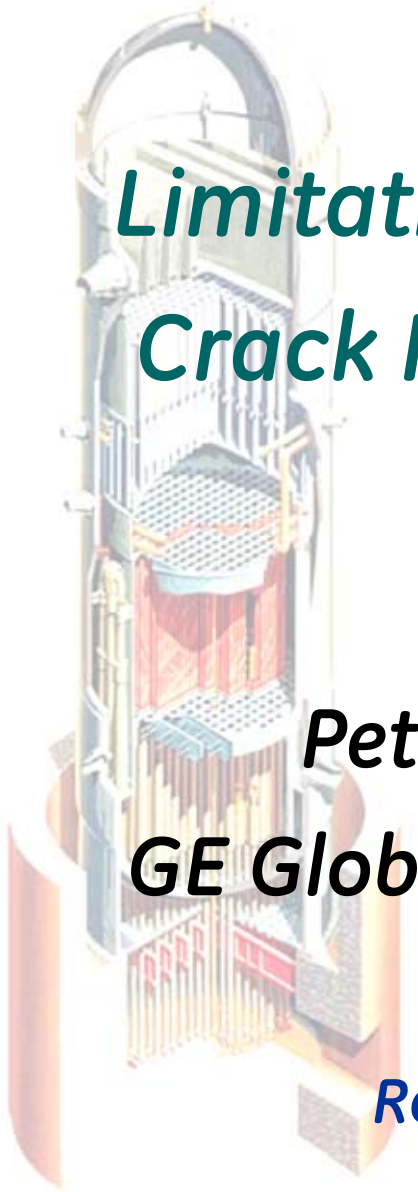

Limitations and Value of Crack Initiation Studies

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NRC Rockville, MD May 2008

Extensive Facilities, Interest & Experience

Despite concerns & criticism for many crack initiation studies:

- *we have done a lot of work on initiation using interrupted testing, large-scale active load initiation testing, U-bends, electrochemical noise & dcpd monitoring for initiation…*
- *four 150-specimen, active-constant-load, continuous monitoring, crack initiation tests systems in use*
- *extensive dcpd monitoring for pre-initiation events, crack initiation, short crack behavior, strain bursts, etc.*
- *strong experience in electrochemical noise and impedance*
- *U-bend, crevice bent beam, initiation from defects, etc.*
- *extensive initiation & short crack studies from blunt notches*

Pragmatic Initiation-centric Approach

Understand Broad Initiation Response and Accelerants

Pragmatic crack initiation studies are valuable when based on:

- *based on plant component data (usually mix of init & growth), as shown by the French for Alloy 600 SG tube & structural parts.*
- *good specimen design, realistic crevices & chemistry, continuous monitoring, and sufficient replicates are employed.*
- *ideal when leveraged using known dependencies from crack growth rate data, e.g., temperature, stress, cold work…*

Just as there is a continuum for BWR & PWR environments in crack growth, so there will be continuum response for most initiation & growth variables – a wise initial assumption to test.

Fundamental Initiation-centric Approach

Fundamental Predictive Approach for Initiation Poses Challenges

Basic challenges we must face in crack initiation studies:

- *dramatically more dependent on unknown & perhaps uncontrollable variability of surfaces of complex welded structures*
- *fundamental challenge of guaranteeing that initiation has not occurred or been circumvented by defects/anomalies.*
- *measurement challenges of representativeness of surface, low sample area, specimen design, detection, single point data…*

We remain at the qualitative, curiosity stage in initiation studies

We must cast the same critical eye on initiation as on crack growth

"Stirring the Pot" on Initiation

Challenge: *what can we achieve in the next 20 years?*

- *not as quantitative or stat. confident as crack growth data*
- *not know most inter-dependencies among SCC factors*
- *not agree how to define or measure "true initiation"*
- *not know what kinds of surfaces and conditions exist on the myriad of plant components, and therefore,*
- *lab data will probably only provide relative effects, and*
- *lab data will not be a genuine predictor of plant behavior, esp. when using extreme tests (RUB, graphite wool….)*
- *plant data provides a reasonable basis for prediction, but only for conditions: materials, TT, SG design…*
- *interesting observations (oxidation along GBs, surface film observations, etc.) may not be proven causal of initiation*

Plant Component Characteristics We May Never Know

- *level & type surface cold work: machining, grinding, contact…*
- *surface finish, esp. in worst case locations*
- *surface geometric anomalies from metal defects, fabrication…*
- *surface heat treatment oxides or near-surface g.b. composition*
- *surface grain structure, esp. nano-grains, etc.*
- *surface contamination from etching, handling, shipping…*
- *surface grain structure, esp. nano-grains, etc.*
- *surface stresses and strain rate from "rogue" grains*
- *unusual plant accelerants – thermal mixing, O_2 injection…*
- *which of 10^{12} – 10^{25} grain boundaries are the vulnerable ones?*

Initiation statistics from SG tubing are reasonable and usable.
Plant statistics on initiation in structural components will be poor

Laboratory Unrepresentativeness

Lab studies often fall short of useful & representative:

- *difficult or impossible to match average or worst conditions in plant components / surfaces*
- *overly-aggressive stresses, strain and strain rates*
- *reverse bending, humps, etc.*
- *graphite wool (impurities), static autoclaves, etc.*
- *large stress relaxation (80+%) in U-bend & related tests*
- *handling, inspection, start-up & shutdown… procedures*
- *small surface area, non-commercial processing & fabrication*
- *failure to recognize cycling: load following, thermal mixing….*
- *small volume sampled, go/no-go result is unlike growth data*

We will observe many curiosities, but must show causality.

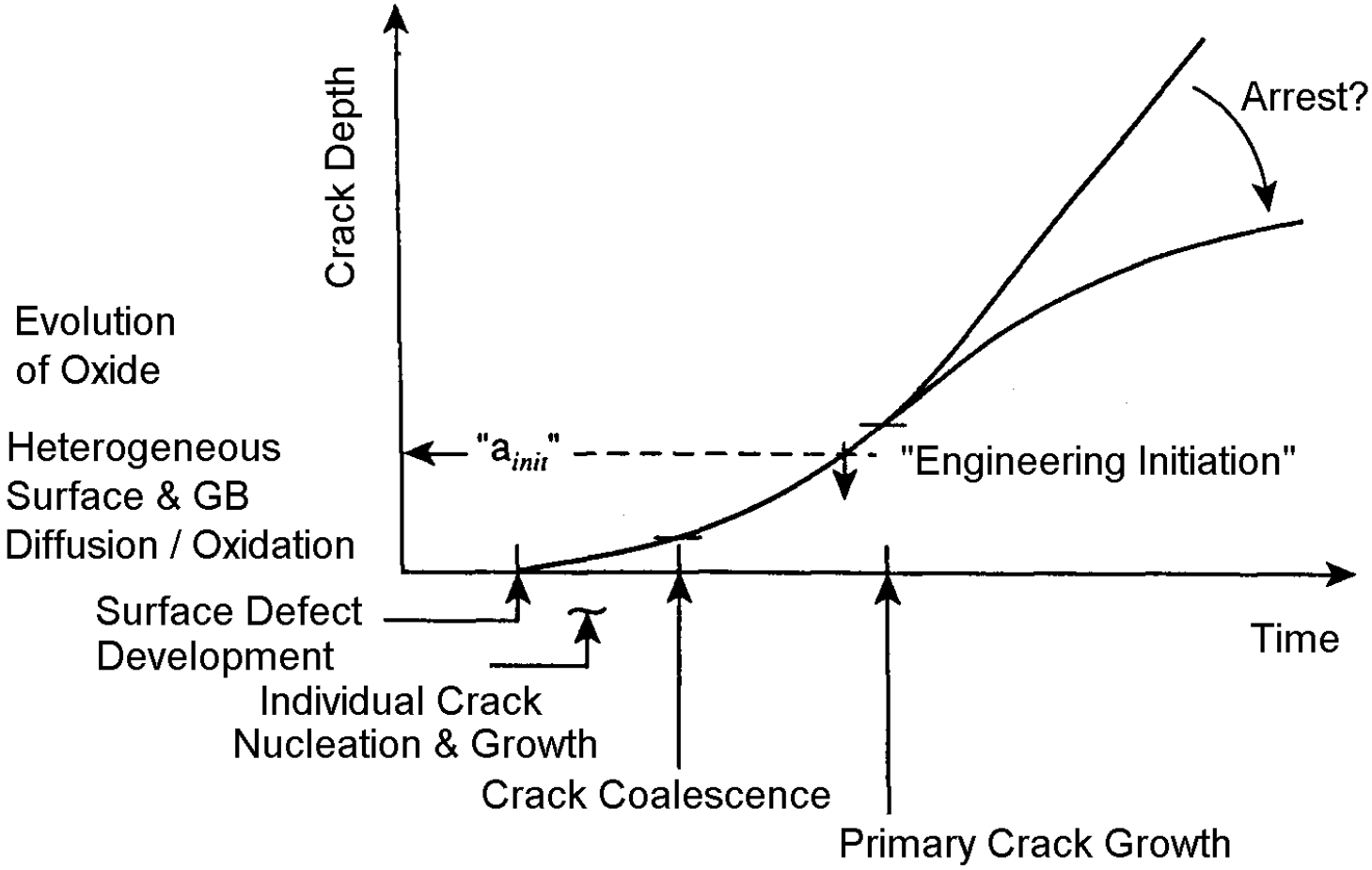
We must balance need-to-know with ability-to-decisively-study

Criteria for Quantitative Initiation Studies

Crack initiation is expected to exhibit a stochastic nature, but quantitative confidence in the data requires:

1. *Sufficient # of replicate specimens to establish a well-defined distribution - typically at least 10. Physical size is also important - small specimens usually give superior properties.*
2. *There be continuous monitoring for "initiation" and ideally at a dimensional scale at or below the grain size. Less critical if no crack initiation is observed, e.g., for an improved material.*
3. *Well-behaved response - e.g., the measured response fits an recognized / established distribution with high correlation.*
4. *The test conditions are representative & stable throughout test.*
5. *Small volume samples & go/no-go result weakens the relevance & usefulness of initiation data compared to growth.*

Schematic of Events in Crack Initiation



What is the Definition / Meaning of Crack Initiation?

Challenge: *what are the crack dimensions or characteristics associated with "crack initiation" ? The gamut includes:*

- *complete failure*
- *any evidence of SCC (all crack sizes often treated equal)*
- *testing to 25% loss in load*
- *post-test destructive exam by metallography or SEM*
- *video, photo or replicate detectability of cracking*
- *in-situ monitoring detectability crack depth vs. time*
- *electrochemical noise monitoring for incipient cracking*
- *eddy current, UT, acoustic emission … indications*
- *development of "long" crack mechanics or chemistry*
- *development of crack of arbitrary dimension (grain size)*

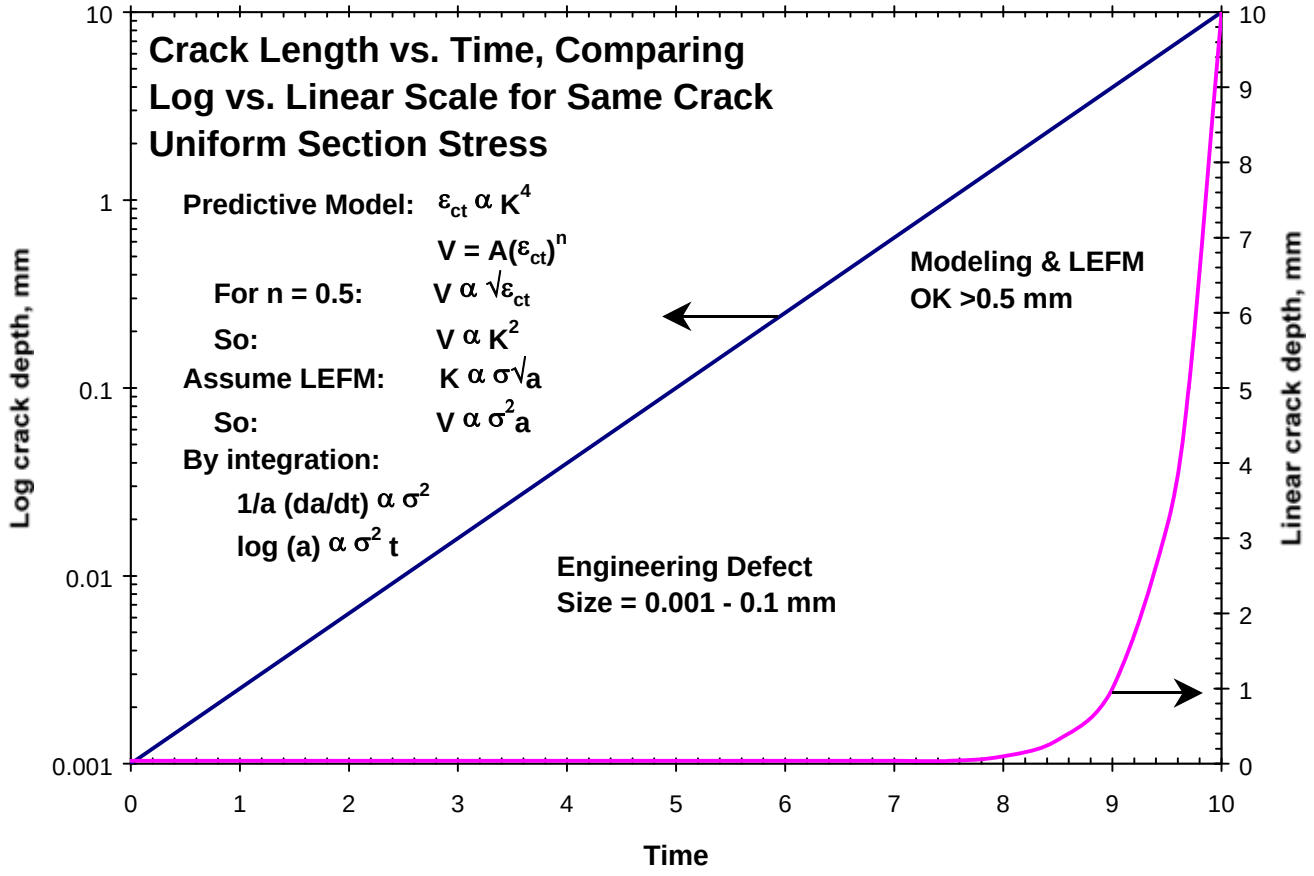
What is the Definition / Meaning of Crack Initiation?

Scientific Definition	Formation of a mechanical distinct geometry that will tend to grow in preference to its surroundings as a sharp crack.
Practical Definition	Detectability that is likely to be achievable in in-situ autoclave investigations in the laboratory, e.g., 50 μm.
Phenomenology – Environment	Chemically short cracks are cracks in which a *mature*, long crack chemistry has not formed.
Phenomenology – Mechanics	Mechanically small cracks are surface cracks growing under plane stress conditions, or where linear elastic fracture mechanics does not directly apply.
Phenomenology – Metallurgy	Metallurgically small cracks are cracks smaller than one grain diameter, or other metallurgical feature.

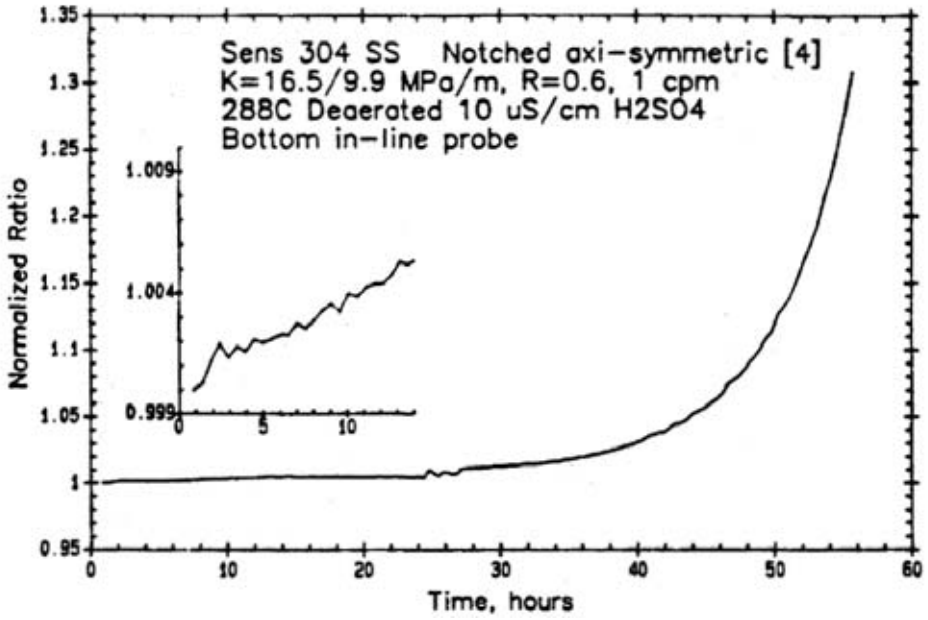
***Proposed Definition:* "Formation of a mechanical distinct geometry that will tend to grow in preference to its surroundings"**

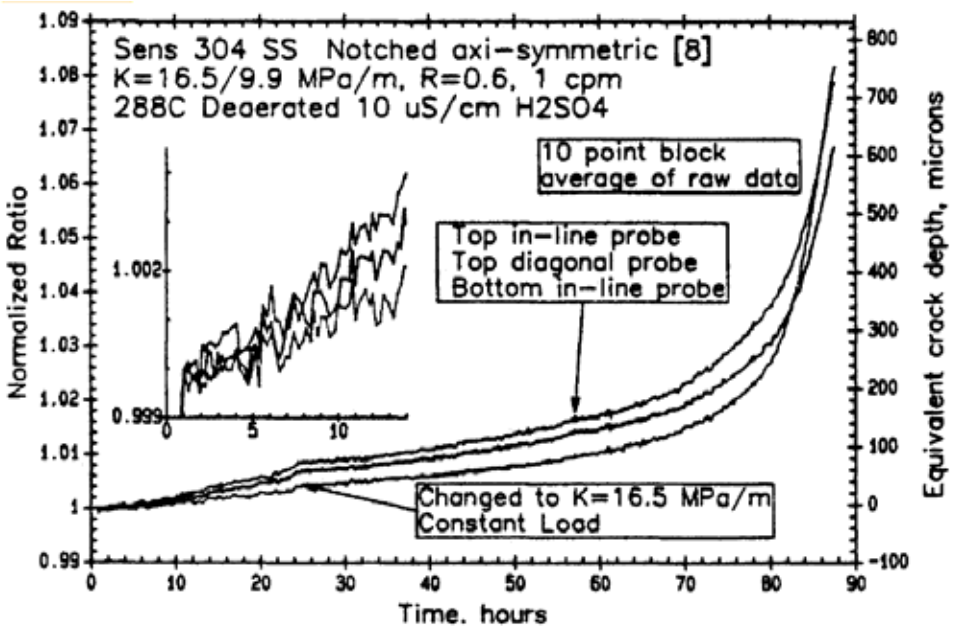
Measurement Techniques Operate on a "Linear" Scale

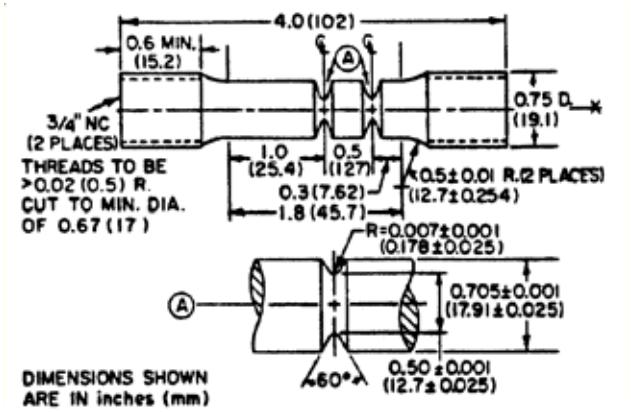
Cracks can grow steadily at a mature rate & be "invisible"



Techniques for Monitoring Crack Initiation
Circumferential Notched Bar + dcpd

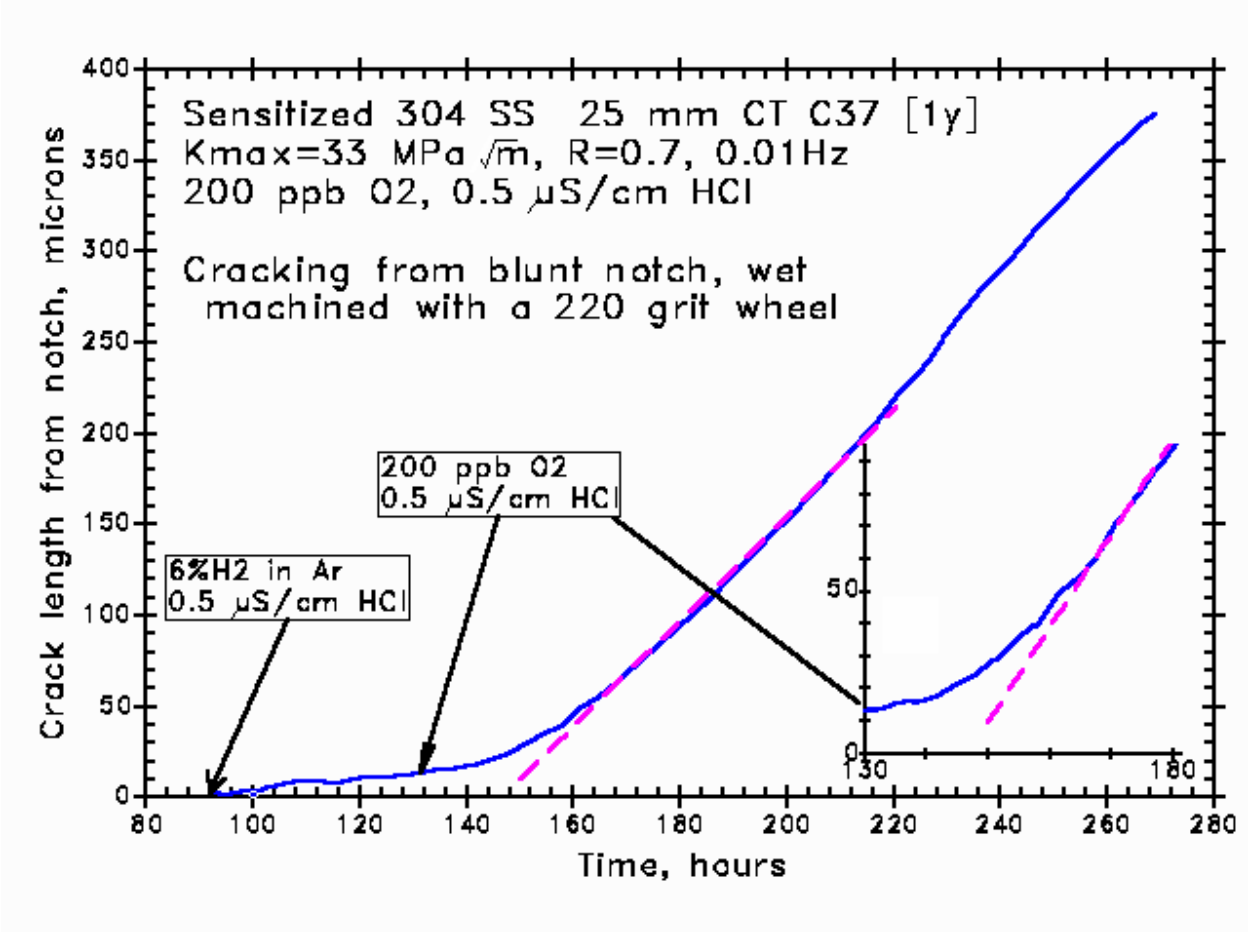


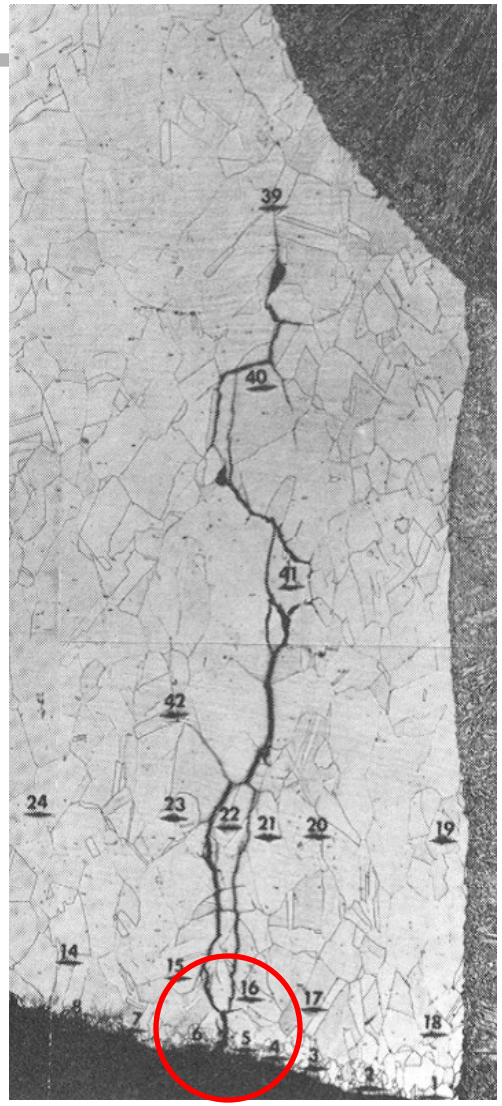




Apart from initiation circumventing circumstances or phenomena, cracks can grow early in life when viewed carefully at high resolution

Nucleation of SCC in Sensitized 304 SS

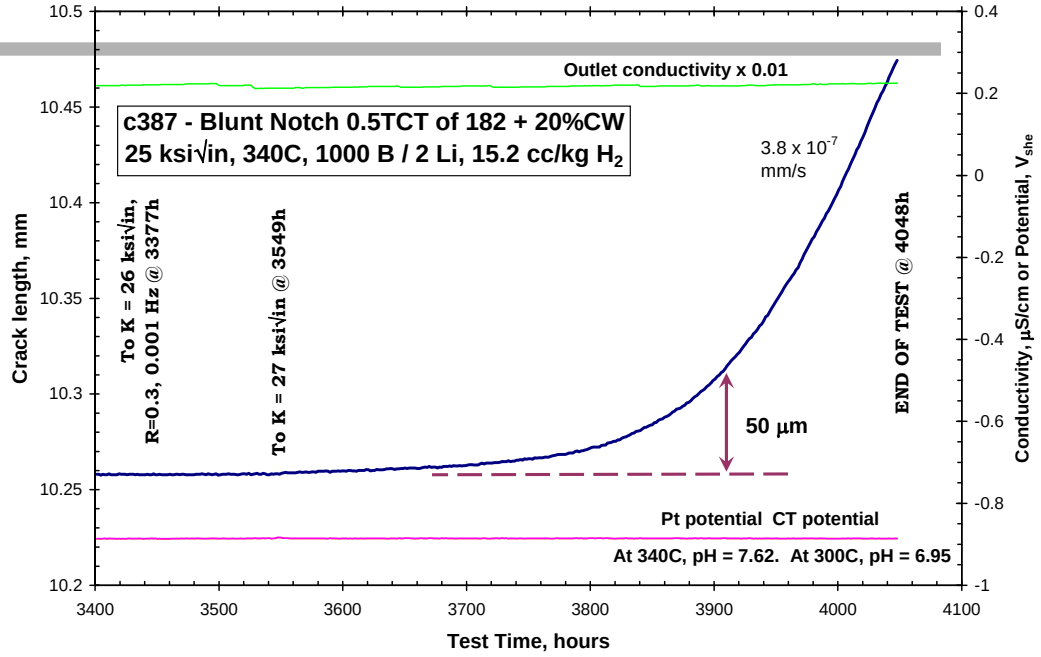


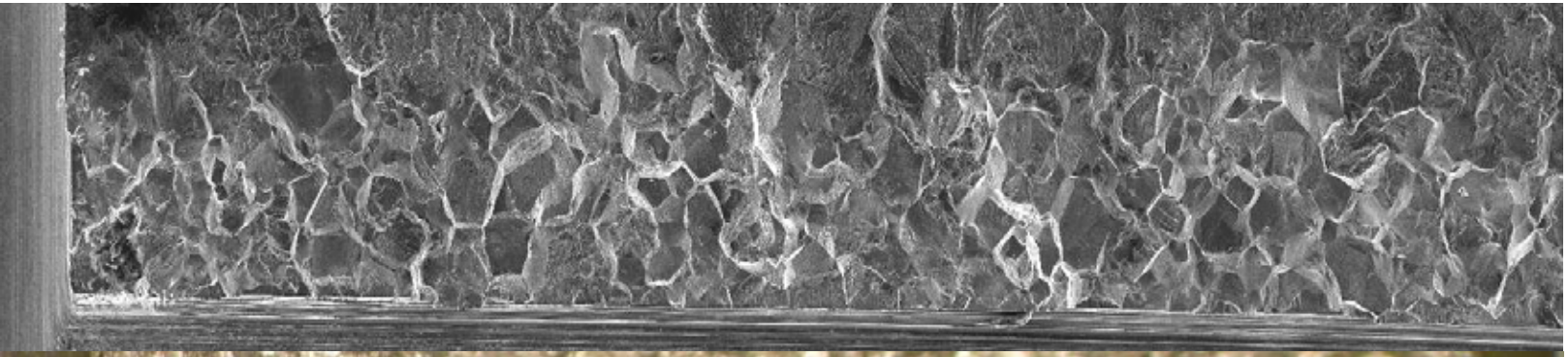


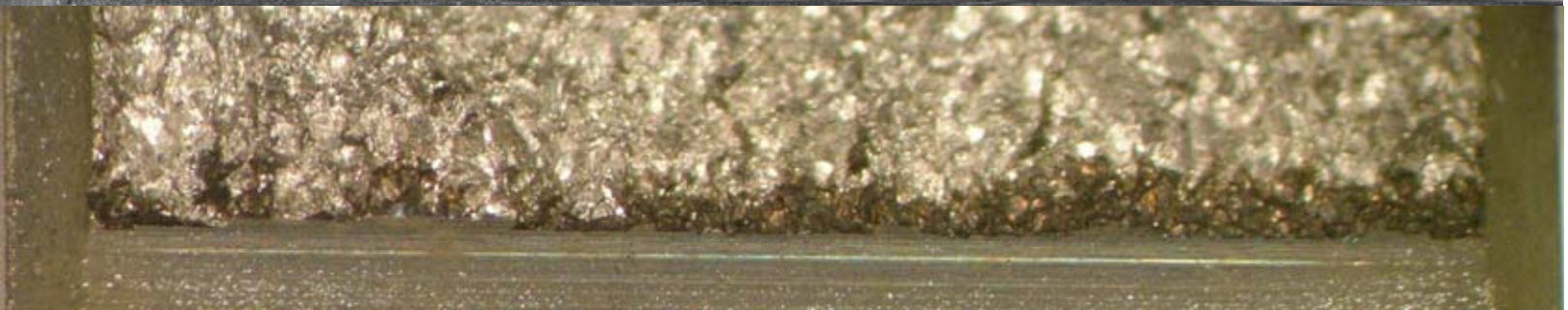
Mature chemistry forms in crack of depth <50 µm
Early growth controlled by crack coalescence

Crack Initiation

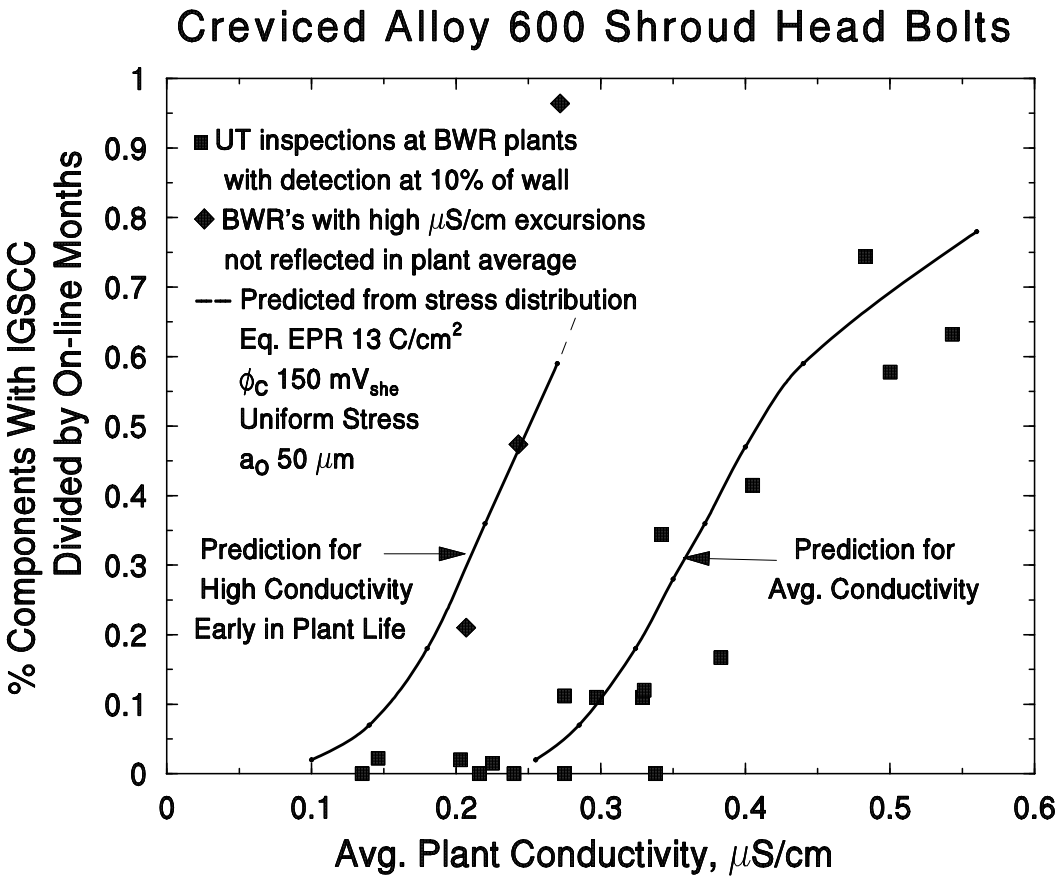
Short Crack Transition in "Wrought 182" in PWR Water at 340 °C







Strong Dependence on Plant Conditions



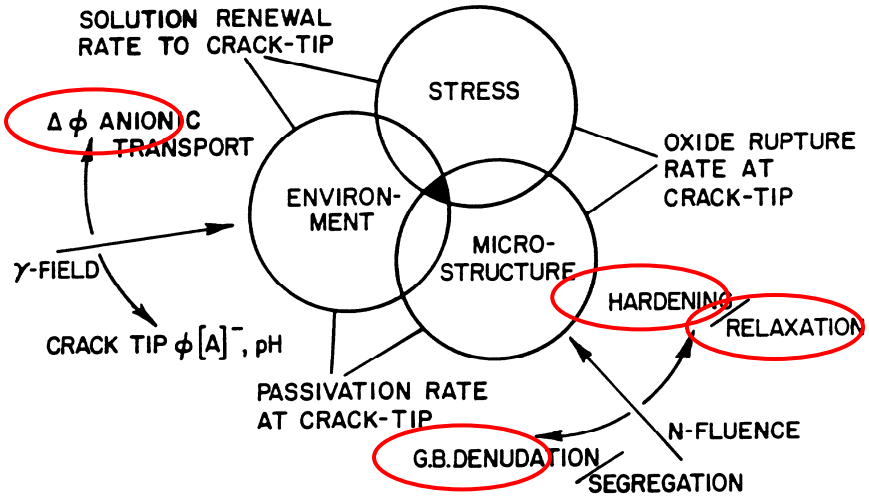
Alloy 600 shroud head bolt predictions show ability to calculation probability or %-incidence of SCC based on stress or other distribution.

Transient conditions, such as high impurities early in plant life, can have a big influence on cracking.

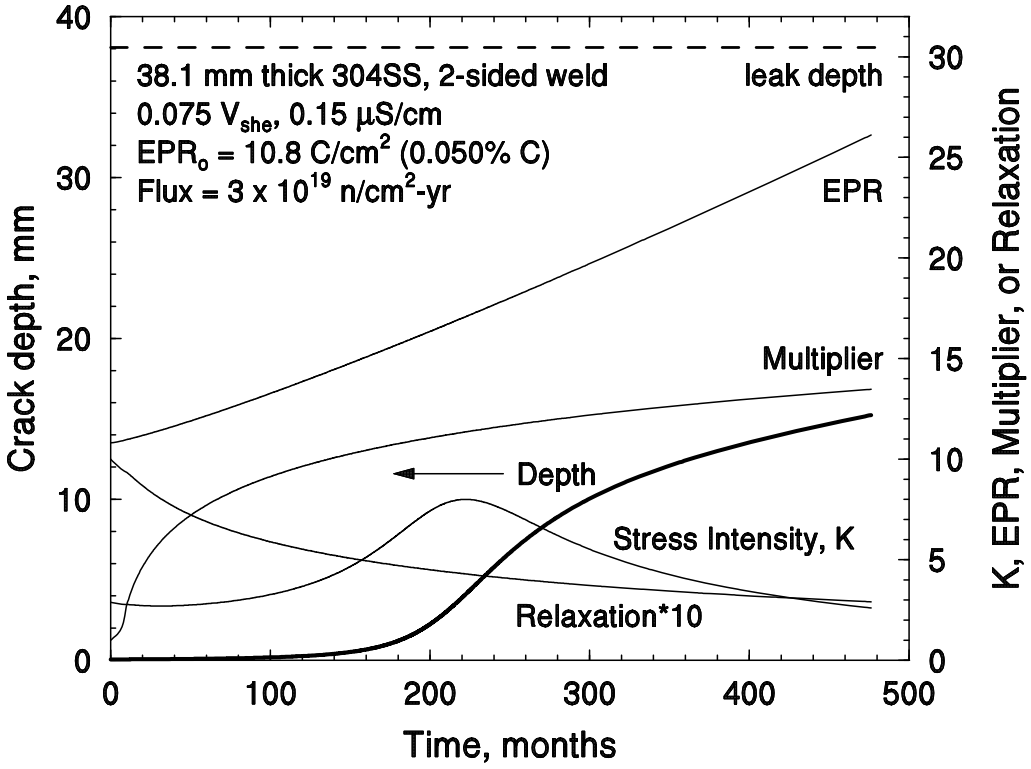
IASCC understanding rests on several factors:

- high corrosion potential from radiolysis
- radiation induced segregation changes gb chemistry
- radiation hardening increases yield strength
- radiation creep relaxation reduces residual stresses

Integrating the simultaneous effects of these variables is critical but requires solid understanding of their inter-dependencies.



Predictions Require Knowledge of Inter-dependencies and Time- & Crack-depth-varying Phenomena



SCC in BWR core shrouds involves complex relationships:

1 – K vs. depth

2 – rad. relaxation vs. time

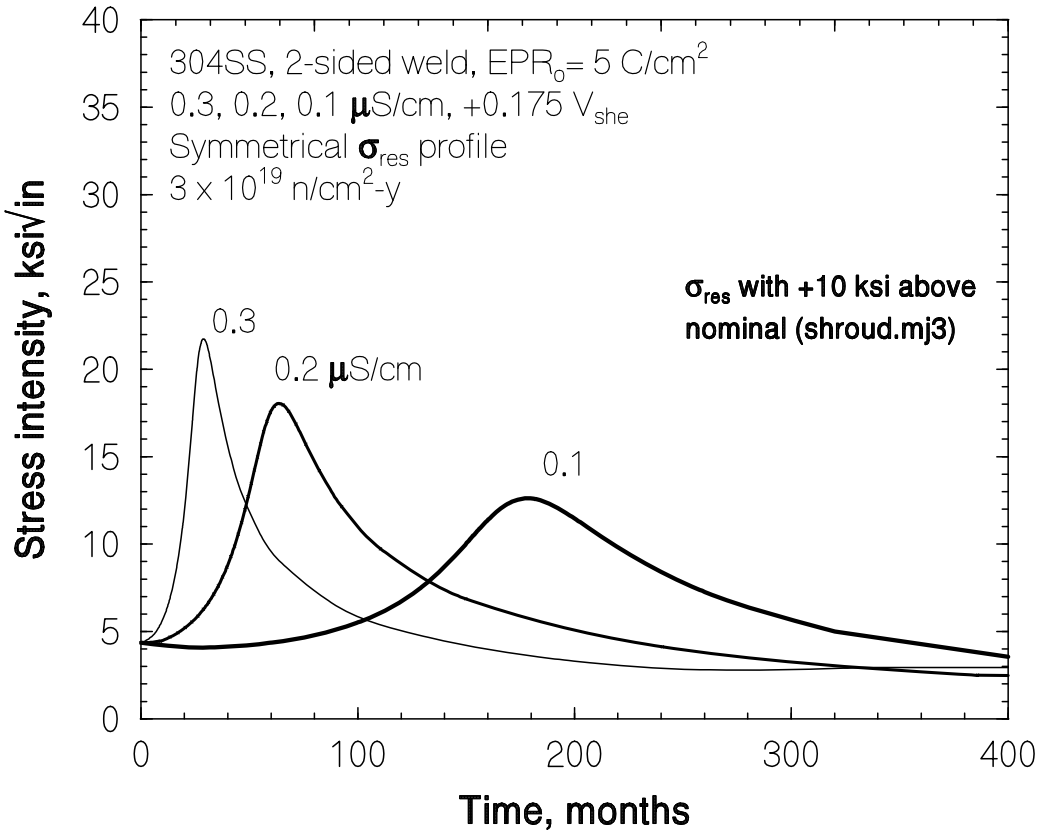
3 – rad. segregation vs. time

4 – rad. hardening vs. time

5 – plant chemistry vs. time, which affects extent of crack growth before relaxation

We're unlikely to understand initiation in this detail in 20 yrs

Predictions Require Knowledge of Inter-dependencies and Time- & Crack-depth-varying Phenomena



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1 – K vs. depth

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5 – plant chemistry vs. time, which affects extent of crack growth before relaxation

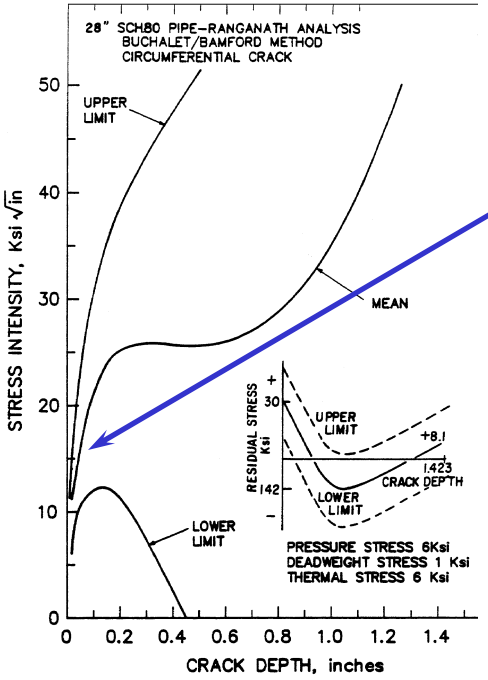
Peak K is higher at 0.3 μS/cm because crack grows faster before relaxation occurs

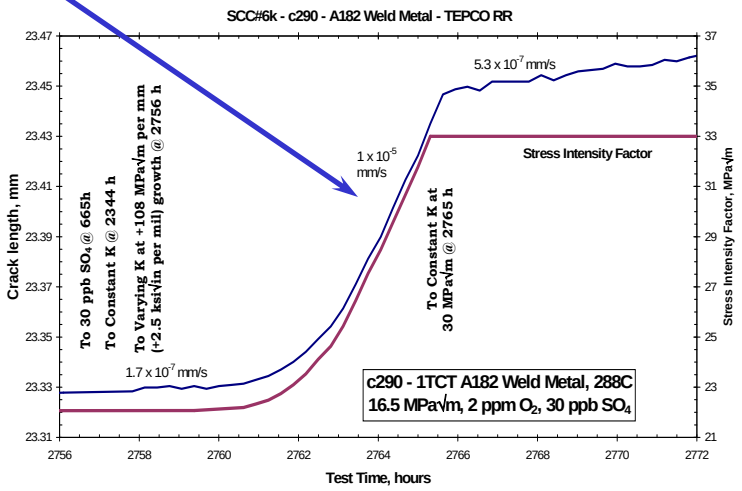
Crack Initiation

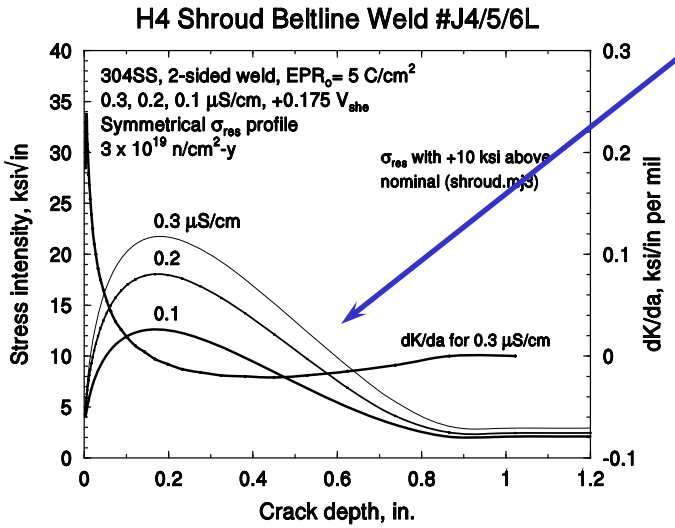
Initial dK/da Rises Rapidly

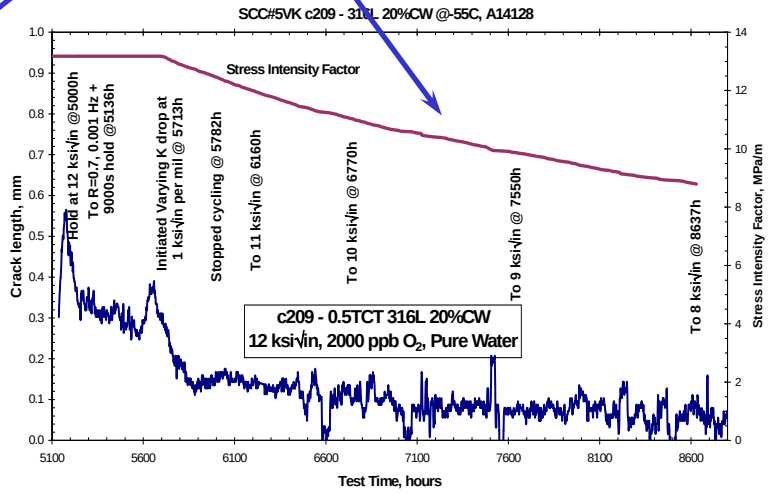
High dK/da is important in early crack growth!

Low –dK/da later is not very beneficial.









Closing Comments

1 – Initiation essential to "massively parallel" cases like SG tubing

2 – Large, complex components, long operation, welding defects, surface inclusions & damage, etc. conspire to make the assumption that initiation is still the limiting factor uncertain & non-conservative.

3 – Test design, # specimens, continuous monitoring, surface area and representativeness, go/no-go observation, etc. complicate the quality of initiation data and must be optimized for quantitative use.

4 – Well designed initiation tests can provide confidence that the crack growth benefit carries over to crack initiation, to ensure that the incidence of initiation will also be decreased and thereby add further confidence that SCC will be dramatically mitigated.