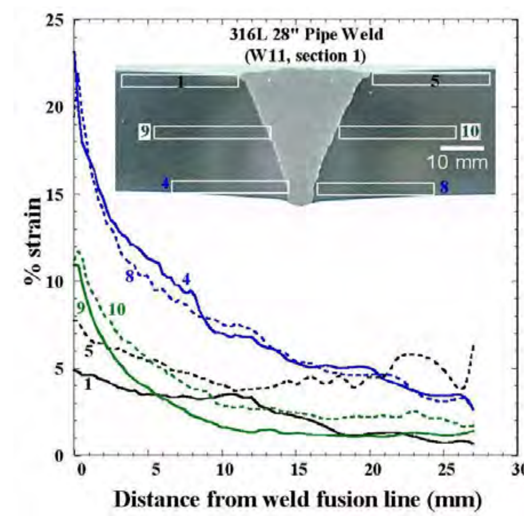
× M024: K = 30MPa√m (at Interface),
(=54 MPa√m(End of Test)), 5 ppb Cl^-

Emerging Issues in EAC

- Cl⁻ Effects on SCC of Low Alloy Steel
  - large effects of ≤3 ppb Cl⁻
  - ↑ in SCC from radiation hardening
- Plant Modification / Upgrades
- O_2 in PWR and CANDU Primary Water
- Cold Work Effects on ECP Benefit
- Bulk Cold Work → Weld Residual Strain
- SCC of Banded & CW Alloy 690
- Effects of Si: high CGR low effect of K & ϕ_c

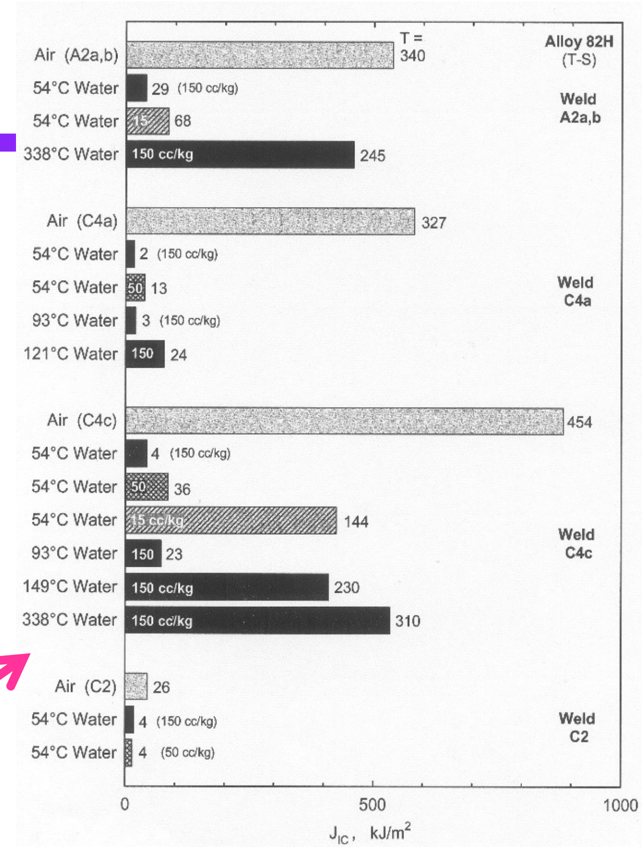
✖ M024: K = 30MPa√m (at Interface), (=54 MPa√m(End of Test)), 5 ppb Cl⁻

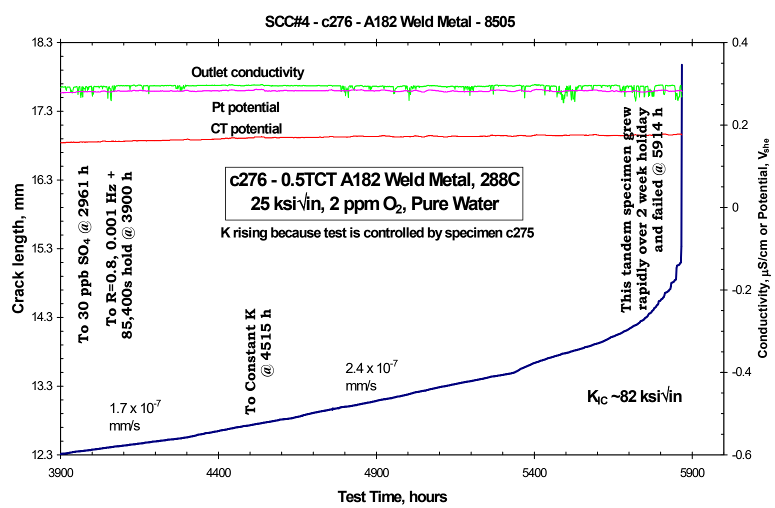




Emerging Issues in EAC

- Re-loading Effects → rapid crack growth
- Corrosion Fatigue Crack Initiation in Austenitic Materials
- dK/da: K changes as crack grows
- K/size Criteria vs. CW & Irradiation
- Environmental Effects
  - ➨ F-R racture Resistance
  - ➨ K_{IC} Fracture Toughness
- Data Quality
- Loss of expertise & R&D capability





Progress is Limited by Excellence of Experiments

- *Complexity of environmental effects with ~"500" variables in ~10 categories involving ~7 major disciplines.*
- *Interdependence among most variables.*
- *Extensive lore based on poor data and wishful optimisms, driven by ASME Code requirement of "immunity".*
- *The nature of SCC, with 6 – 10 orders of magnitude range in growth rate for specific mat'ls, environments & loads.*
- *40 – 100 year life puts heavy demands on design & data.*
- *Tests need to guide & test our thinking and modeling. Lore, opinion and intuition need careful examination.*
- *Accelerated, 1-dimensional testing won't get the job done.*

The Realities of SCC – Challenging Lore

- Ubiquity – SCC occurs in all structural materials in hot water.
- Commonality among materials, BWR vs. PWR environments, loading, irradiation, etc. is high, and mechanisms appear similar.
- Dynamic strain appears to be essential to sustaining SCC.
- Thresholds and immunity are generally, and perhaps always, fiction. The ASME design codes simply rely on SCC immunity.

  Our experiments, our designs, our thinking, our mechanisms often reflect this fundamental error/assumption.
- Interdependencies pervade SCC response. We too often think in terms of single variables and linearity.
- SCC measurement capability remains rudimentary, with initiation far more primitive than growth.

Simplistic, short-term tests has obscured many realities of SCC