“First Principles” Prediction of Environmentally-Assisted Degradation in Water Cooled Reactors

and why would you want to do this?

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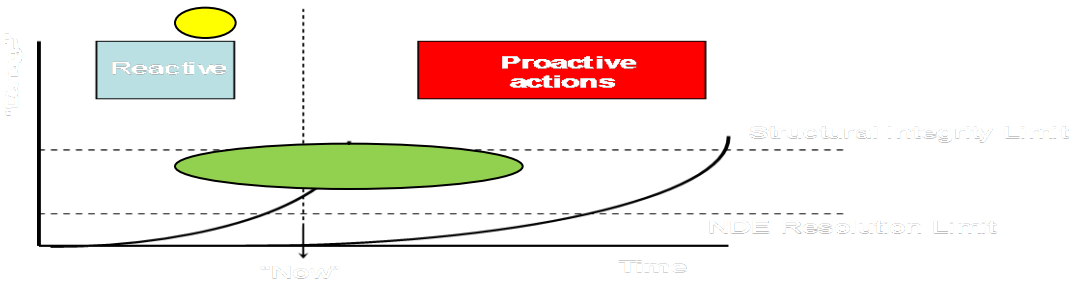
The Broad Picture

Overal Objective

To identify components that may be expected to undergo degradation, so that mitigation actions may be implemented before significant challenges to structural integrity and safety arise.



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Movement towards proactive management requires life prediction capabilities;

- Past plant experience
- Empirical knowledge of effect of operating parameters on degradation kinetics
- Quantitative understanding of degradation mechanism

Numerous Materials Degradation Modes

Corrosion

- General, Uniform
- Flow Accelerated
- Localized
  - Intergranular attack
  - Galvanic
  - Crevice
  - Pitting
  - Microbiologically-induced
  - Environmentally-assisted cracking
    - Stress corrosion cracking
    - Strain induced cracking
    - Corrosion fatigue
    - Hydrogen embrittlement

Mechanical

- Ductile failure
- Brittle failure
  - Thermal embrittlement
  - Irradiation embrittlement
- Fatigue
- Weld defects

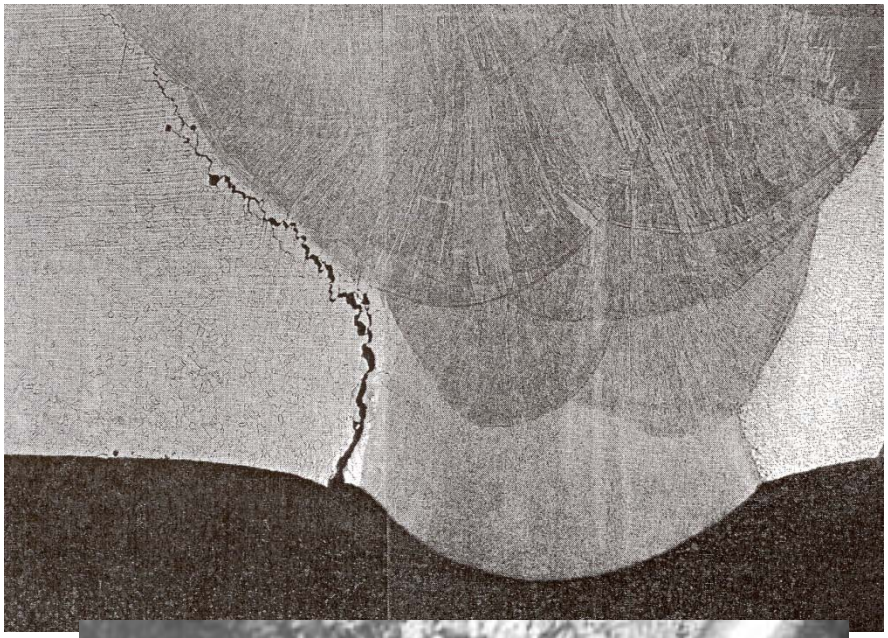
Concentrate on Environmentally-Assisted Cracking in BWRs

Stress Corrosion Cracking of Structural Alloys in BWRs

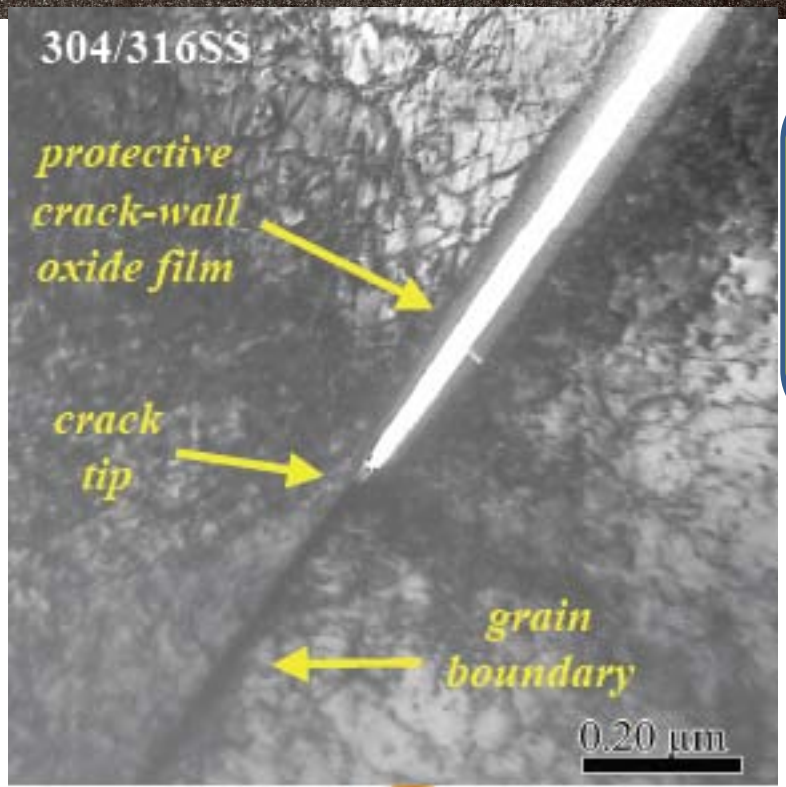
Background and plant experience

Component and Mode of failure	Alloy	Time Period
Fuel cladding, irradiation assisted SCC	304	1960's
Furnace sensitized safe ends, IGSCC	304,182, 600	↓
Weld sensitized small dia. piping, IGSCC	304	
Weld sensitized large dia. piping, IGSCC	304	
Furnace sensitized weldments & safe ends, IGSCC	182/600	
Low alloy steel nozzles, thermally induced vibration	508	1980s
Crevice induced cracking	304L / 316L	↓
Jet pump beams, IGSCC	X750	
Cold work induced IGSCC of "resistant" alloys	304L	
Low alloy steel pressure vessel, TGSCC	A533B/A508	
Irradiated core internals, IASCC	304,316	
IGSCC / IASCC of low carbon and stabilized st st	304L,316L 321,347	2000s

Concentrate on Stainless Steels



Pipe test results showing IGSCC In a 400mm. (16 ins.) Type 304 pipe HAZ (Gordon and Gordon, 1987))

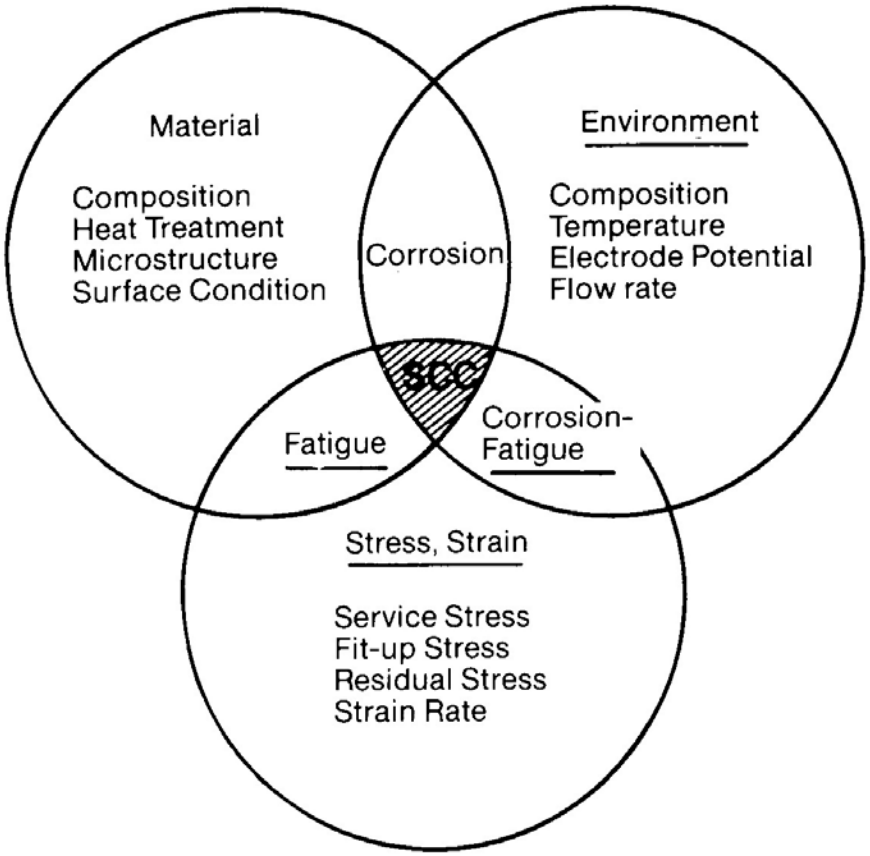


Extremely tight crack tips, which has a bearing on the mechanisms-based life prediction approaches

Bruemmer et al

The Early (1970s) Understanding of SCC

Conjoint material, stress and environment requirements for stress corrosion cracking (Speidel)



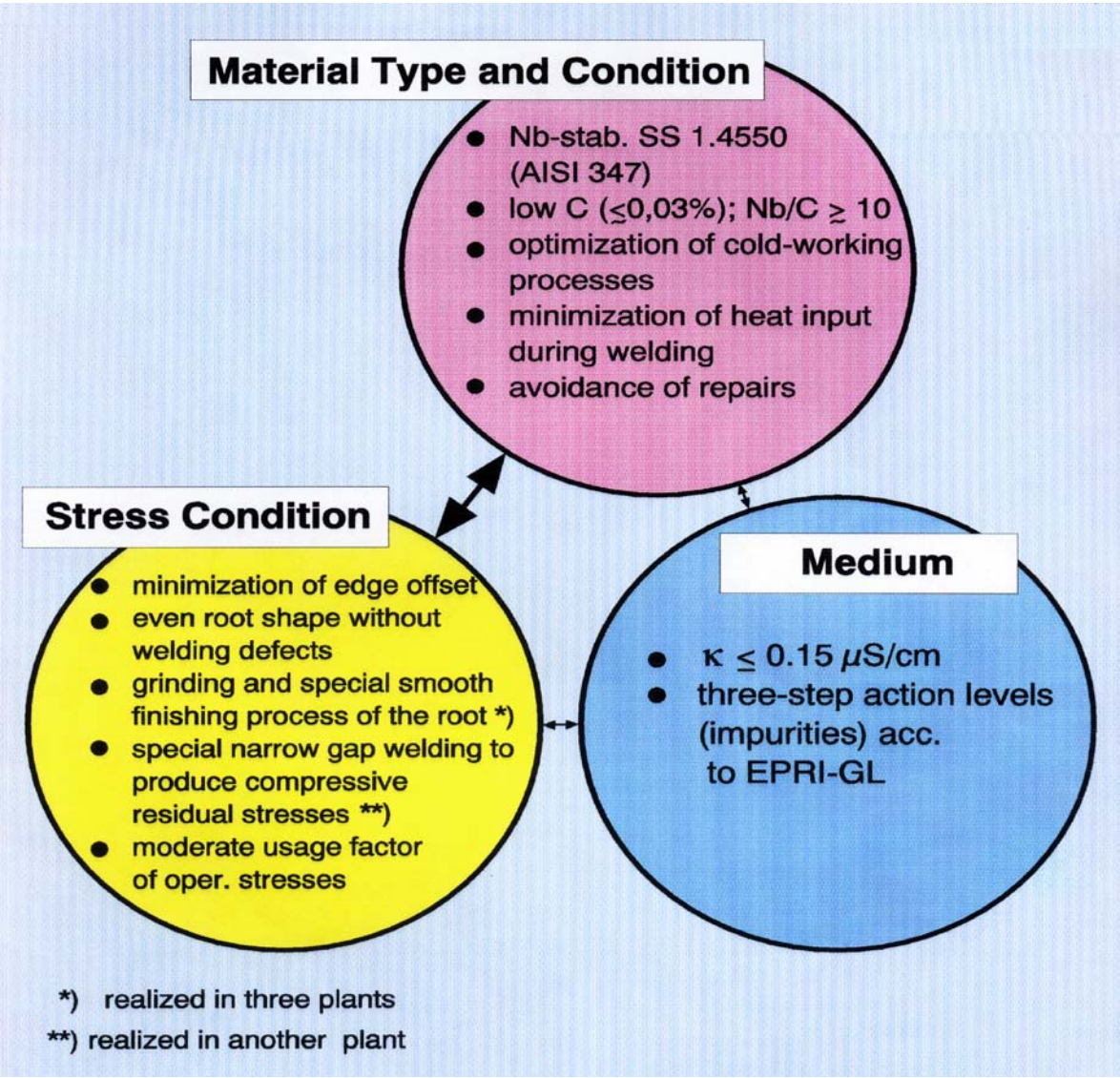
Interactions with other degradation modes

- General Corrosion and FAC
- Embrittlement
- Fatigue

The Good News;

- The need for conjoint requirements for SCC means that the "frequency" of cracking is relatively low.
- The remedial actions seem rather obvious; remove one or (preferably more) of the conjoint requirements

Renewal of Austenitic Stainless Steel Piping; Measures taken against IGSCC in German BWRs



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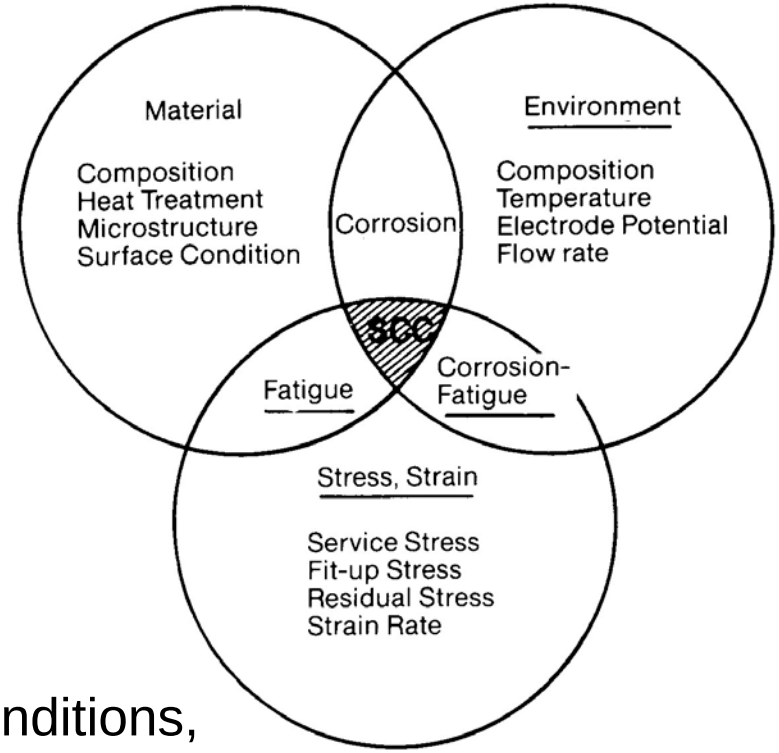
Conjoint material, stress and environment requirements for stress corrosion cracking (Speidel)



The Bad News;

- Because of the wide range of required conditions, and the uncertainty of their definition and interrelationships, it is difficult to *quantitatively* predict the cracking susceptibility for a given component.

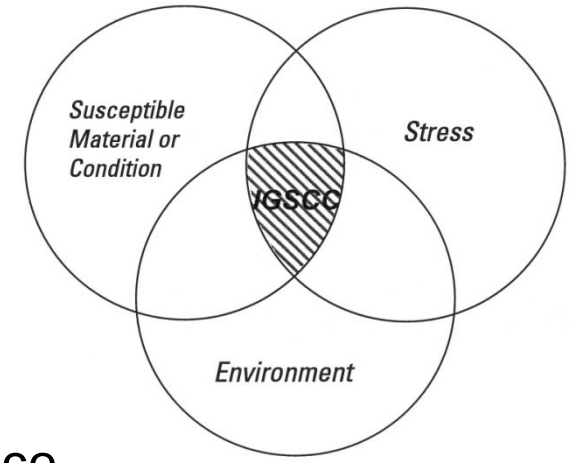
- The presence of one “overlooked” parameter (e.g. cold work) can negate the beneficial effect of an “obvious” beneficial action (e.g. desensitized structure).

This way of looking at SCC tells us nothing about the quantitative “Factors of Improvement” associated with mitigation actions

Stress Corrosion Cracking of Austenitic St St in BWRs

Controlling system parameters

- Chromium
- Carbon
- Silicon
- Ti, Nb
- Heat input
- Crevices
- % Cold work
- Neutron fluence
- Yield stress
- etc.

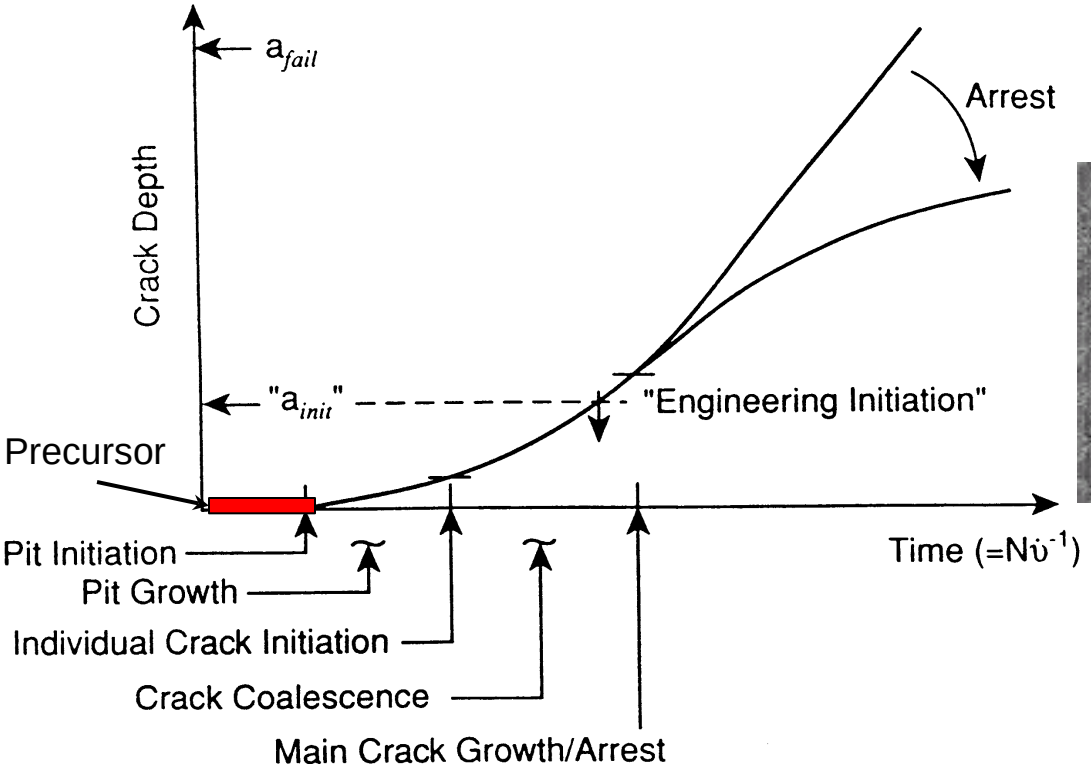


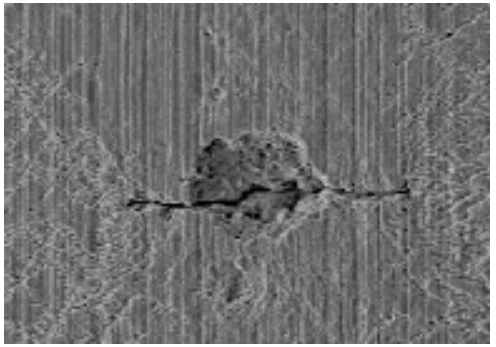
- Residual stress
- Fit-up stress
- Pressurization stress
- Dynamic loading
- Crack depth
- % Cold work

- Oxidising species (O_2, H_2O_2)
- Flow rate
- Temperature
- Chloride, Sulfate
- Crack depth
- etc.

- Conjoint requirements
- Strong secondary effects

Complex Interactions
How do these control the kinetics of cracking?

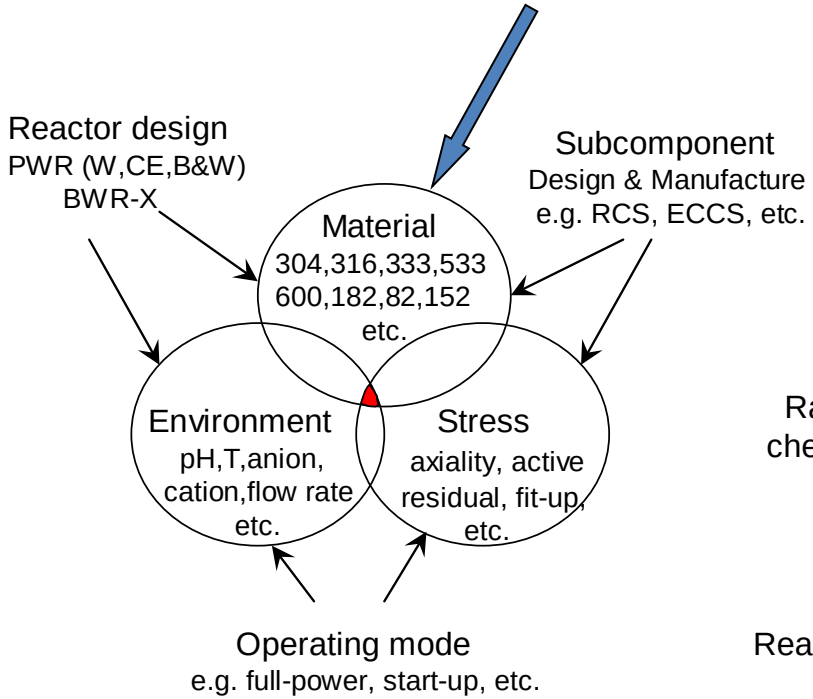


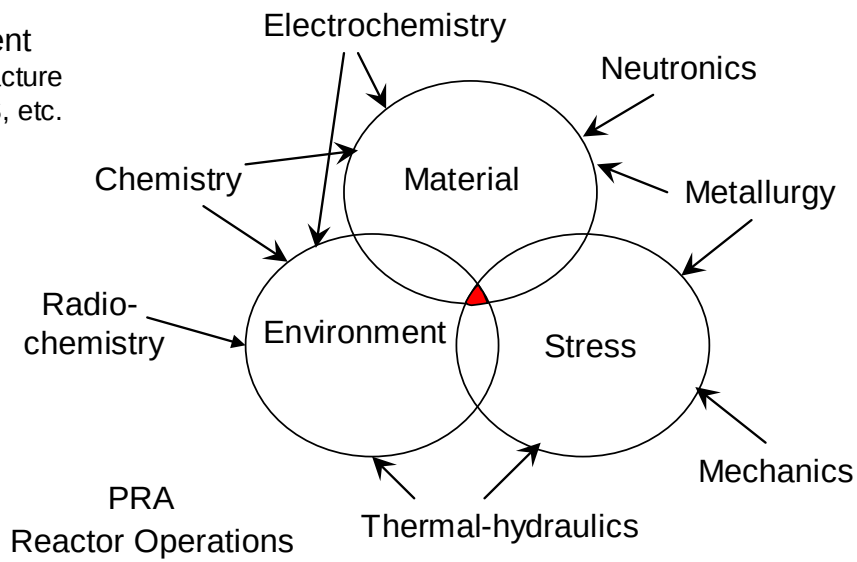


a_t = f (material, stress, environment)

Manage Uncertainty!
- **Aleatory**
- **Epistemic**

- Carbon and low-alloy steels
- Wrought stainless steels
- Cast stainless steels
- Nickel-base alloys
- High strength materials





Complex interactions;

- Small system changes drastically alter degradation kinetics
- No one person (or organization) is going to solve this problem

Three Basic Approaches to Life Prediction:

- Plant experience.
- Empirical Correlations Based on Combinations of Plant and Laboratory Data.
- A Quantitative Understanding of the Mechanism of Cracking

Need a combination of all three approaches

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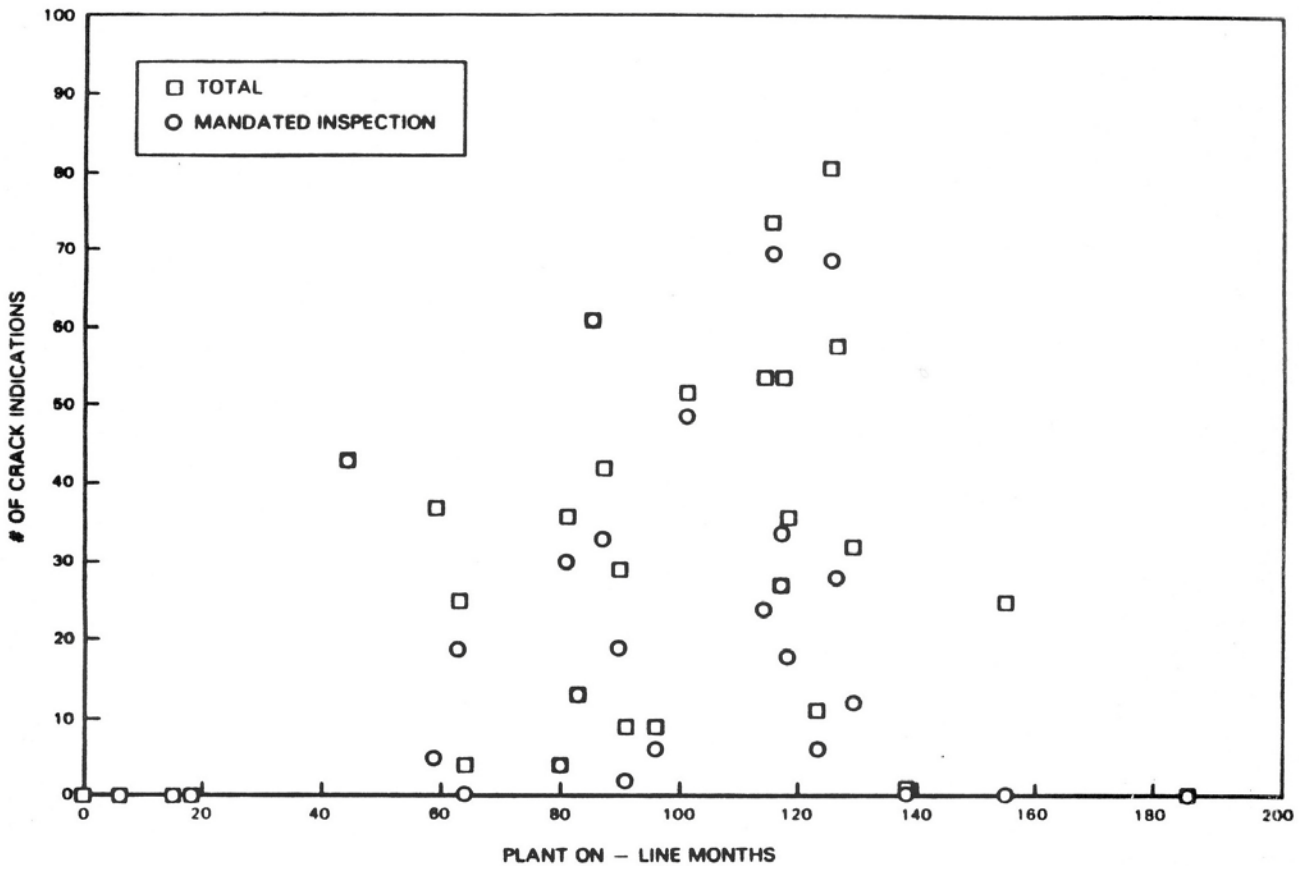
Plant Experience.

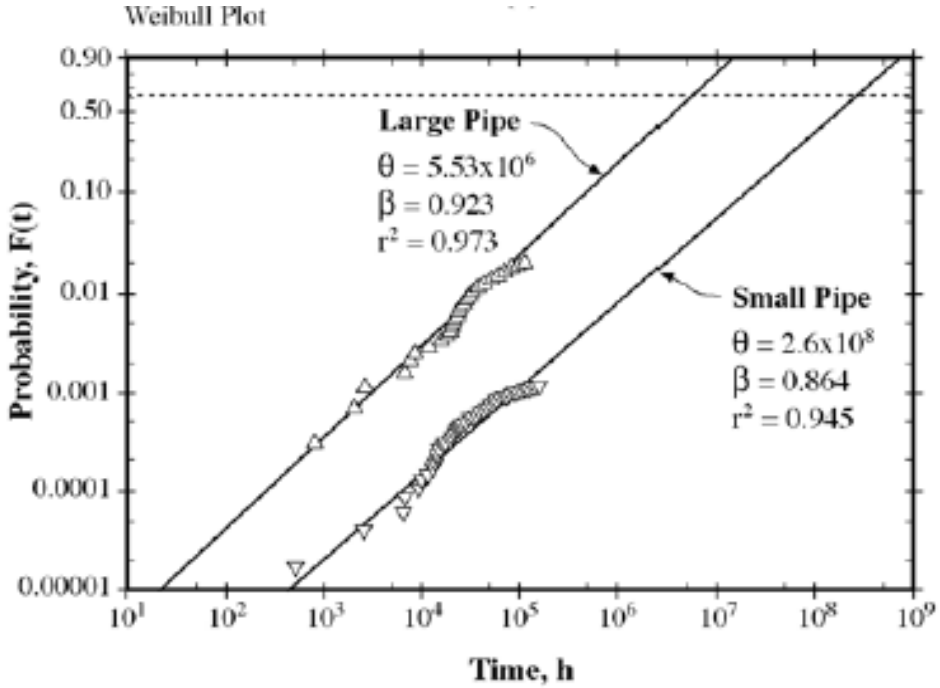


Relationship between incidences of cracking in BWR piping and operational time [Klepfer, 1975].

- **Inadequate definition of system**

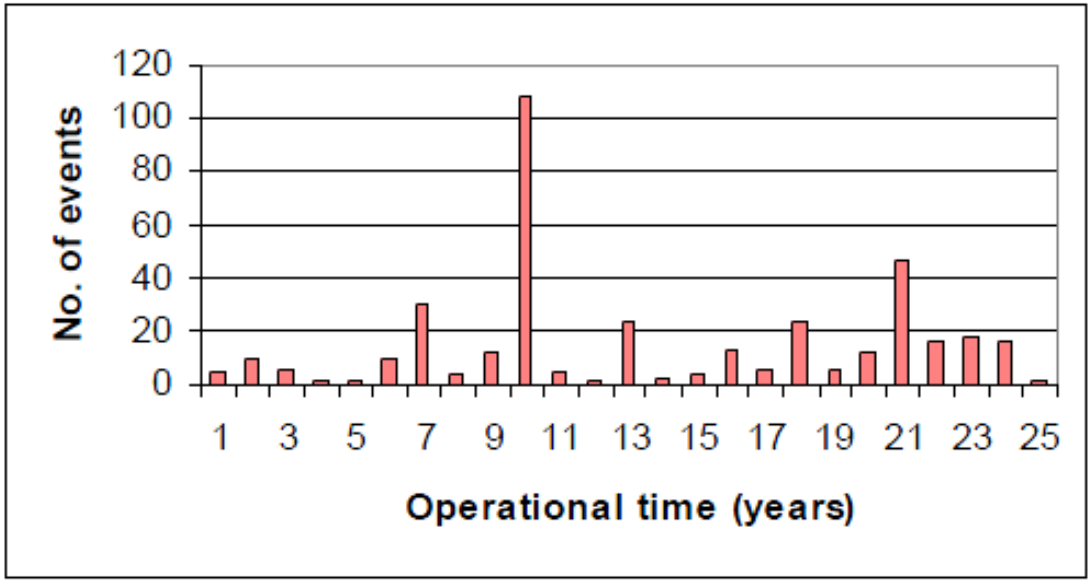
"Stainless steel piping in BWRs" is not good enough !

Plant Experience (2).

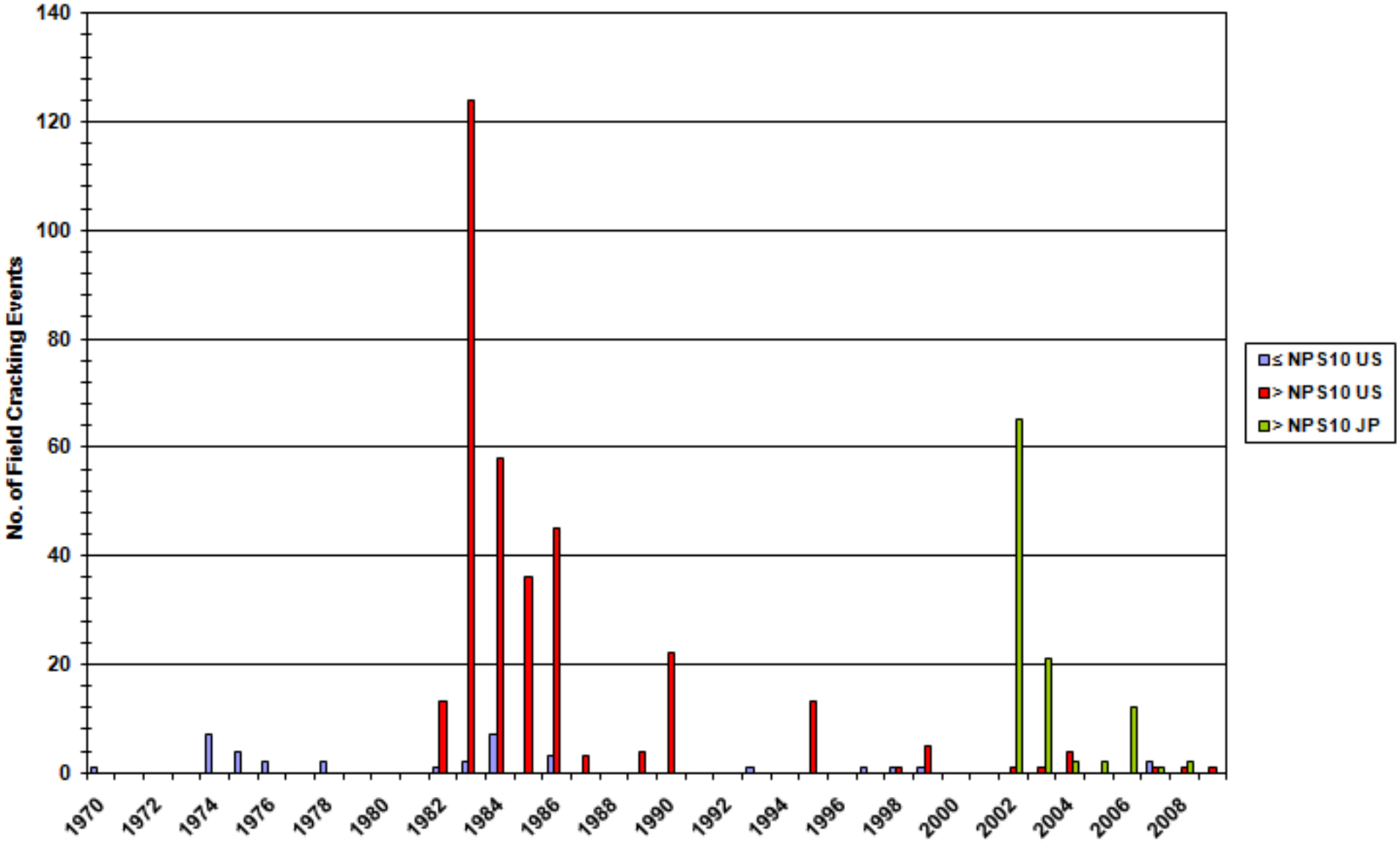


Probability of failure of Type 304 stainless steels in 2" and 4" diameter pipes in operating BWRs [Eason &Shusto,1986].

- Stochastic events lead to aleatory uncertainties.
- Different definitions of component failure.
- Different frequency and NDE resolution limits

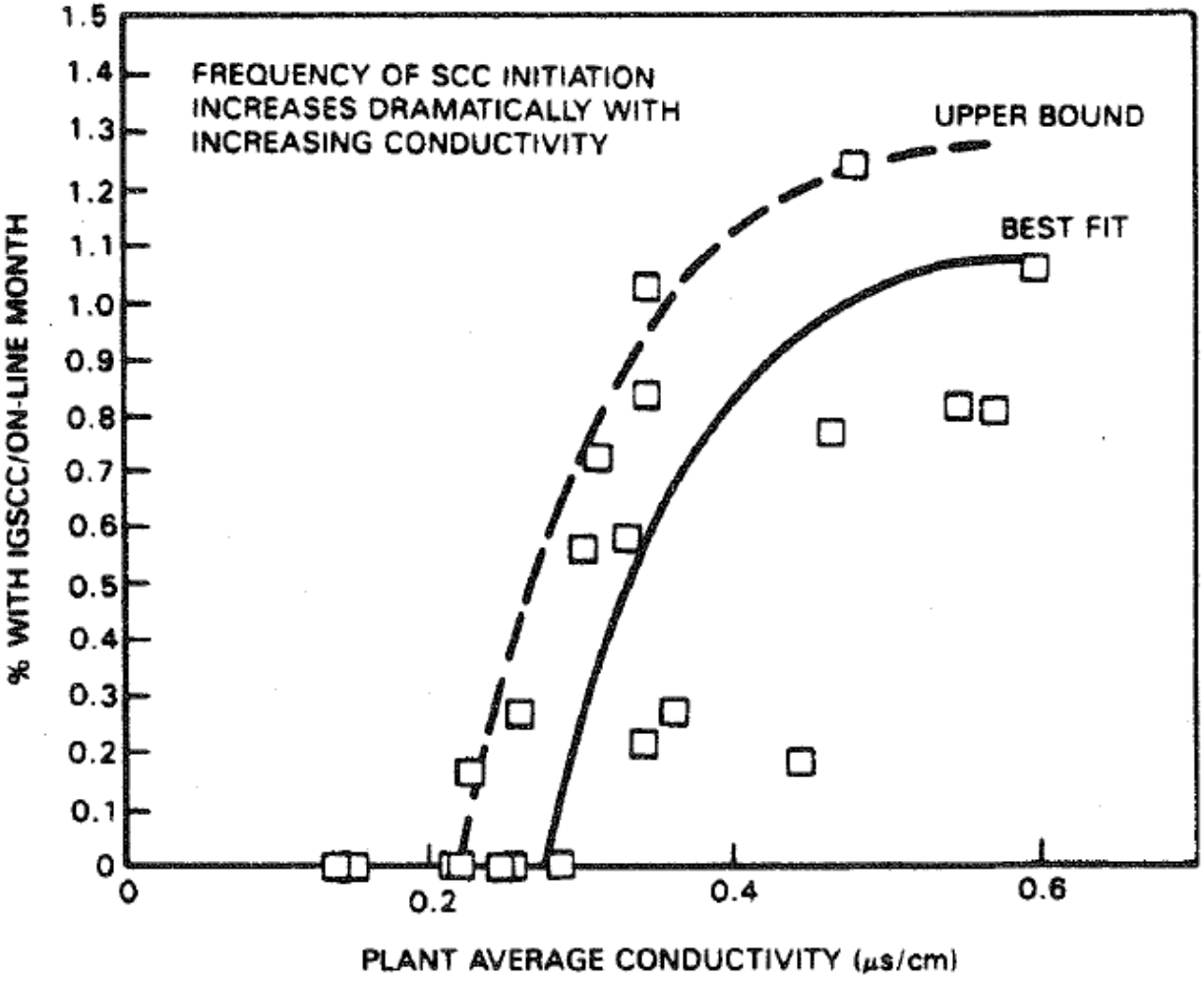


Number of cases of IGSCC per operational year (including components not examined in-situ) [Gott, 2001]



The number of field cracking events as a function of calendar year in BWR stainless steel piping (diameter>10") in the USA (red bars) and Japan (yellow bars).

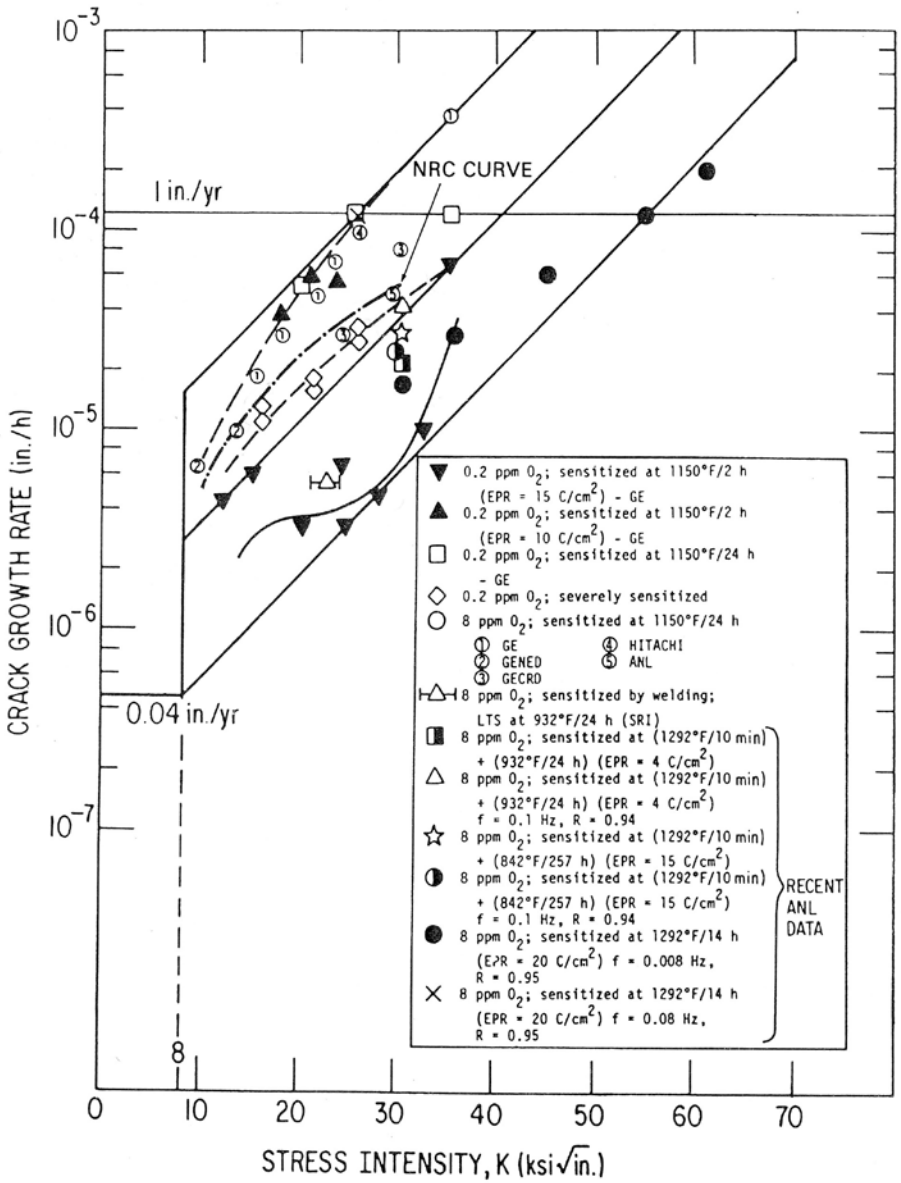
However, there are some clear correlations e.g. Water Purity



WHY?

The effect of average coolant conductivity on the incidence of cracking of IRM/SRM instrumentation tubes (Brown and Gordon, 1987).

Empirical Correlations Based on Combinations of Plant and Laboratory Data.



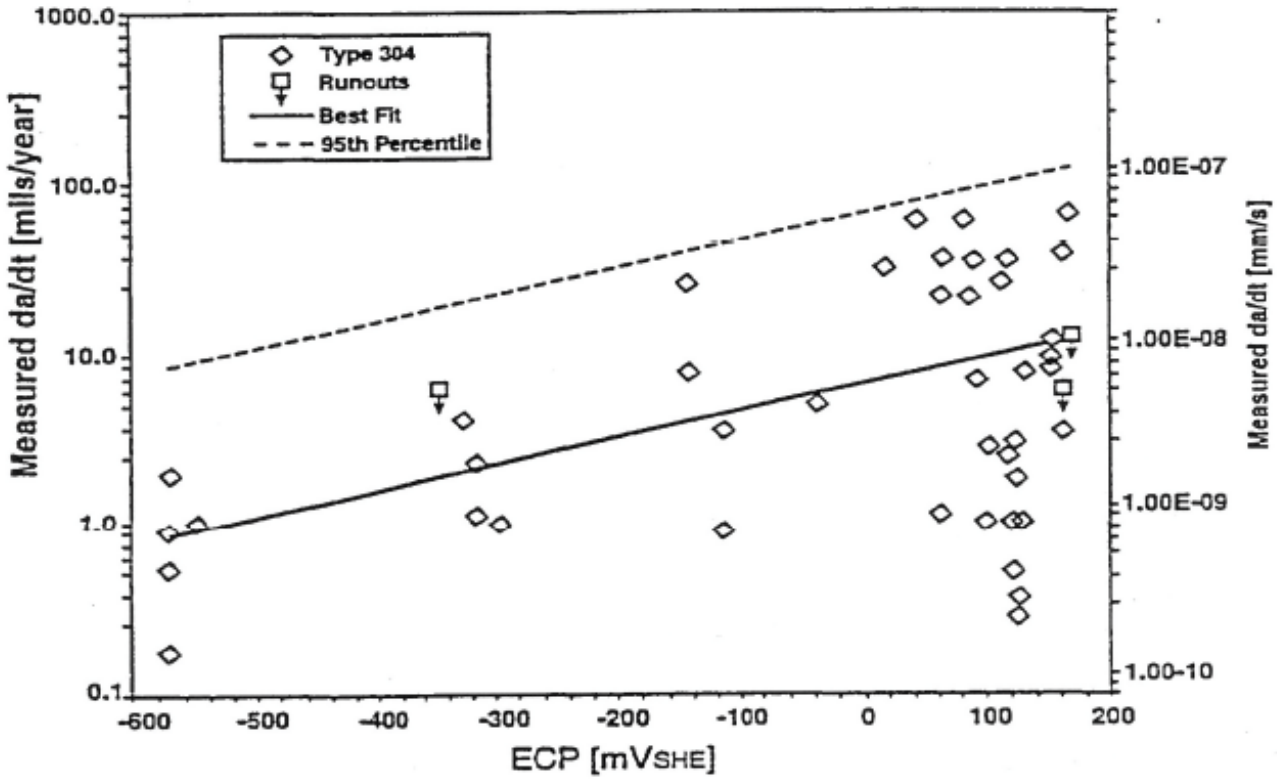
Scatter in data base if relevant system parameters are not measured or controlled

Quality control of data bases

Crack propagation rate data for sensitized stainless steel as a function of stress intensity in oxygenated 288 water [USNRC,1988].

Empirical Correlations Based on Combinations of Plant and Laboratory Data (2)

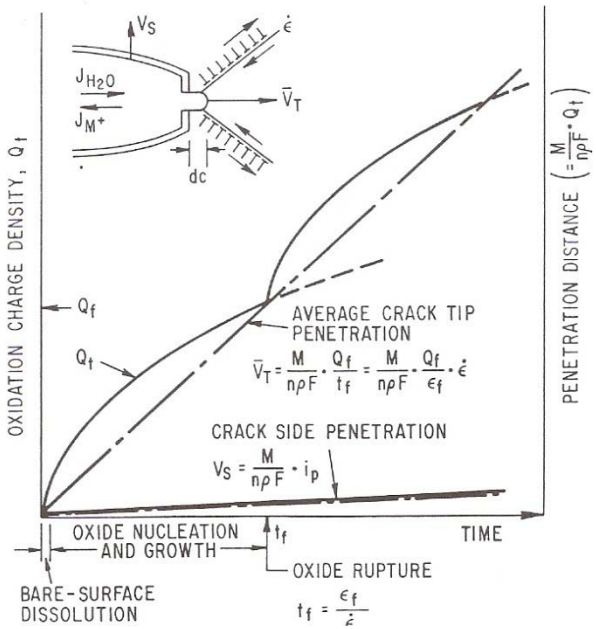
$$\ln(V) = 2.181 \ln(K) - 0.787\,\kappa - 0.586 + 0.00362\,\varphi_c + 6730/T - 35.567$$

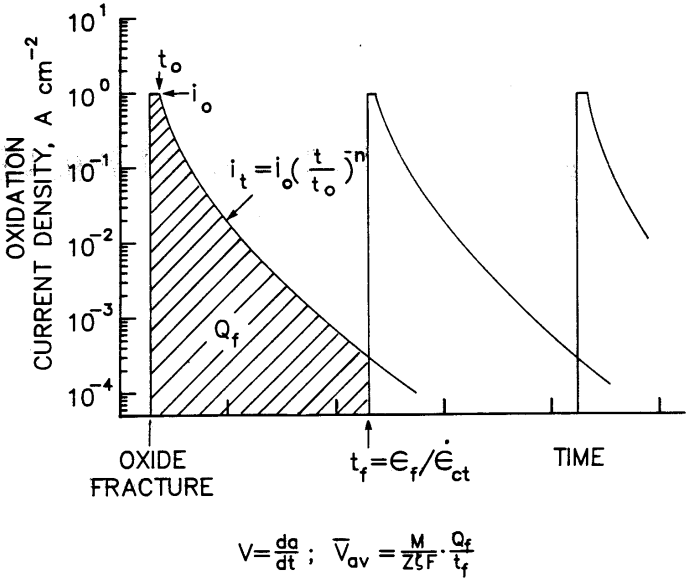


Comparison between prediction (according to Equation 4.1) and observation of the crack propagation rate vs. corrosion potential relationship for Type 304 stainless steel in BWR water (EPRI, 1996)).

Even "censored data" can lead to prediction equations with poor correlation factors – Now What?

Slip Oxidation Mechanism for Crack Propagation

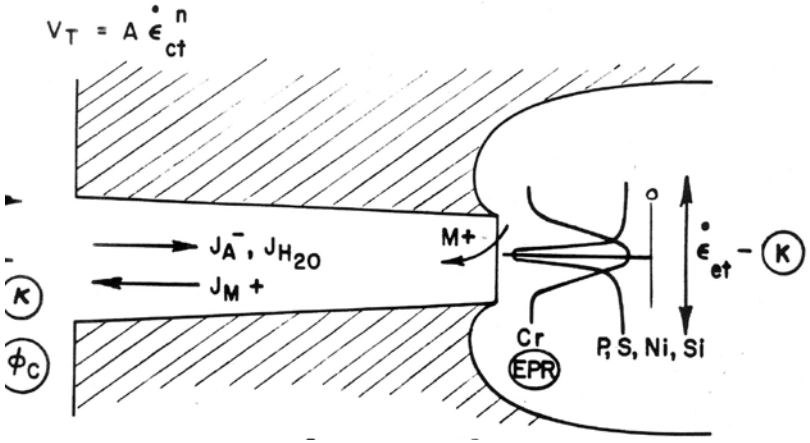


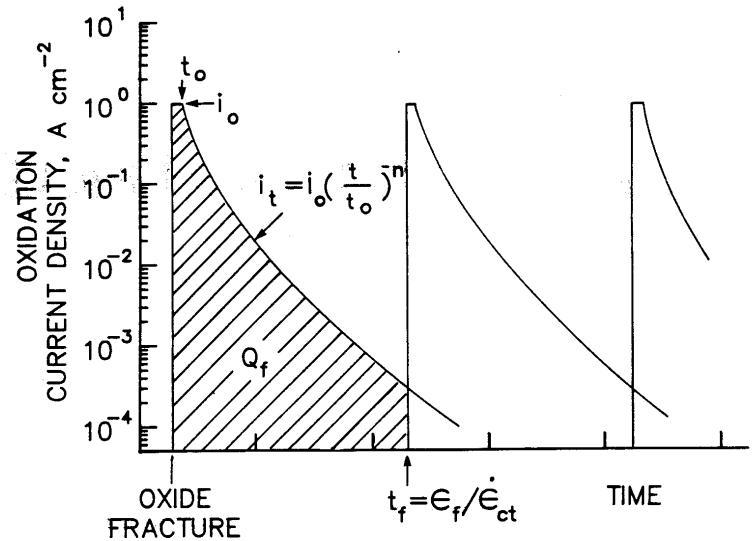


$$V = (M/zpF)(i_o t_o^n/(1-n)\ \varepsilon_f^{\,n})\ (d\varepsilon/dt)_{ct}^{\,n}$$

(a) Schematic oxidation charge density-time relationship for strained crack tip and unstrained crack sides. (b) Changes in oxidation current density following the rupture of the oxide at the crack tip. The crack advance is related faradaically to the oxidation charge density, Qf, which will be a function of the bare surface dissolution rate, io, the passivation rate, n, the fracture strain of the oxide, ε f, and the crack tip strain rate (Ford).

Proposed for austenitic and ferritic alloys in BWR environments



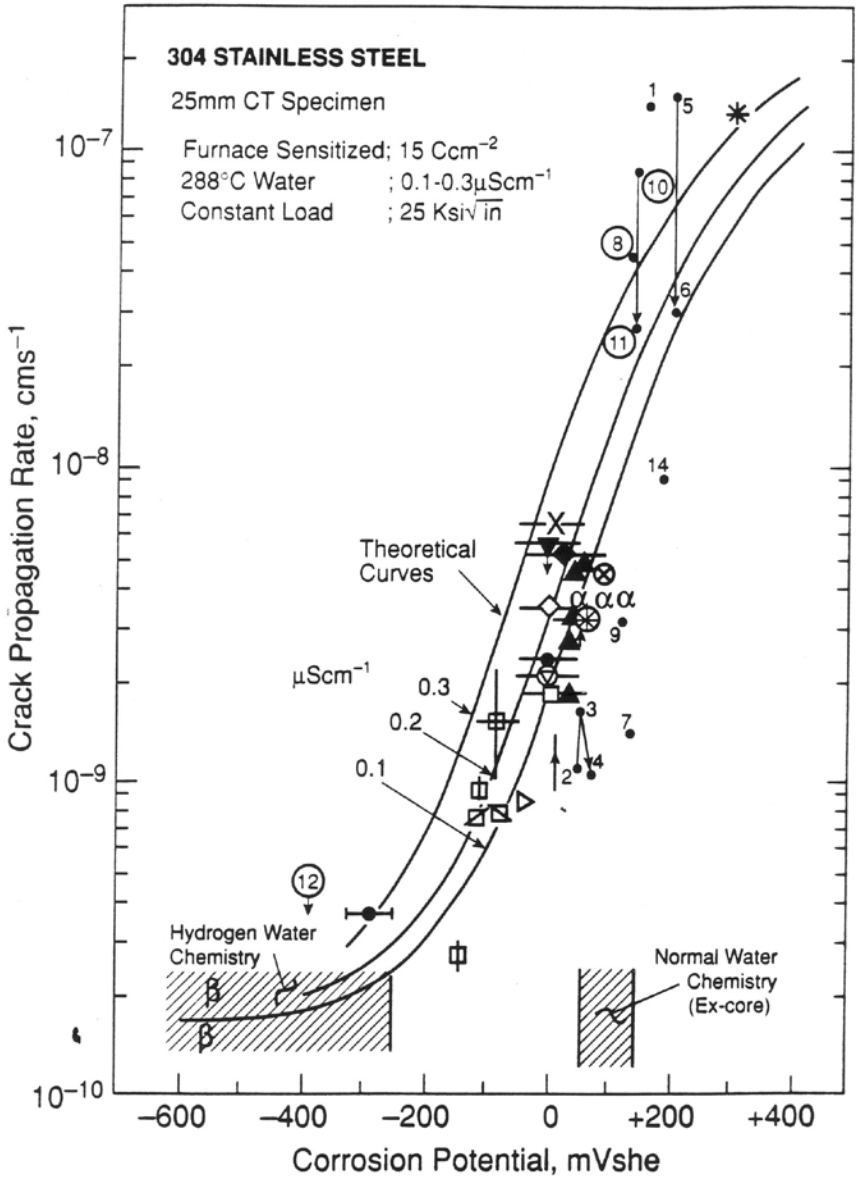


$$V = (M/zpF)(i_o t_o^{\,n}/(1-n)\ \varepsilon_f^{\,n})\ (d\varepsilon/dt)_{ct}^{\,n}$$

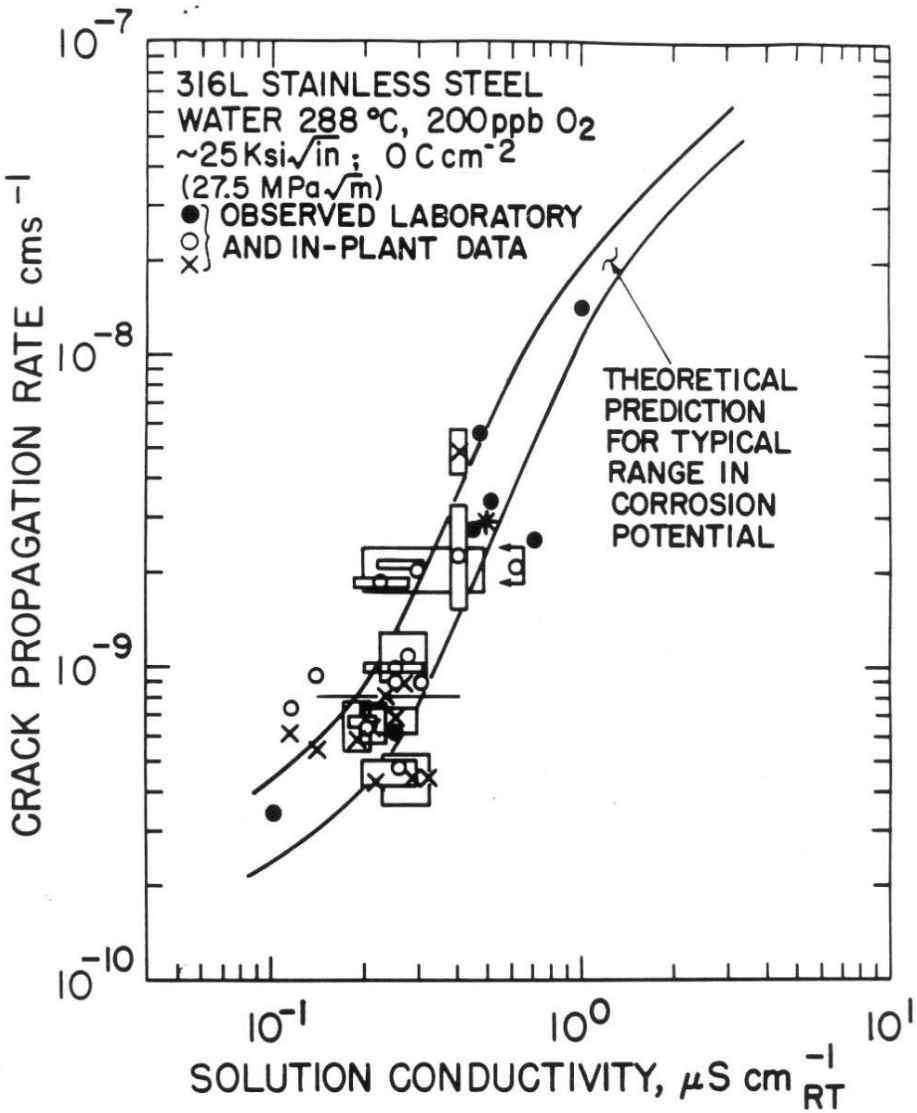
Fundamental algorithm may be formulated in terms of engineering parameters

- Crack tip composition (e.g.Cr) in terms of bulk metal composition and heat treatment
- Crack tip environment in terms of bulk environment
- Oxidation rates for crack tip “system”
- Crack tip strain rates in terms of stress, stress intensity, etc.

10 years work

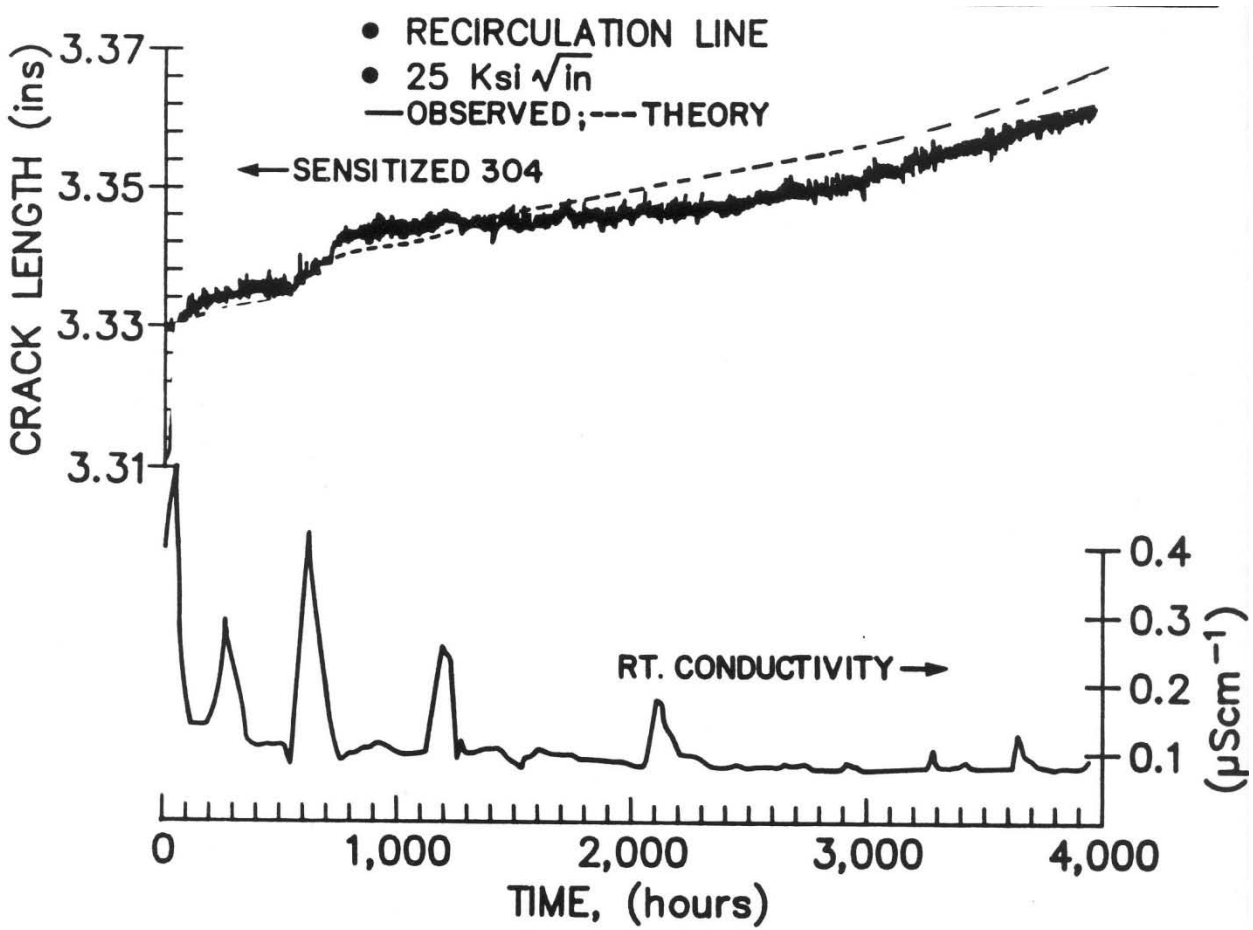


Observed and predicted relationships between the crack propagation rate and corrosion potential for sensitized type 304 stainless steel in 288°C water under constant load.Water conductivity in range 0.1-0.3 μS/cm.



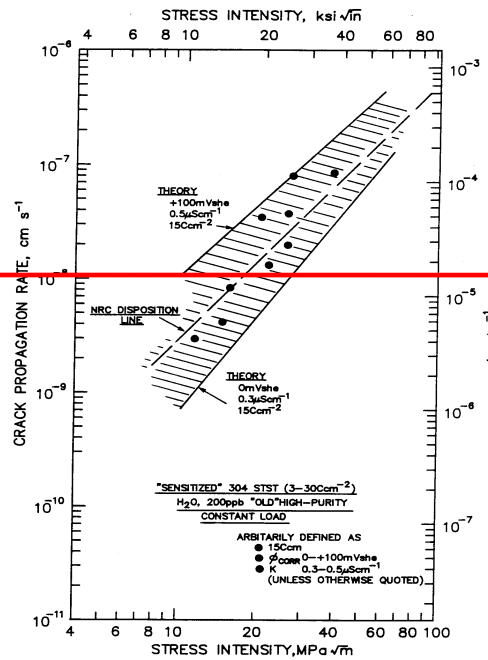
Observed and predicted relationships between the crack propagation rate and water conductivity for 316L stainless steel under constant load (25 ksi √in) in 288°C water containing 200 ppb oxygen

Stress Corrosion Cracking of Austenitic St St in BWRs



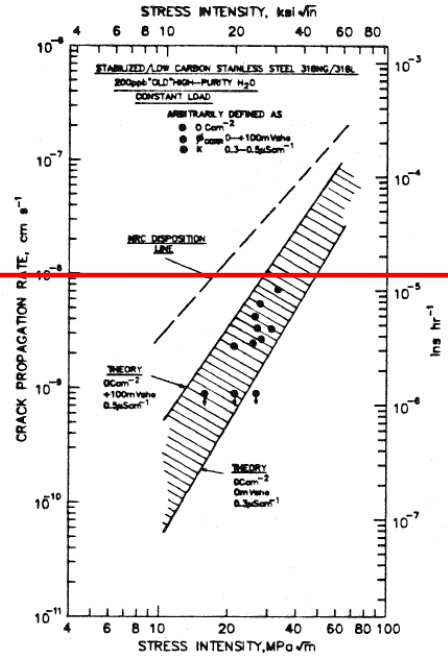
Observed and predicted crack depth vs. time relationship for sensitized stainless steel during conductivity transients observed in reactor operation (Ford).

Transients during startup



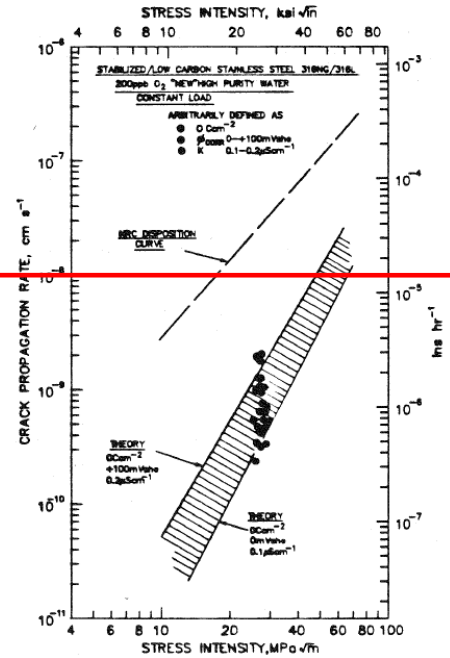
Sen 304

0.3-0.5μS/cm

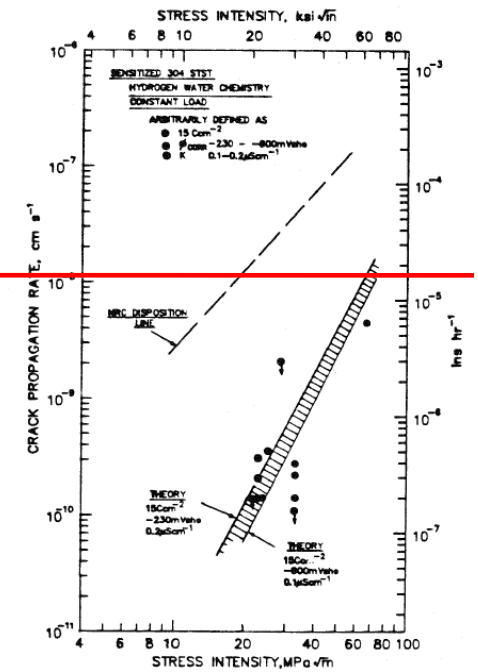


304L/316L

0.3-0.5μS/cm



304L/316L

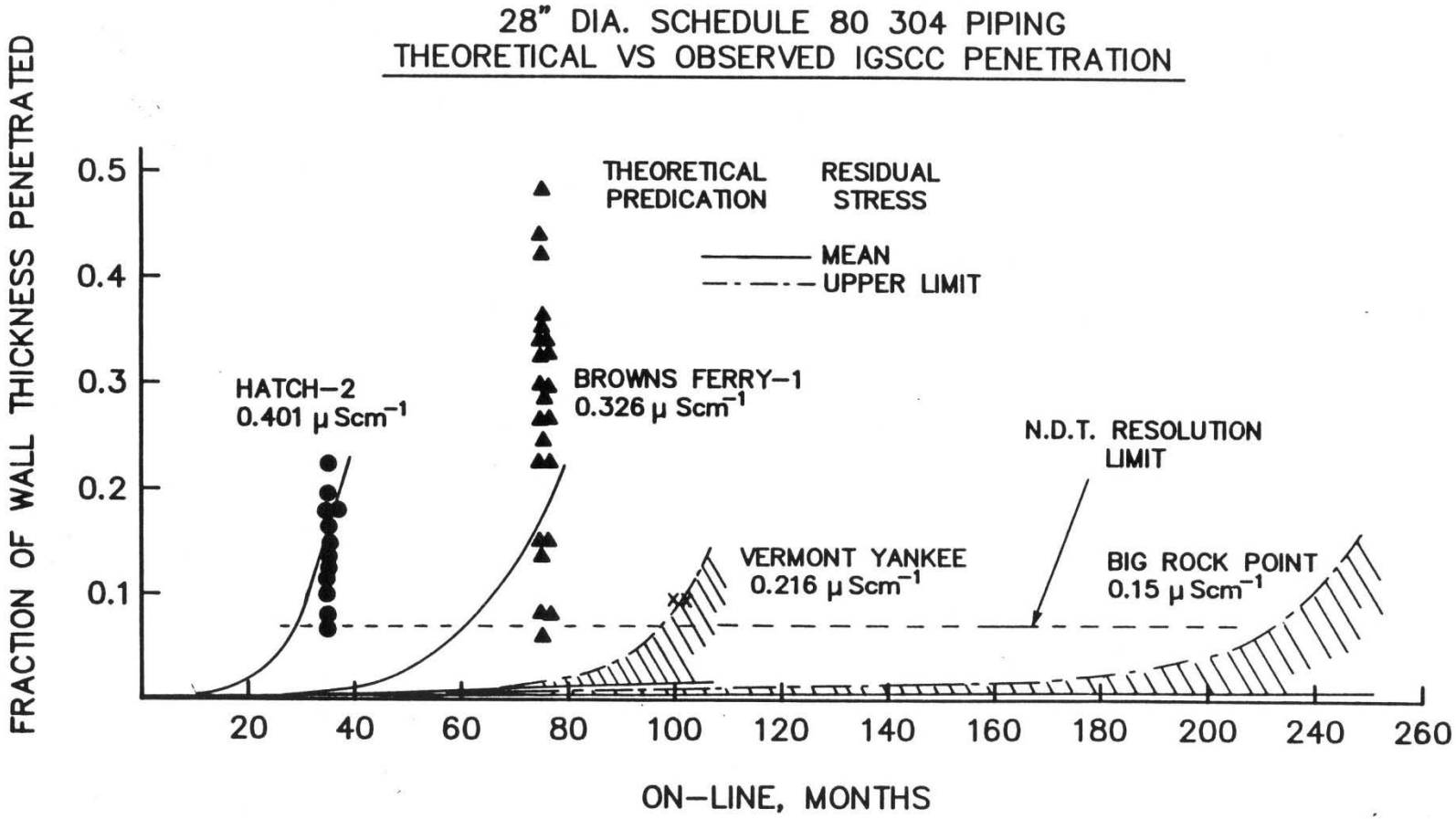


Sen 304

HWC

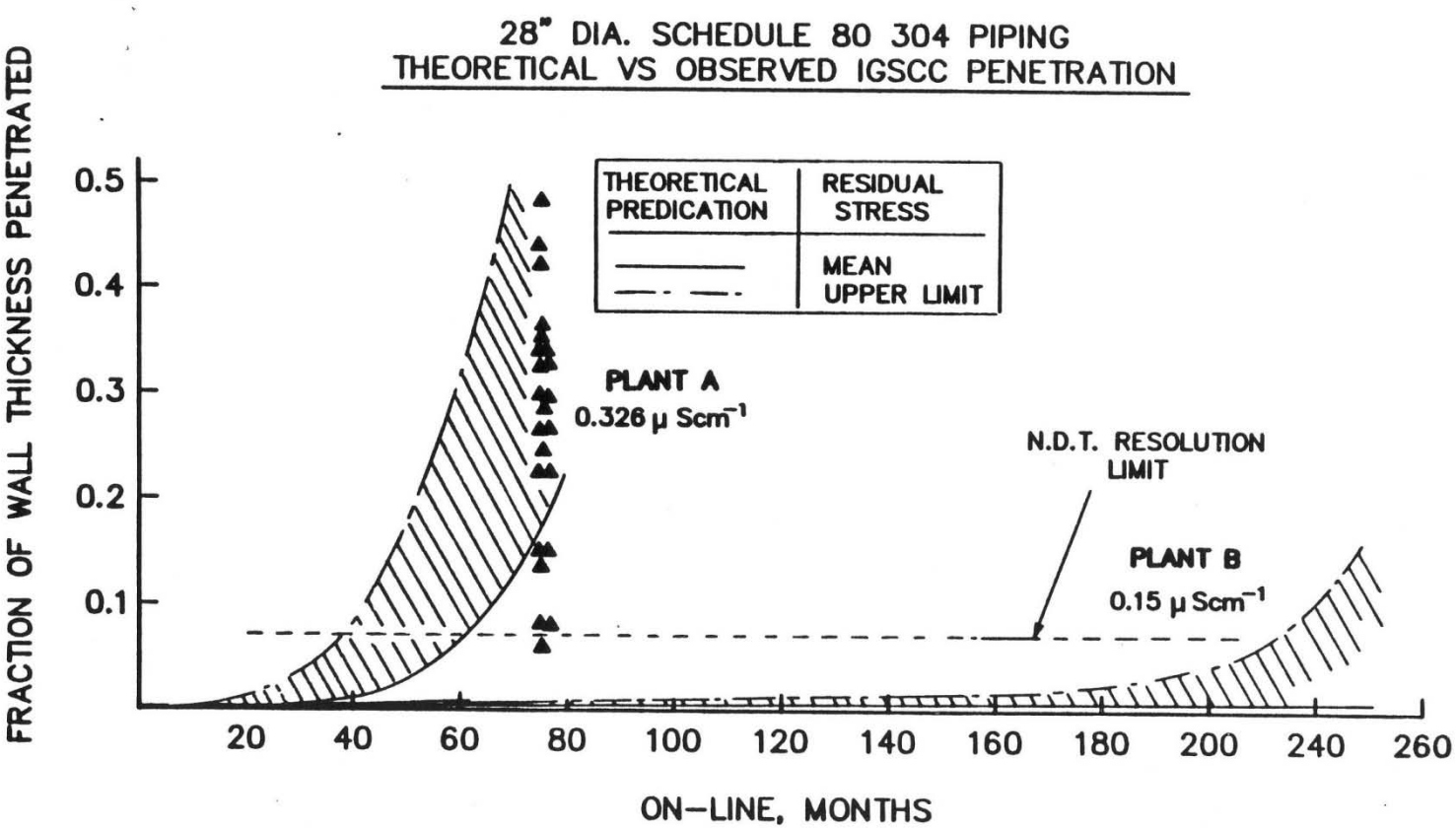
- Effect of stress intensity factor on propagation rate is predicted
- Sensitivity very much dependent on degree of grain boundary sensitization and water chemistry conditions
- Relevance of disposition V vs.K relationships very dependent on relevant reactor material and water chemistry conditions

Stress Corrosion Cracking of Austenitic St St in BWRs



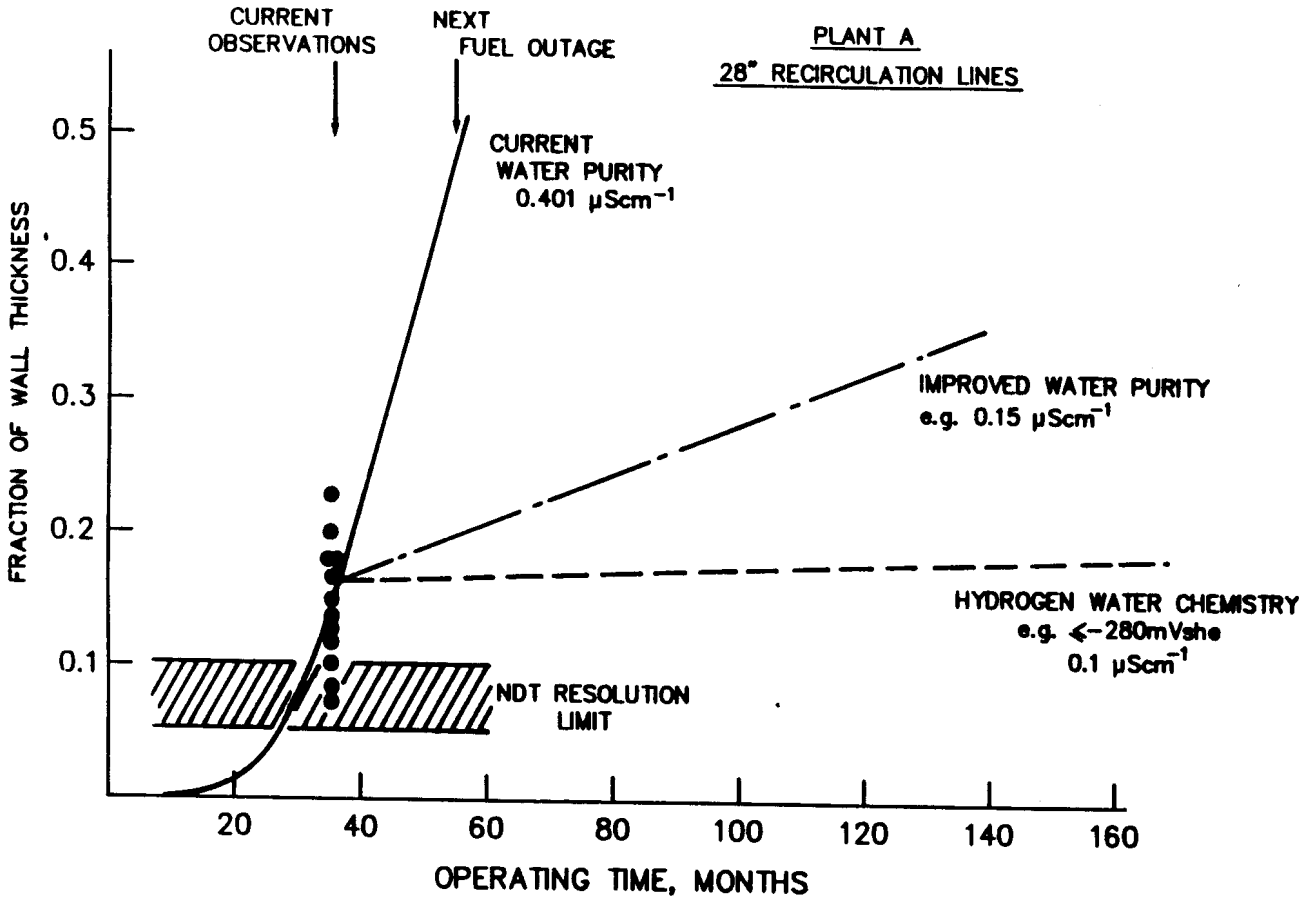
Theoretical and observed crack depth v. operational time relationships for 28" diameter Schedule 80 304 stainless steel piping for various Boiling Water Reactors operating at different mean coolant conductivities (Ford).

Mean rates of degradation can be predicted



Theoretical and observed crack depth v. operational time relationships for 28" diameter Schedule 80 304 stainless steel piping for two Boiling Water Reactors operating at different mean coolant conductivities. Note the bracketing of the maximum crack depth in the lower purity plant by the predicted curve that is based on the maximum residual stress profile, and the predicted absence of observable cracking in the higher purity plant (in 240 operating months) (Ford).

Stress Corrosion Cracking of Austenitic St St in BWRs



Predicted response of defected piping for defined changes in water chemistry in BWR plant (Ford).

Magnitude of response to mitigation actions can be predicted

Conclusions -1

i.e. “and why would you want to do this?”

- Environmentally-assisted cracking in LWRs is an extremely complex phenomenon.

- Understanding and quantification of EAC requires inputs from numerous “arts” centered on interactions between reactor vendors, utilities, regulators, national labs and universities.

- Development of a “fundamental understanding” is not an “academic exercise”
  - it is a pragmatic necessity that provides a basis for interpreting the engineering data upon which regulatory and operation decisions are made.

- There is a mechanistic basis for predicting crack propagation for stainless steels in BWRs and this has been expanded to cover;
  Irradiation assisted cracking.
  SCC of nickel-base alloys and carbon/low alloy steels.

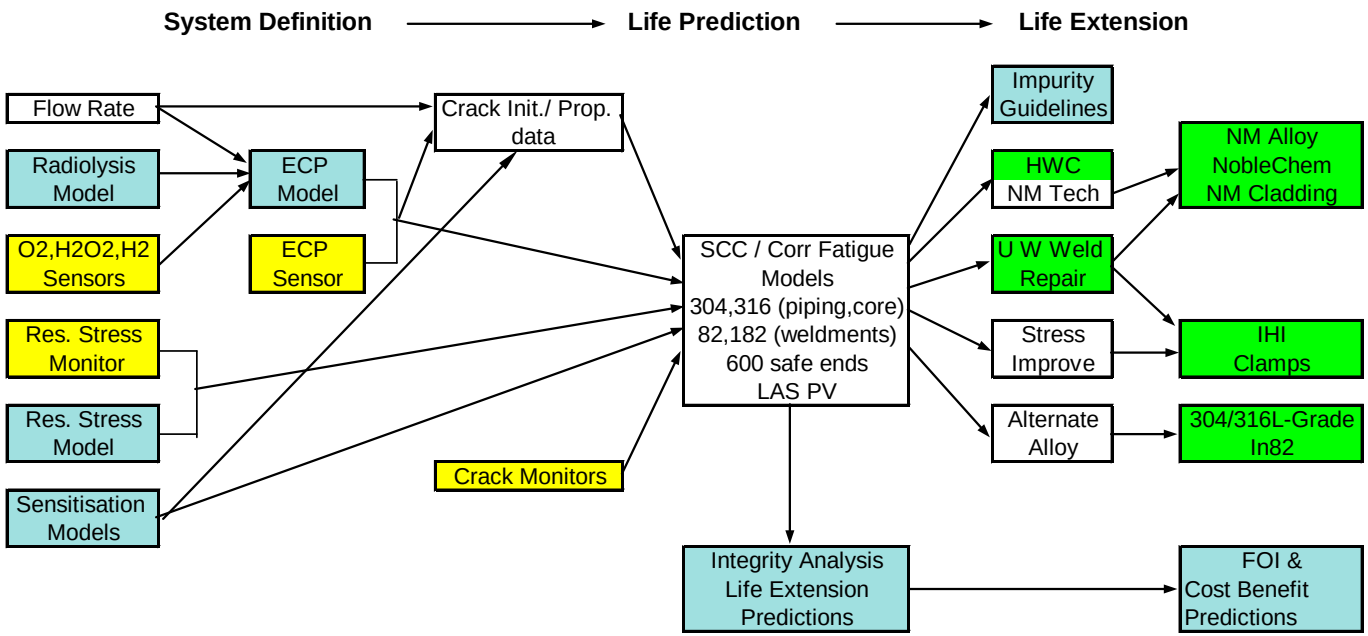
There are numerous fundamental issues still to be resolved.

e.g. Crack initiation.
Details of plasticity at crack tips
Mass transport in nanometer dimension crack tip opening displacements
Formal treatment of aleatory and epistemic uncertainties for time-dependent phenomena.

Conclusions -2

- Coordinated movement towards proactive management.

- Mitigation actions for the “obvious” degradation modes in place.

- What might give us “unpleasant “ surprises?
  - Degradation modes other than EAC. e.g. FAC, MIC.
  - Interactions between degradation modes e.g. thermal embrittlment & EAC
  - Lack of prediction capabilities for EAC “micro-crack” initiation.
  - Fracture resistance/ environment interactions
  - “The devil is in the details”

The Ultimate Real-Time Monitoring and Diagnostics Capability