ASSESSMENT OF THE INTEGRITY OF PIPELINES SUBJECT TO CORROSION-FATIGUE, PITTING CORROSION, CREEP AND STRESS CORROSSION CARCKING

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Presentation Outline

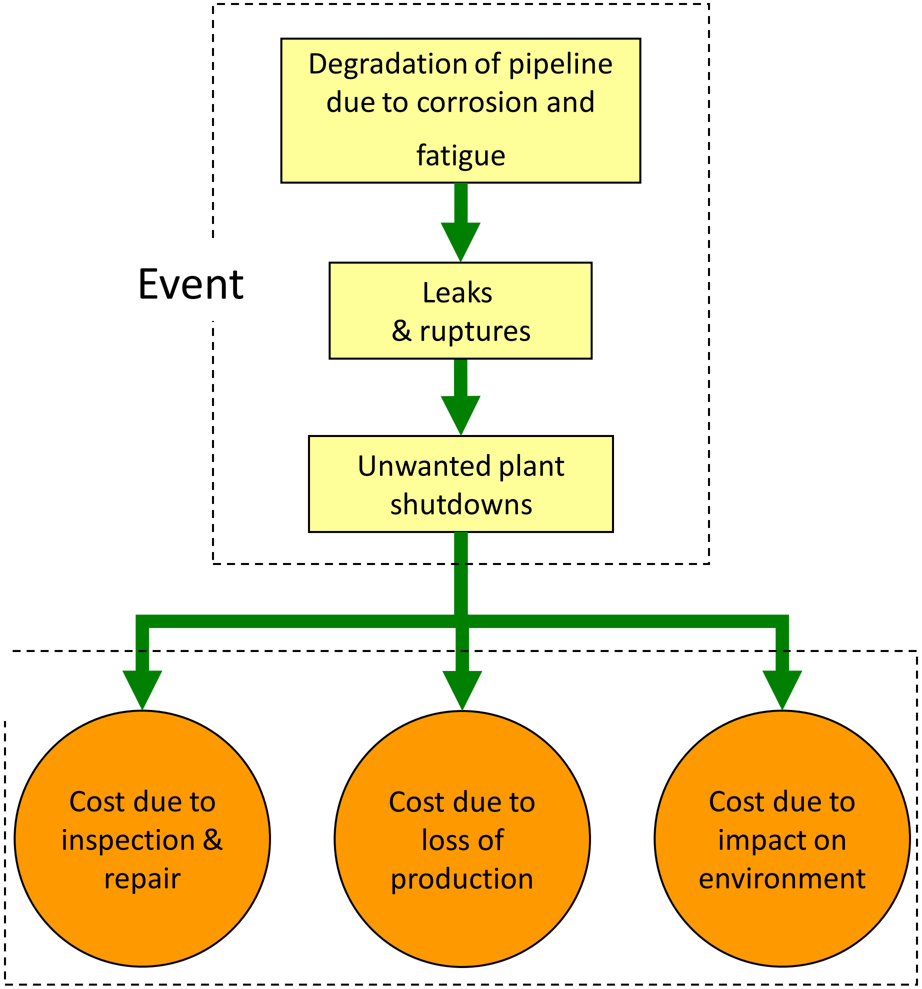
- Background
- Objectives
- Failure Mechanism Modeling and Applications
  - Corrosion-Fatigue
  - Pitting Corrosion
  - Creep
  - Stress Corrosion Cracking
- Conclusions

Objectives

- Develop Physics-based computationally simple probabilistic models for routine reliability assessments and health monitoring in the oil industry
  - PoF (Physics of Failure) models capture material degradation and failure mechanism and can be extrapolated to different levels.
  - Probabilistic models can adequately represent all of the factors that contribute to variability (e.g. material properties , Inspection devices accuracy, human errors, etc.)
  - Use of the probabilistic models to estimate reliability of components (our interest is pipeline reliability)

Problem Statement

Pitting and Fatigue leading to Pipe Failure - Ductile Iron



Corrosion Inside the Pipe

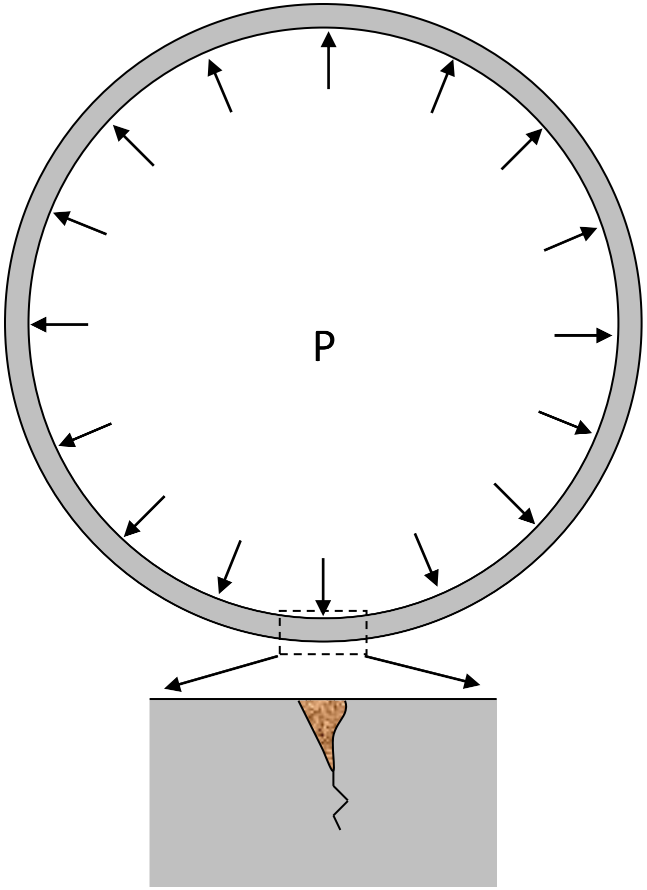
Consequences

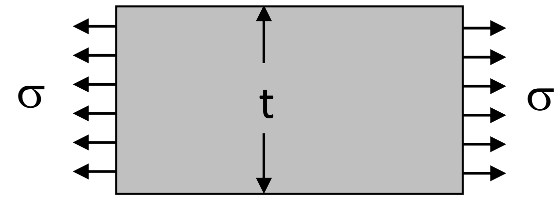
Problem:
Cost of corrective maintenance

Solution:
Predictive maintenance

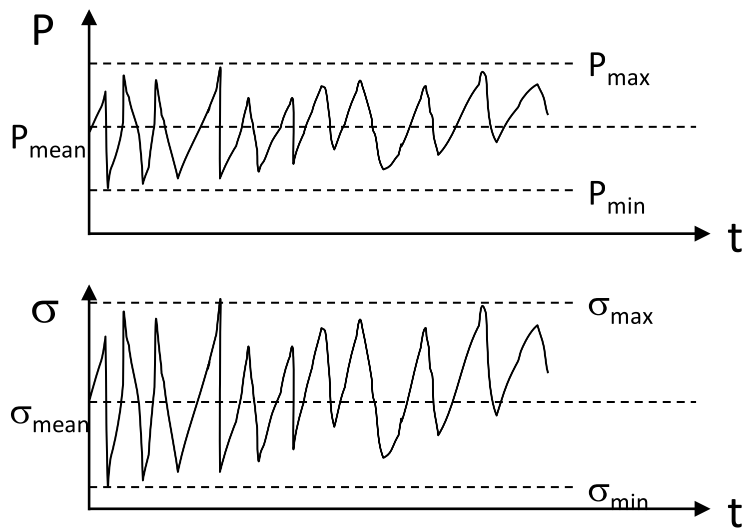
Pictures from: (http://your-tech-assistant.eltex-pipe.com)

Corrosion-Fatigue in Pipes

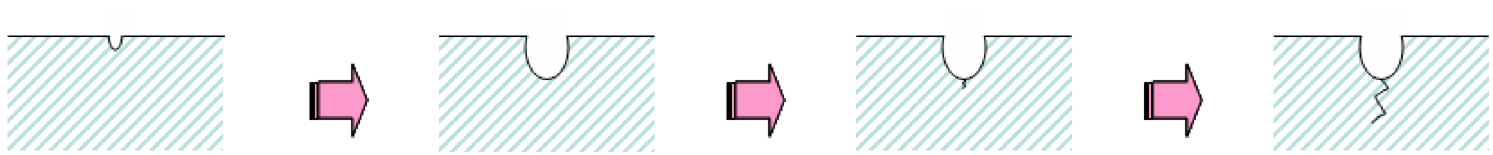




$$\sigma = \frac{PD}{2t}; \frac{t}{D} << 1; D = diameter; t = tickness$$



Corrosion-Fatigue Modeling Approach



Pit Nucleation

Pit Growth

Crack Nucleation (Pit to crack transition)

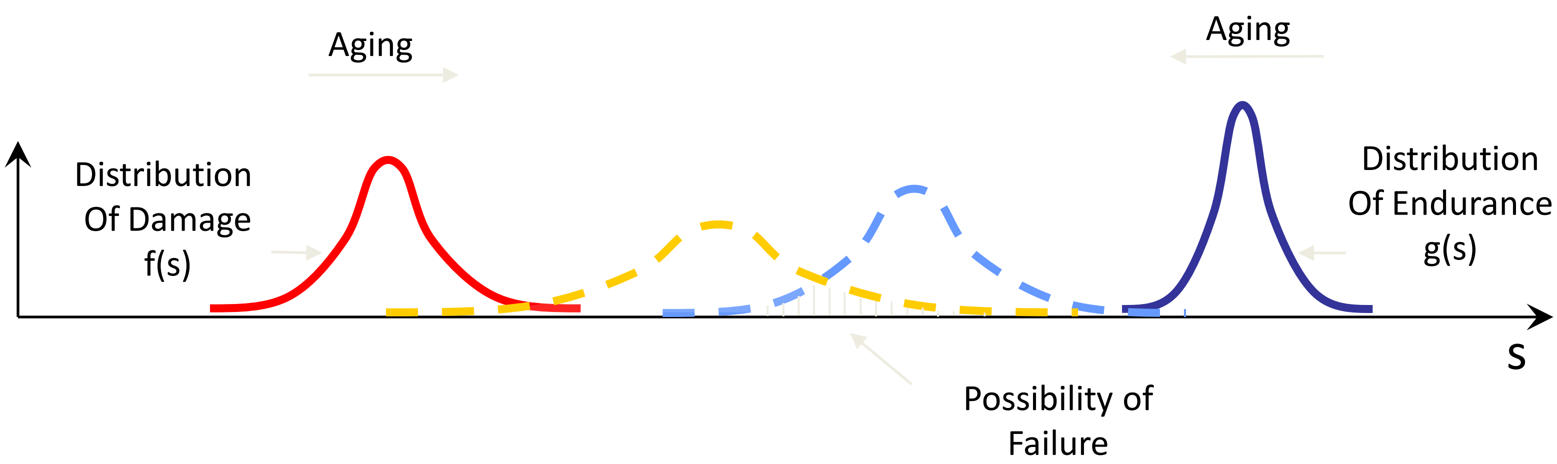
Crack Growth

Corrosion is Dominant

Fatigue is Dominant

The criterion for transition : $\left(\frac{da}{dt}\right)_{crack} \geq \left(\frac{da}{dt}\right)_{pit}$

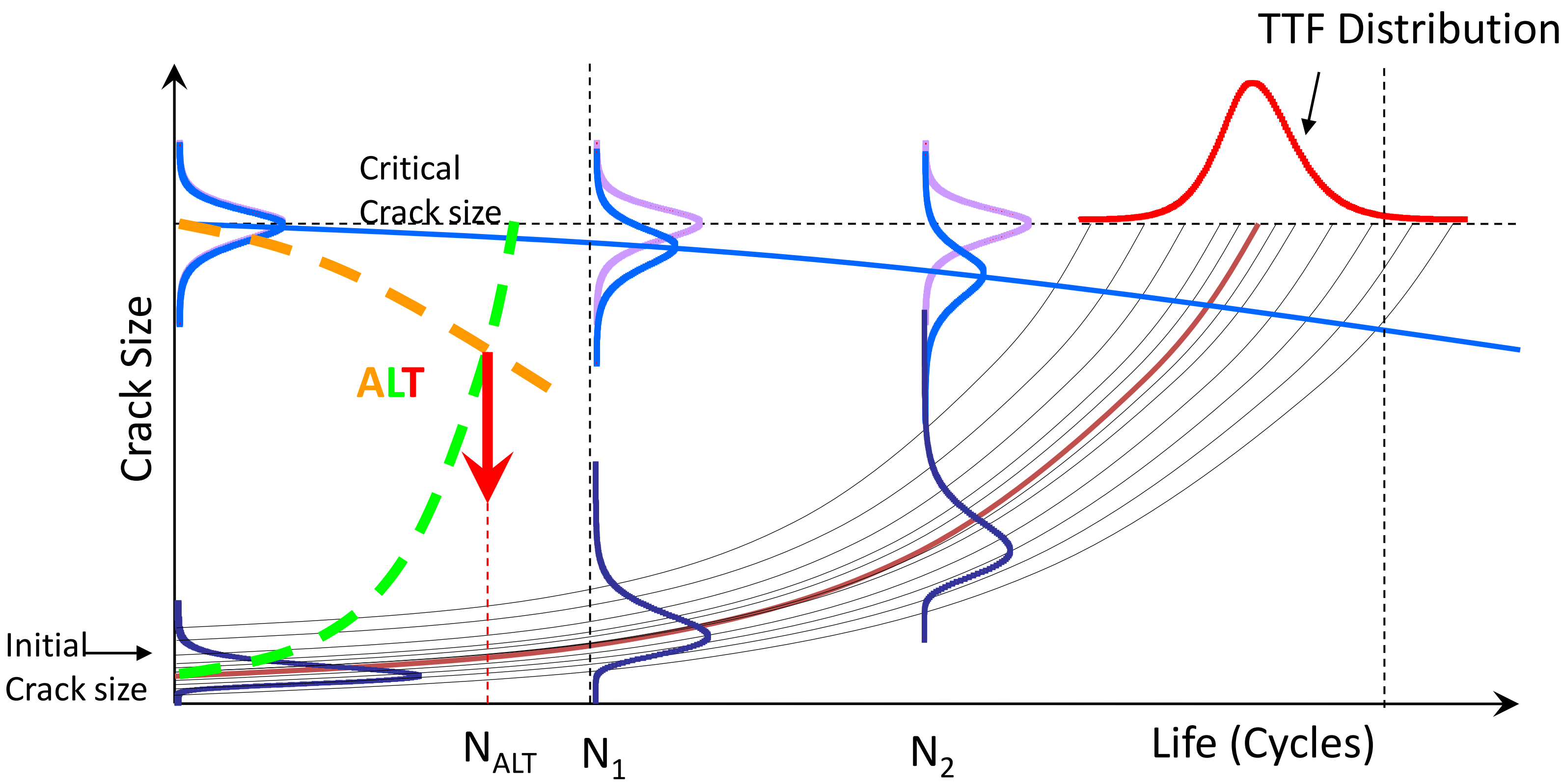
Damage-Endurance Reliability Models



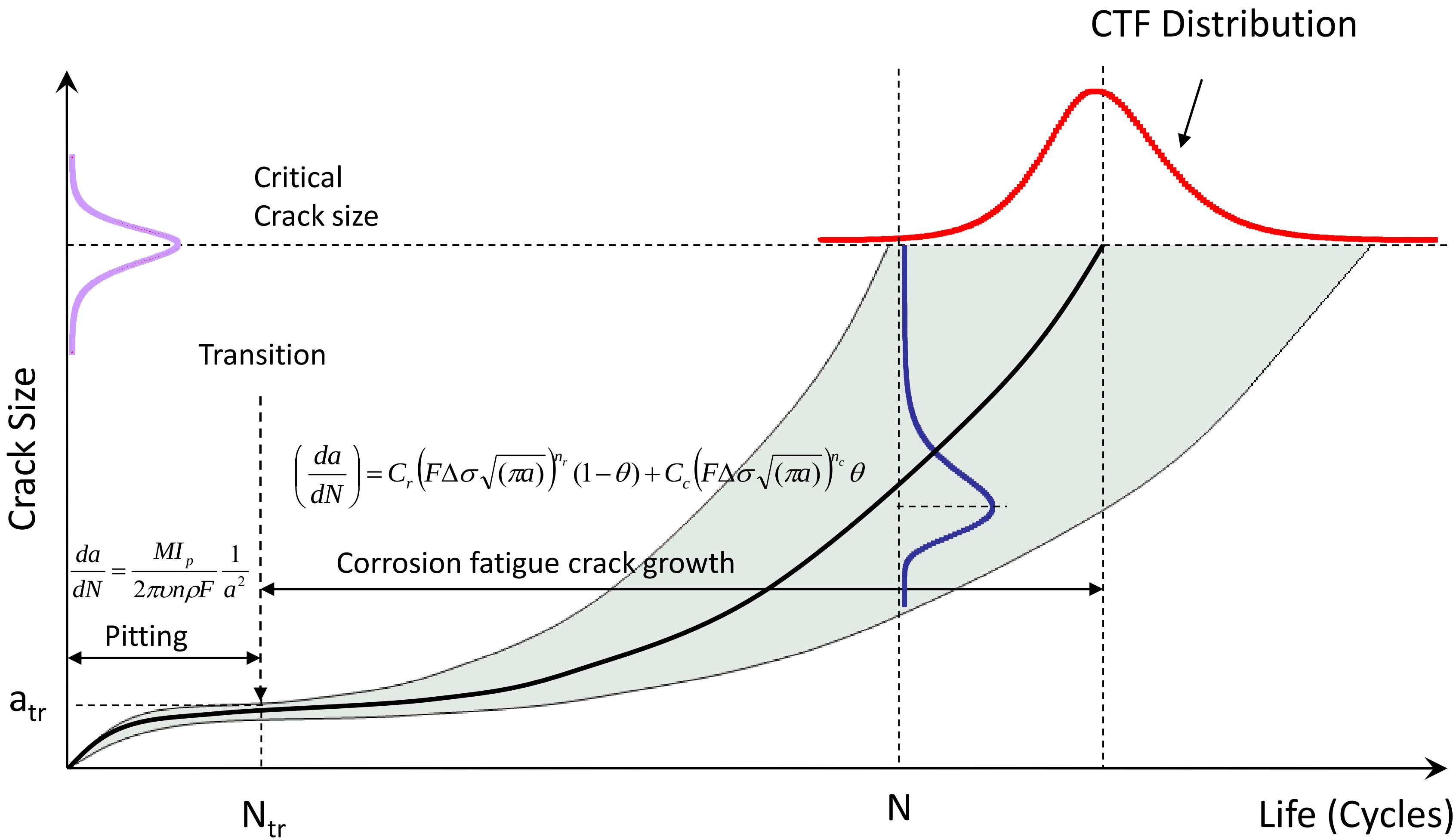
$$P(Damage > Endurance) = \int_0^{\infty} \left\{ \int_0^{s} g(x)dx \right\} f(s)ds$$

Probabilistic Fracture Mechanics Approach to Fatigue Reliability

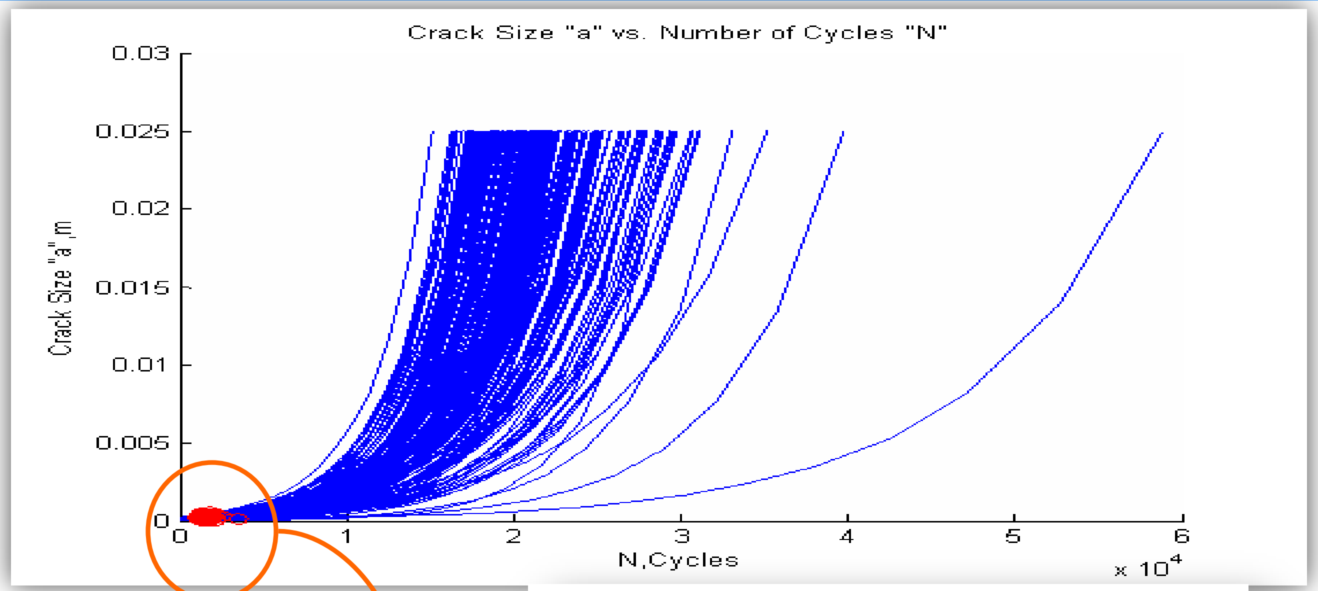
Damage-Endurance Model

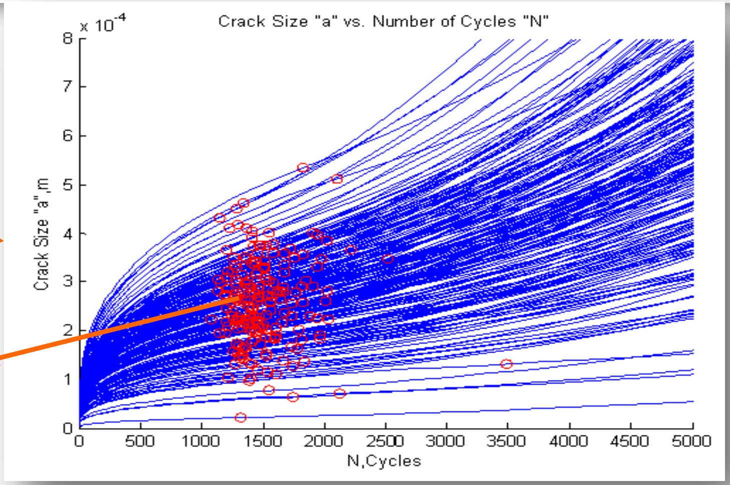


Damage-Endurance Modeling Corrosion-Fatigue



Physics-Based Simulation Results





These are the (N_{tr}, a_{tr}) Coordinates

Semi-Empirical Simplified Model Development

Find the correlation of A & B with the physical parameters of the pipeline:

- **Loading Stress "σ"**
- **Loading Frequency "ν"**
- **Temperature "T"**
- **Flow Characteristic "C" (e.g., Ip, [Cl$^-$], pH, …)**

$$Damage, D = f(v_i, t_i | \Theta)$$

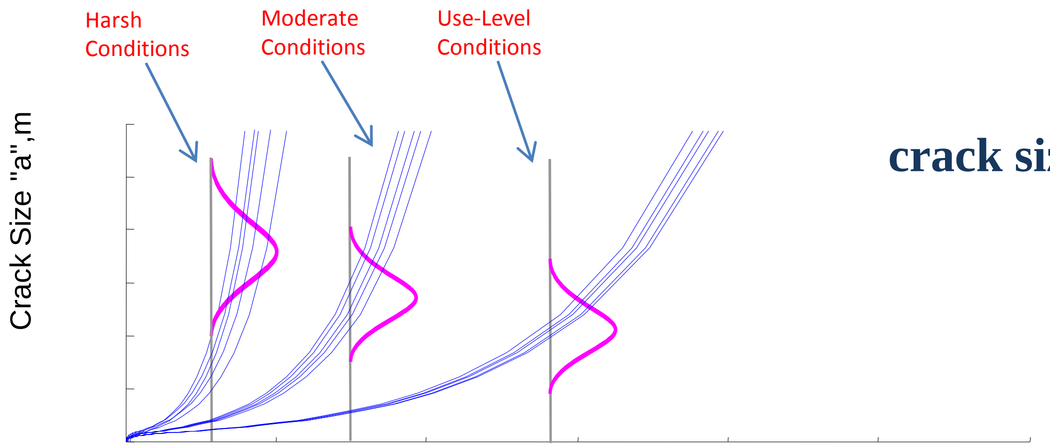
$$D \approx \text{e.g. crack size, a}$$

$$v_i \approx \text{variables (e.g. T}, \sigma, \nu, [\text{Cl}^-], \ldots)$$

$$t_i \approx \text{index of time (e.g. N,...)}$$

$$\Theta \approx \text{vector of model constants (e.g. } \varepsilon_i, A, B, \ldots)$$

Proposed Simple PoF-Based Corrosion-Fatigue Semi-Empirical Model



crack size vs. stress, cycle, etc.

$L(a_i) = LN(\mu_i,\sigma_i)$

$\mu_i = \ln[f(s_i, T_i, v_i, Ip_i, N_i)]$

$$a_i = \left[A \cdot s_i^{0.182} \cdot v_i^{-0.288} \cdot Ip_i^{0.248} \cdot N_i^{1/3} + B \cdot s_i^{3.24} \cdot v_i^{-0.377} \cdot Ip_i^{0.421} \cdot N_i^{2} \cdot e^{(4\times 10^{-10} \cdot s_i^{2.062} \cdot v_i^{0.024} \cdot N_i)}\right]$$

$$where\ a = crack\ size,\ v = load\ frequency,\ s = stress\ amplitude\ , I_p = Current\ intensity,\ N = cycle\ No.$$

$$L(a) = f(a) = \frac{1}{\sigma \cdot a\sqrt{2\pi}} \exp\left[-\frac{1}{2\sigma^2}(\ln a - \ln(A \cdot s^{0.182} \cdot v^{-0.288} \cdot Ip^{0.248} \cdot N^{1/3} + B \cdot s^{3.24} \cdot v^{-0.377} \cdot Ip^{0.421} \cdot N^2 \cdot e^{(4\times 10^{-10} \cdot s^{2.062} \cdot v^{0.024} \cdot N)}))^2\right]$$

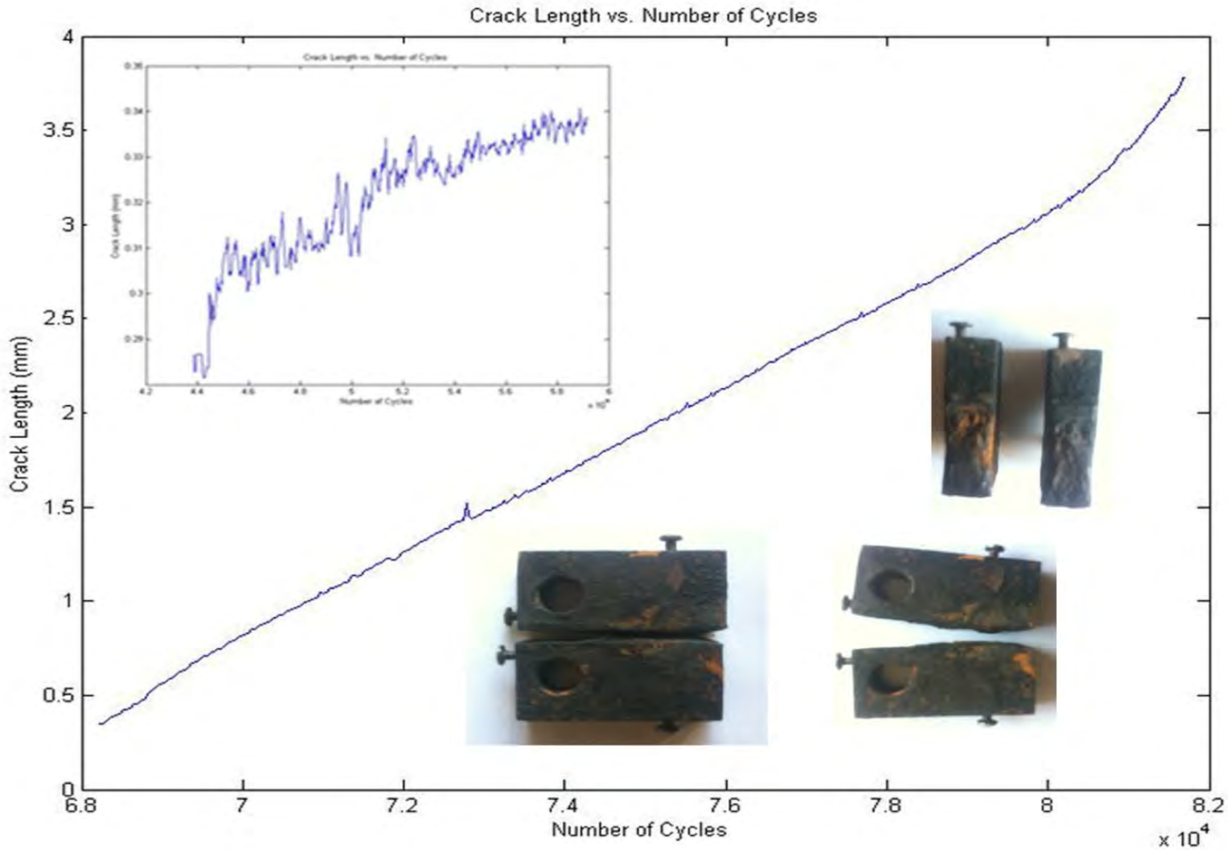
Data Collection: Experimental Validation

Corrosion-Fatigue Testing

Set-Up (Cortest Test Facility)

Cortest Corrosion-Fatigue Testing Results

- Crack length vs. number of cycle from Cortest corrosion-fatigue testing:
  - in sea water of 250 ppm $Na_2S_2O_3$ -$5H_2O$ at 383 K, and 100 and150-MPa,
  - at different frequencies of 0.004 Hz and 0.00165 Hz.
  - Pictures from broken specimen with connected screws(for applied current and voltage) are shown at the bottom.



Broken specimen from Cortest corrosion-fatigue testing

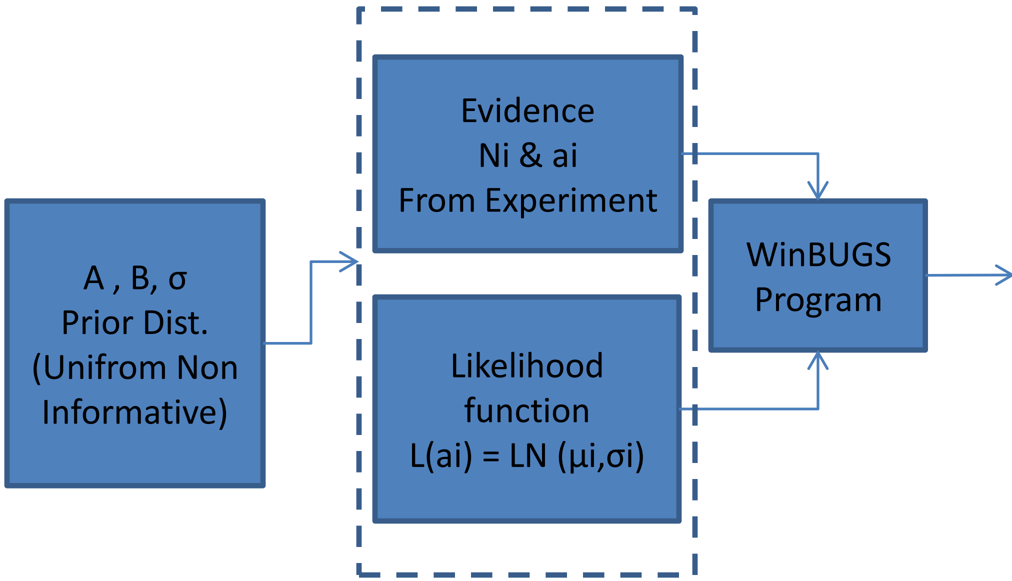
- Broken specimen (two side views plus broken surface parts)

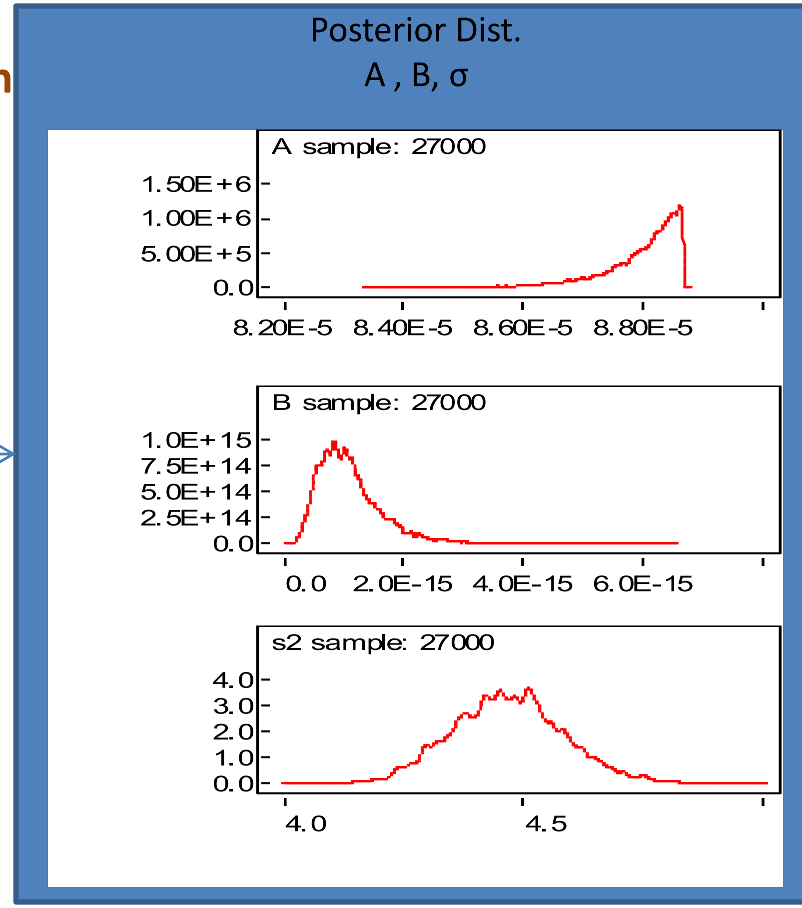


voltage - current - connections

Model Parameter Estimation

Bayesian Inference Framework using Markov Chain Monte Carlo Simulation Approach





Posterior Marginal Lognormal Distributions and s, A & B

A $\begin{cases} \mu_A = -9.34 \\ \sigma_A = 7.41\text{x } 10^{-3} \end{cases}$

B $\begin{cases} \mu_B = -34.524 \\ \sigma_B = 0.4686 \end{cases}$

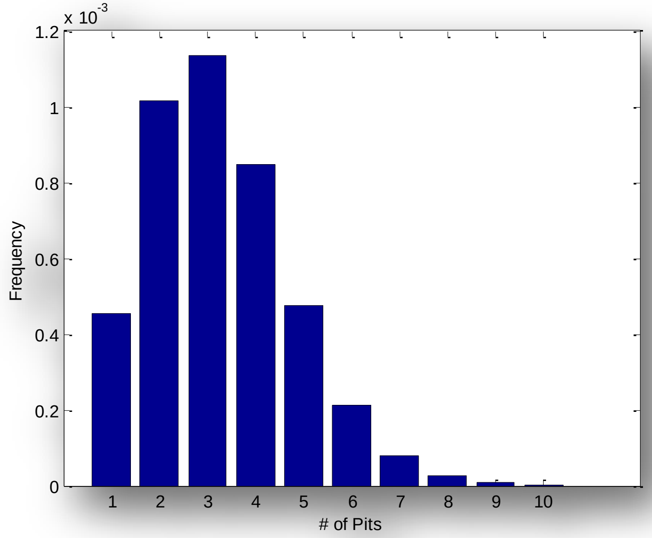
s2 $\begin{cases} \mu_{s2} = 4.468 \\ \sigma_{s2} = 1188 \end{cases}$

Reliability and Health Monitoring Application

A harsh pipeline environment:

- Higher Loading Stress

Frequency of Exceedance for Each Observed Number of Pits in the Refinery Pipeline.

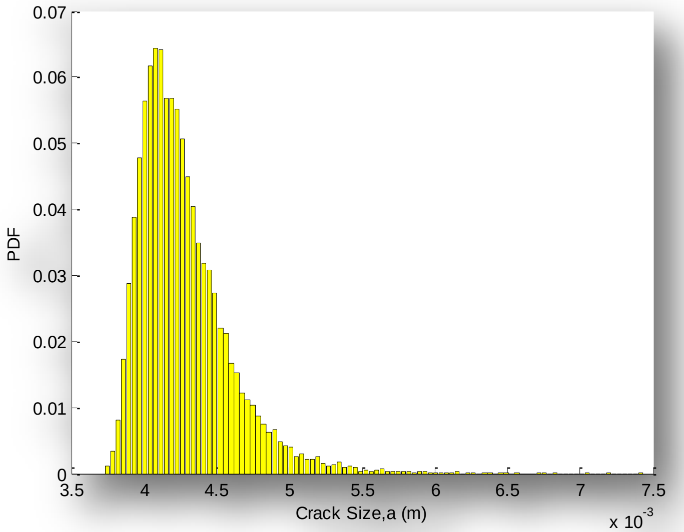


The new frequency of exceedance for the bulk pipeline is estimated to be 548 pits/25 yrs life of pipeline!!!! → Drastically Increased

Reliability and Health Monitoring Application (Cont.)

Run simulation

Using proposed Empirical Model



- "a_i" Lognormal distribution:

μ= -5.47 ; σ=0.06

Pitting Corrosion (Phase II)

- With Collaboration from PI Summer Interns Abdullah M. Al Tamimi & Mohammed Mousa Mohamed Abu Daqa

Background

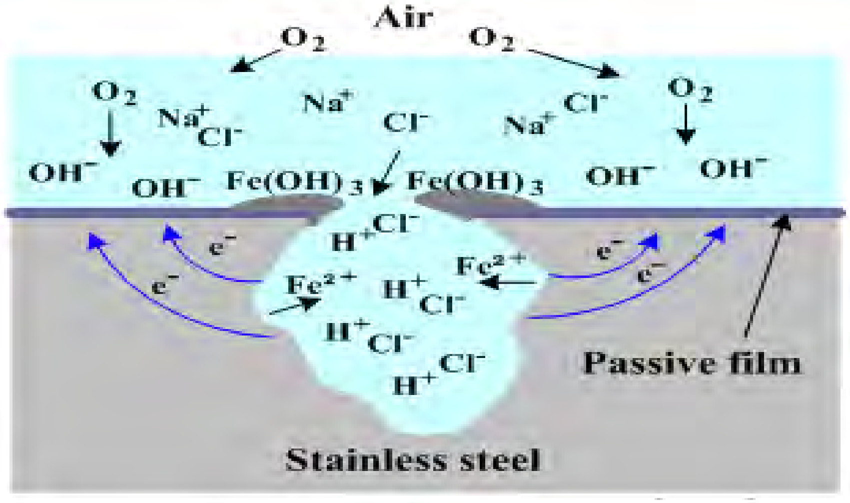
Pitting Corrosion (X70Carbon Steel)

- Pitting Corrosion: An electrochemical oxidation reduction process, which occurs within localized holes on the surface of metals coated with a passive film.
- It might be accelerated by chloride, sulphate or bromide ions in the electrolyte solution.
- Pitting corrosion has a great impact on the oil and gas industry.
- There are three main stages for the pitting corrosion to occur:

1-Pit Initiation

2- Pit Propagation

3-Fracture:



Objectives of Pitting Corrosion

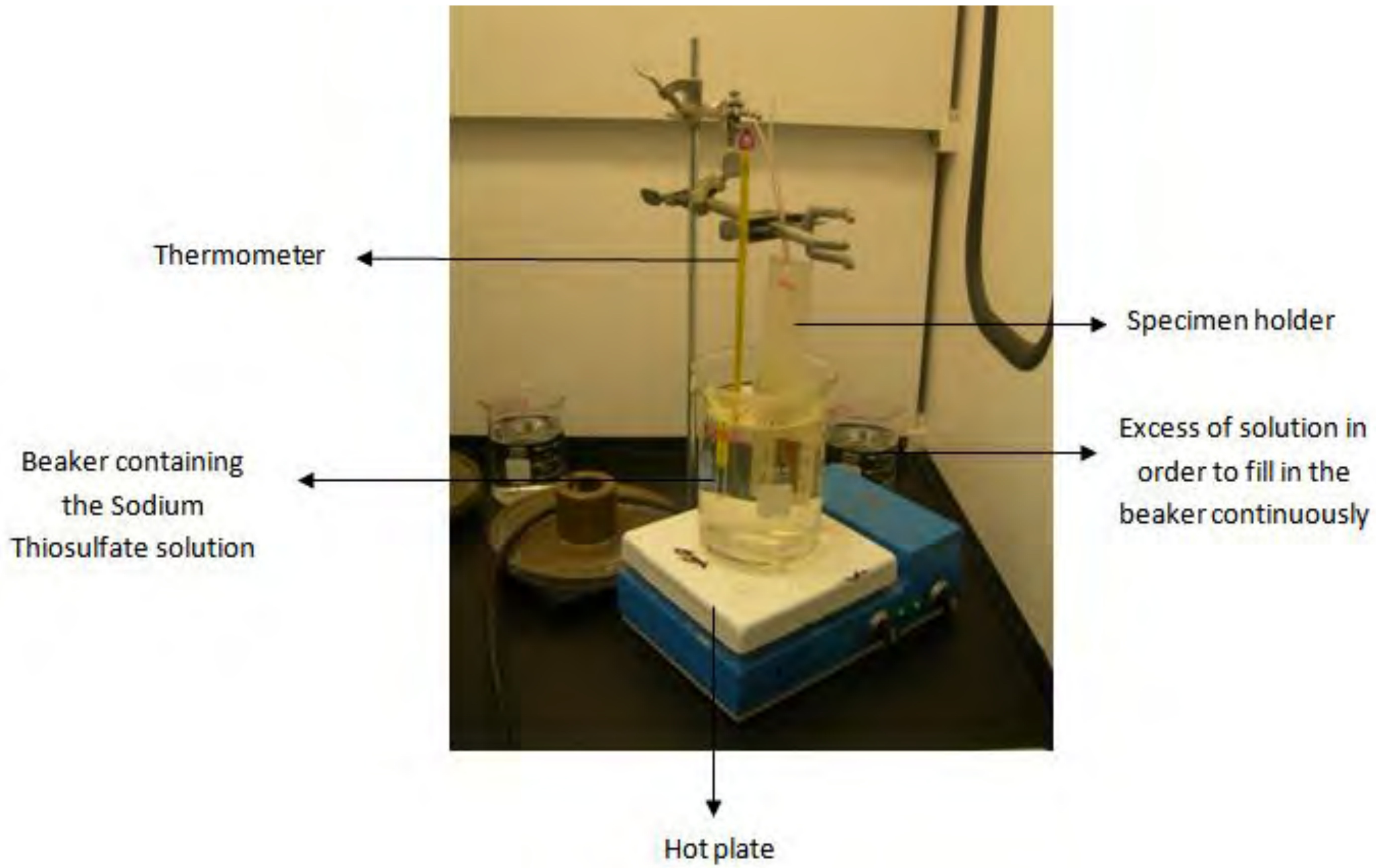
- **Objectives**
  1. Measuring pits depth,
  2. Measuring pits density, and
  3. Measuring the mass loss.
- **Two Corroding Environments (X70 Carbon Steel at 323 K)** :

  - **H_2S = $Na_2S_2O_3$-$5H_2O$** with 100 100ppm, 150ppm, 200ppm, 300ppm and 400ppm concentration, in 5,10, 24 hours time period;

  - **Chloride(Sea Water)** with 100 100ppm, 150ppm, 200ppm, 300ppm and 400ppm concentration, in 5, 10, 24 hours time period.

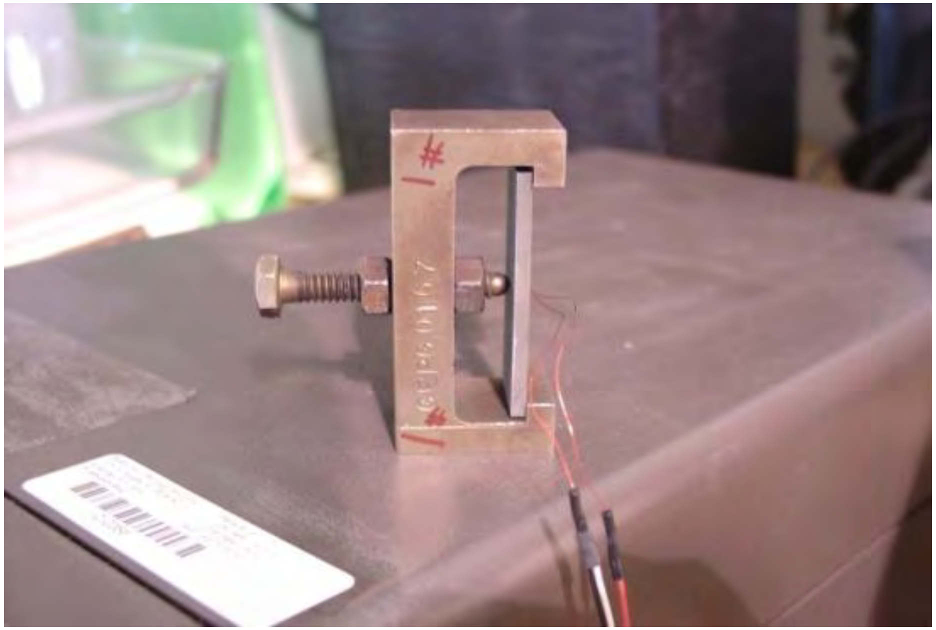
Experimental Setup/1

- The scheme of the experimental setup:



Experimental Setup/2

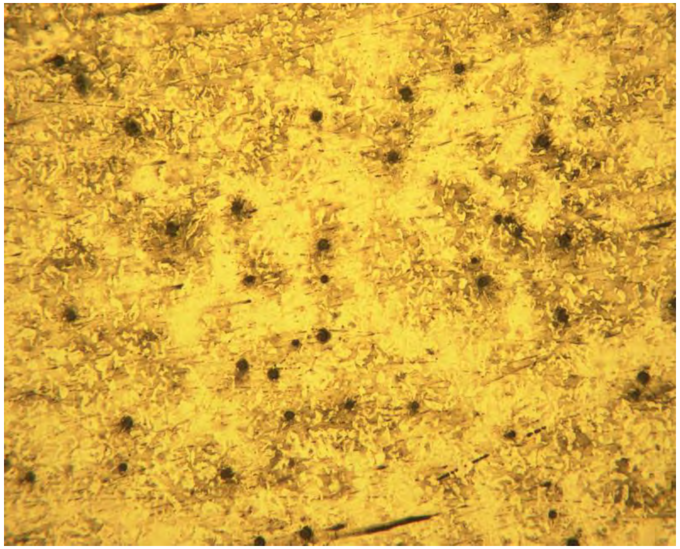
- The scheme of the experimental setup:



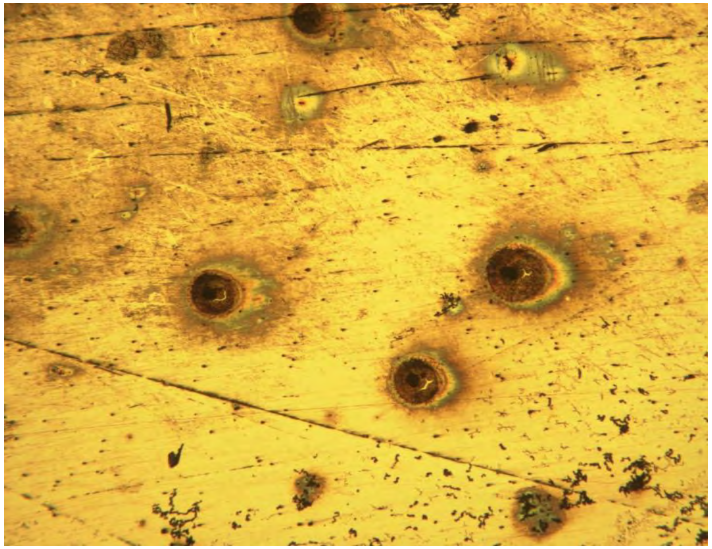
Static stress corrosion specimen with a strain gage on it to measure the applied stress.

Examples of Pitting Corrosion H_2S and Chloride-Results

- Morphology of the samples are studied by:
  1- Optical Microscope, Nikon Optiphot 66
  2- Sensitive Weighing Machine, METTLER TOLEDO AB104
  3- Scanning Electron Microscope, HITACHI SU-70 SEM
- Morphology of Pits on X70 Carbon Steel surface in corrosive environments



in H_2S (Mx200)



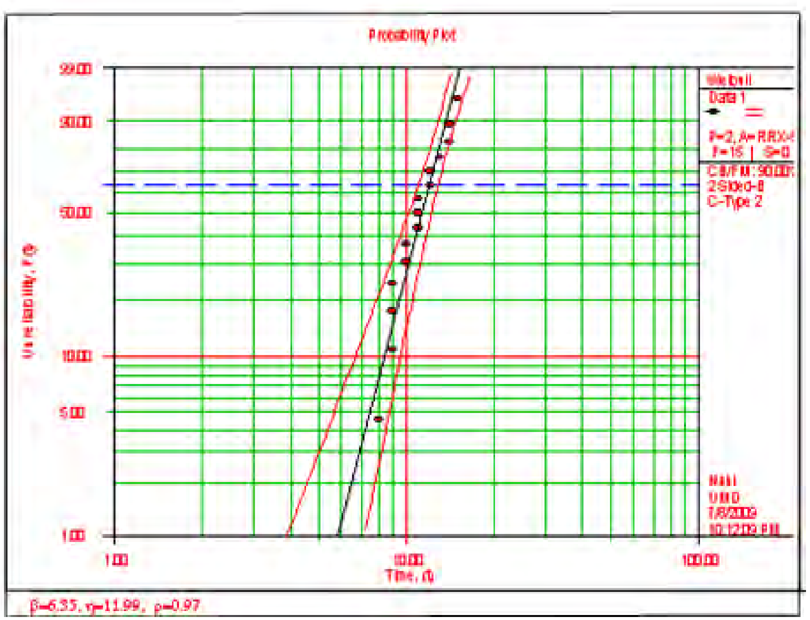
in Chloride (Mx200)

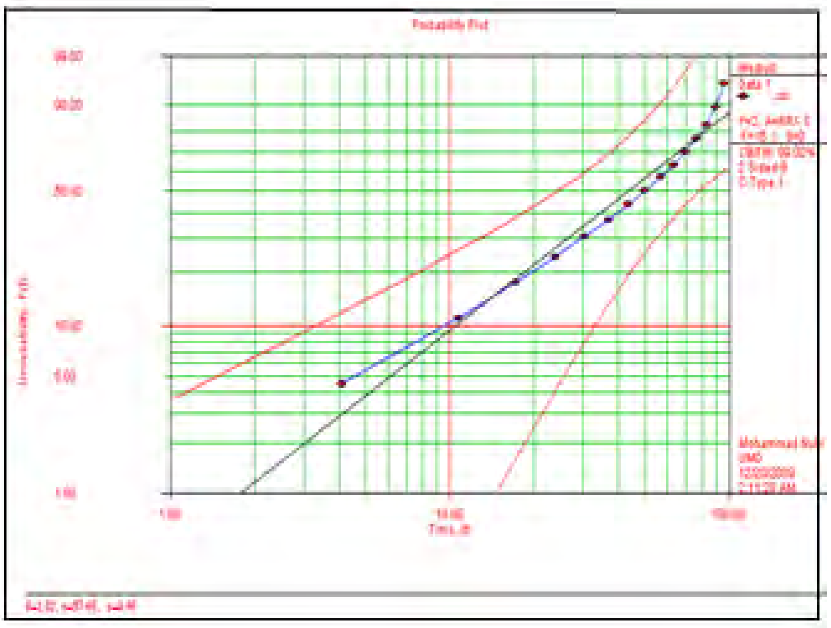
Pitting Depth of X70 Carbon Steel (H_2S and Chloride-Results)

- Pit depths for unstressed samples (left for H2S, right for Chloride) followed Weibull distributions.

$$D_{H_2S} \sim Weib(\beta = 6.55 \quad , \quad \alpha = 11.99\mu m)$$

$$D_{[Cl^-]} \sim Weib(\beta = 1.32 \quad , \quad \alpha = 57.68\mu m)$$



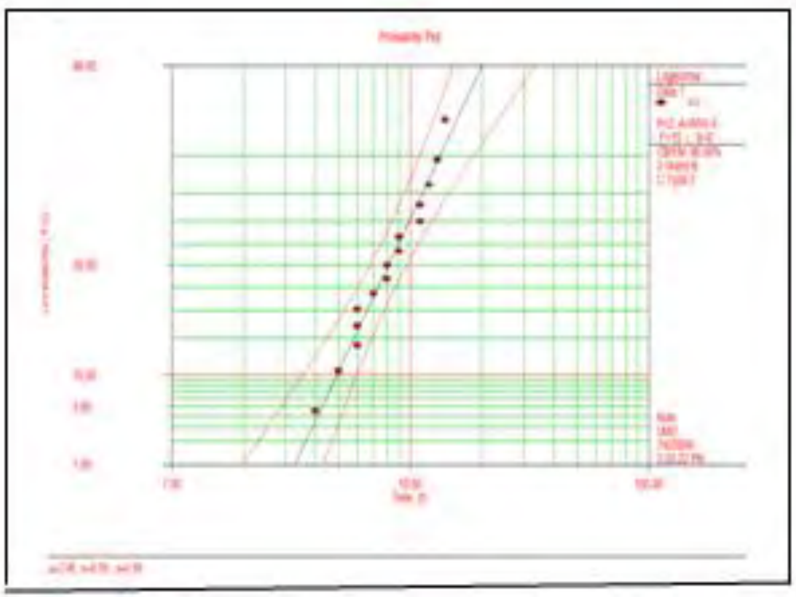


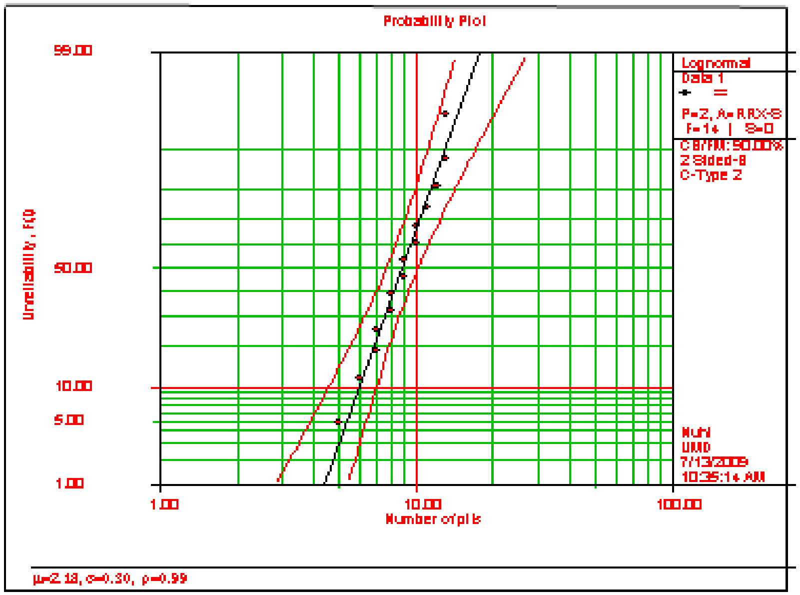
Pit Depth Distribution 400 ppm

Pitting Density of X70 Carbon Steel (H_2S and Chloride-Results)

- Pit densities followed the lognormal distributions.

$$PD_{[h_2S]} \sim LN(\mu = 3.06 \;,\; \sigma = 0.39) \qquad PD_{[Cl^-]} \sim LN(\mu = 2.18 \;,\; \sigma = 0.30)$$

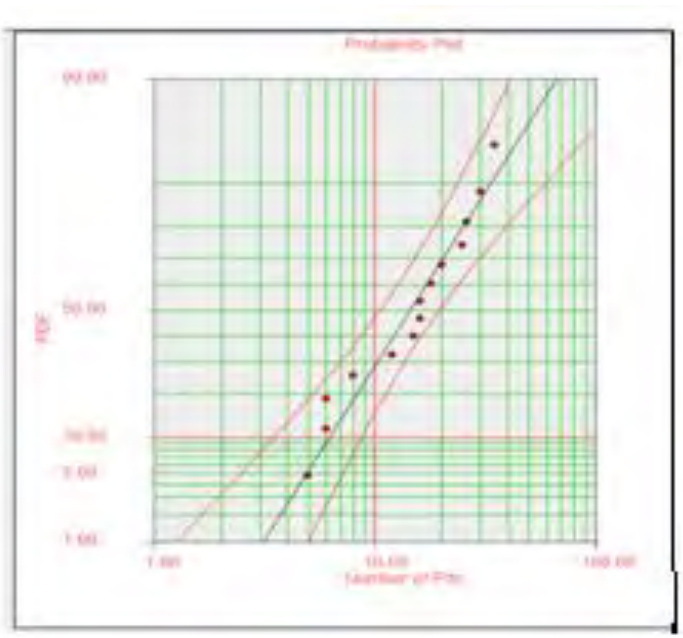


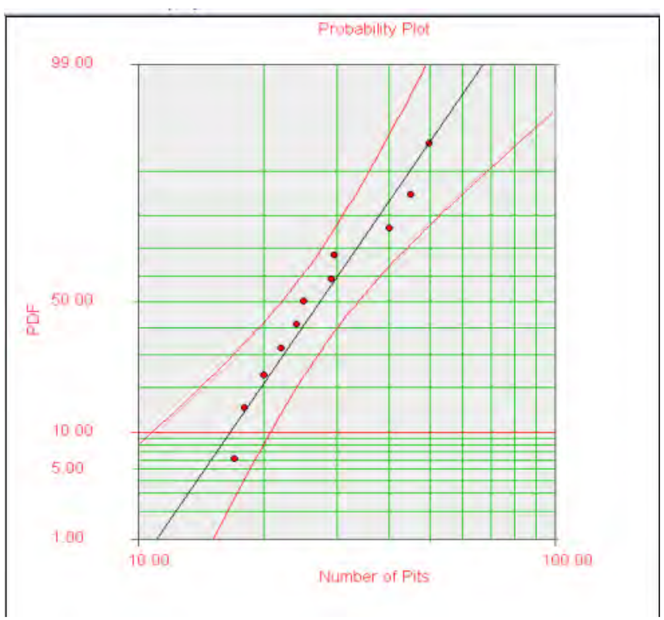


- Pit Density distribution 400ppm, 5hours are given in [pits/cm^2]
  The actual mean: [8 pits/cm^2] (left), [9 pits/cm^2] right

Estimation of Pitting Corrosion Characteristics (stressed and unstressed)

- 250 ppm H_2S (Sodium-thio-sulfate) at 80^oC (353K).
- Mean Intensity: 14 in 250x250 μm^2 ($0.0625\ mm^2$).
- The lognormal plotting diagrams of the unstressed and stressed



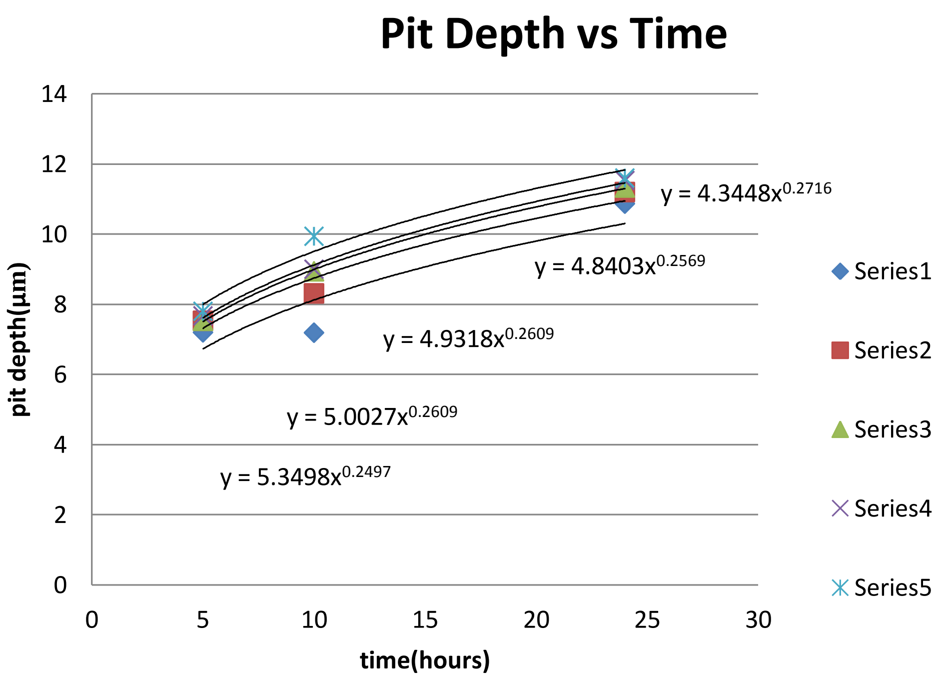


Unstressed : $\rho = \mathcal{LN}$ (μ=2.67, σ=0.66)

Stressed : $\rho = \mathcal{LN}$ (μ=3.31, σ=0.39).

Pit Growth Rate Model

- Pit depths (d) increases with the concentrations according to a power law and time according to the $t^{1/3}$-law (justified by the literature): $d = A\,t^m$



Creep Modeling Background

- Creep is the time-dependent, thermally assisted deformation of materials under constant static load (stress).
- Mathematical description of the process is difficult and is in the form.

$$\dot{\varepsilon} = f(\sigma, \quad T, \quad t)$$

- Creep at low temperatures (primary stage) are described by:

$$\varepsilon = \varepsilon_0 + \alpha \quad \log(1 + \gamma \quad t)$$

$$\varepsilon = \varepsilon_0 \beta \quad t^{1/3}$$

  - where α, β and γ are material constants;
- There is no general agreement on the form of the equations at high temperatures.

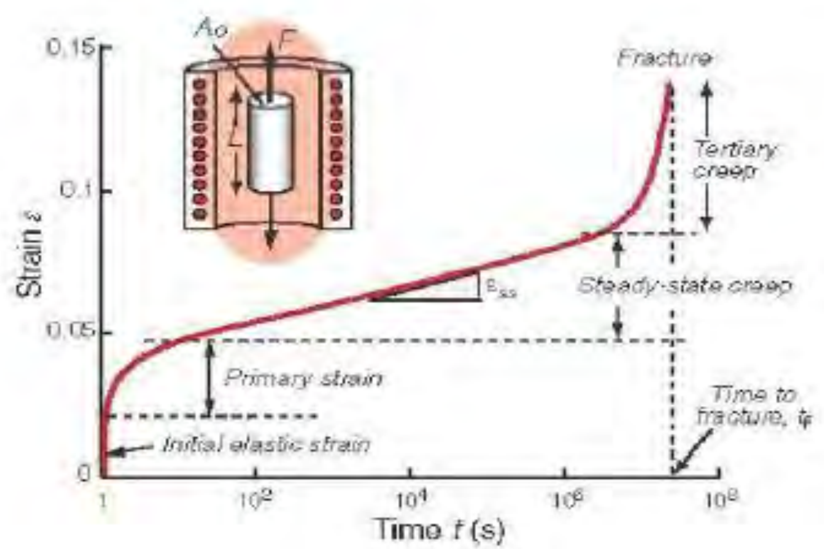
Creep Modeling Background (Cont.)

- A typical creep curve shows three distinct stages with different creep rates, determined by several competing mechanisms from:

  - strain hardening,

  - softening processes such as recovery and crystallization,

  - damage processes such as cavitation, necking and cracking.



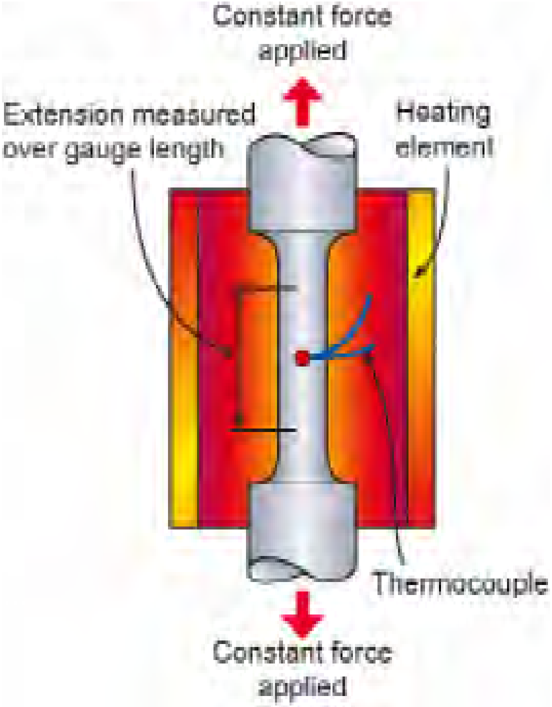
- Creep testing and the creep curve, showing how strain ε increases with time t up to the fracture time. [http://faculty.mercer.edu/bubacz_m/Links/CH13.pdf]

Creep Approach Modeling

- Only literature search completed with some preliminary experimental preparations. The approach includes
  1. Using simulation of detailed models propose an empirical model.
  2. Perform accelerated creep tests.
  3. Use experimental results to assess parameters and uncertainties of the proposed empirical model accelerated life testing.

Creep Accelerated Test Set up

- The creep test is carried out by applying a constant load to a tensile specimen maintained at a constant temperature, (according to ASTM E139-70).

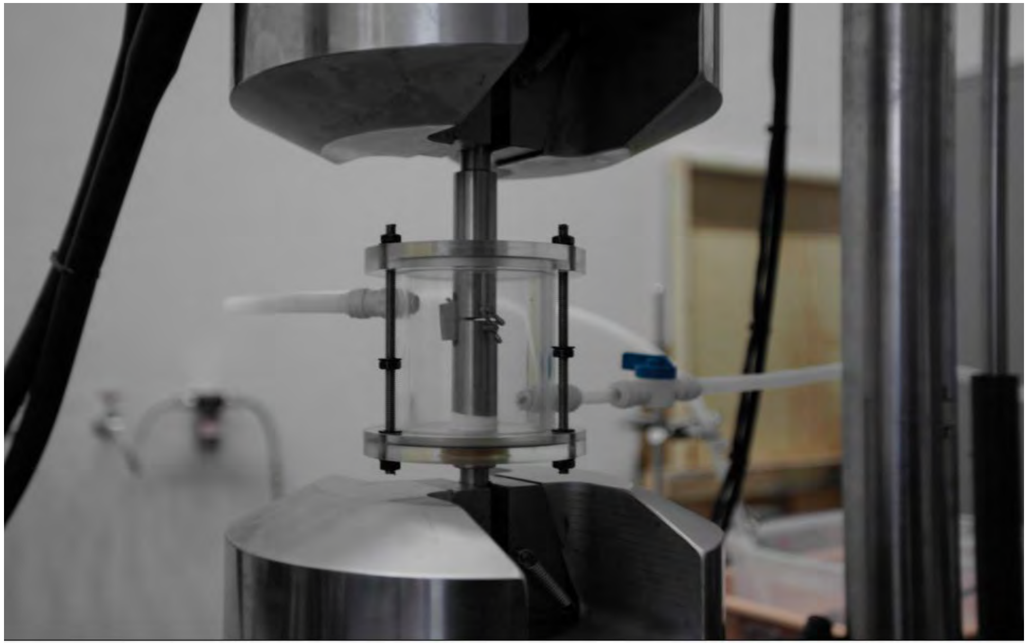


[http://www.sut.ac.th/engineering/Metal/pdf/MechMet]

Creep and SCC Experimental Setup

- Two chambers designed for creep and SCC tests under different environmental conditions and applied stress:
- Left: chamber for Dog-bone
- Right: chamber for CT-specimen (The prototypes specimens at work, installed on MTS-machine).

Dog-bone –specimen

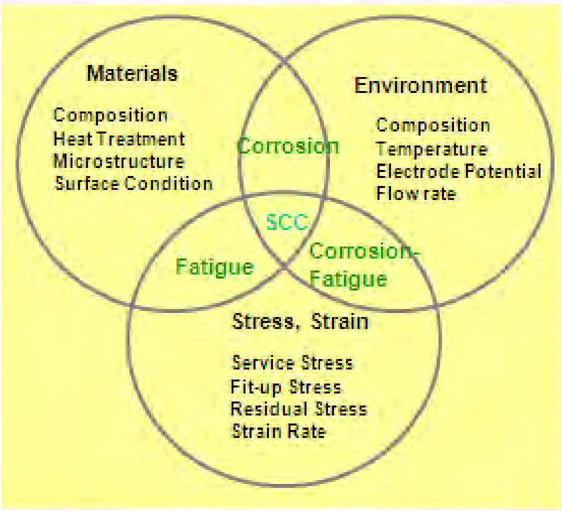


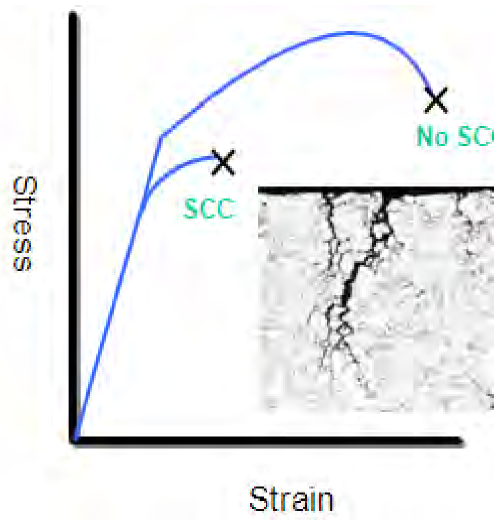
CT-specimen

Stress Corrosion Cracking (SCC)

- SCC is a combination of static tensile stress below yield and corrosive environment.
- Tensile stresses may be external forces, thermal stresses, or residual stresses.
- The kinetics of SCC depends on three necessary conditions:

1. **The chemical and metallurgical state** of the material (chemical composition , thermal conditions, grain size, presence of secondary phases and precipitate, etc.)
2. **The environmental conditions** (environmental composition, temperature, pressure, pH, electrochemical potential, solution viscosity etc.)
3. **Stress state** (uniaxial, triaxial, etc.) and on crack geometry of the material.





Stress Corrosion cracking(Factor Affecting)

- General relationship for the penetration of SCC following commonly accepted dependencies (after Staehle).
- There are many submodes of SCC and, because of the large number of variables in Staehle's equation, there is a great range of possibilities in the study of SCC. This contributes to the complexity of the subject

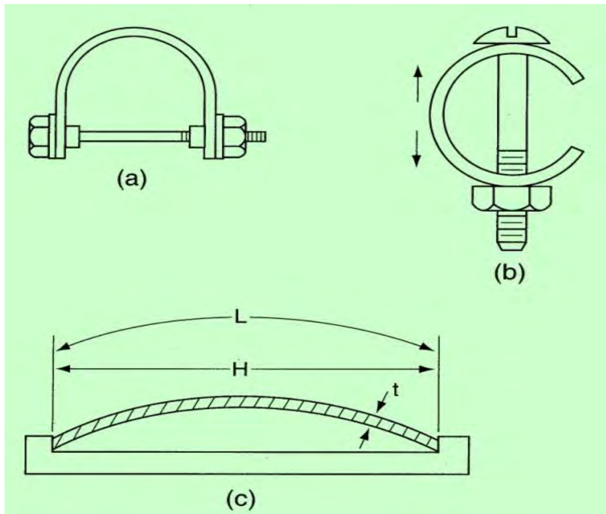
$$X = A.[H^+]^n.[x]^p.\sigma^m.e^{(E-E_0/b)}.e^{Q/RT}.t^q$$

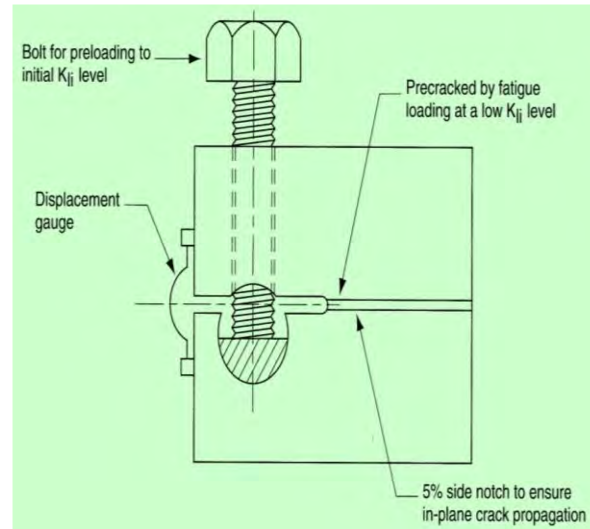
- Where X is the depth of SCC penetration;
- A depends on alloy composition and structure;
- $[H^+]$ is PH; x is the environmental species;
- σ is stress;
- E is electrochemical potential;
- Q is the activation energy;
- R is gas constant; T is temperature;
- t is time;
- n, p, m, b, q are empirical constant

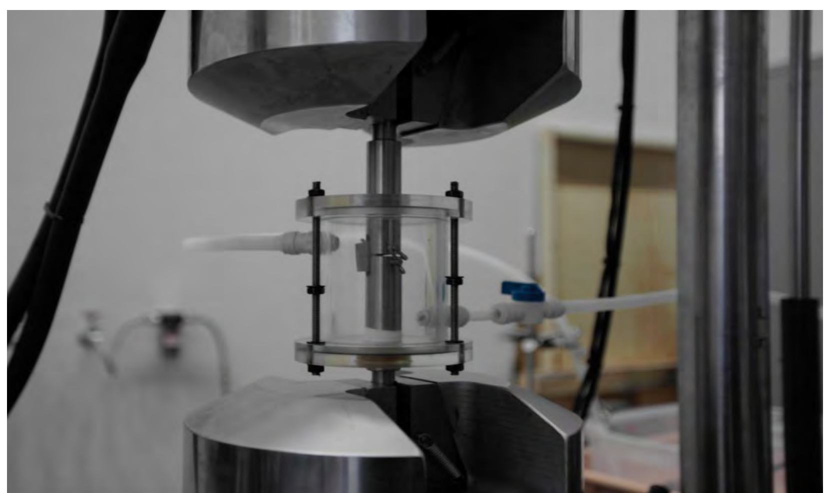
[Kenneth R. Trethewey; Materials & Design; Volume 29, Issue 2, 2008, Pages 501-507]

SCC Planned Tests

- Tests on statically loaded (stressed) smooth specimens

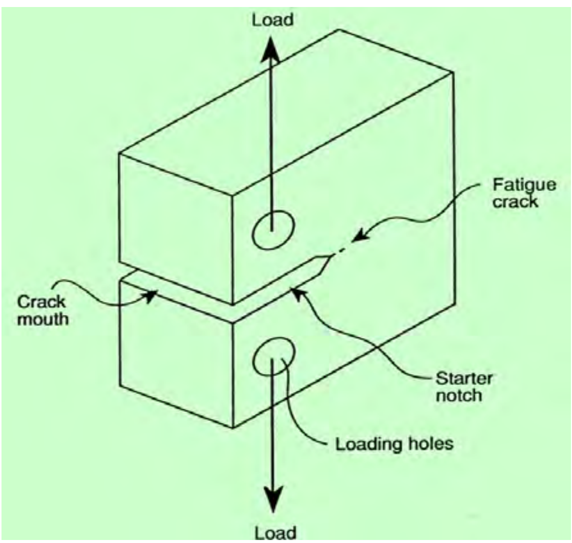




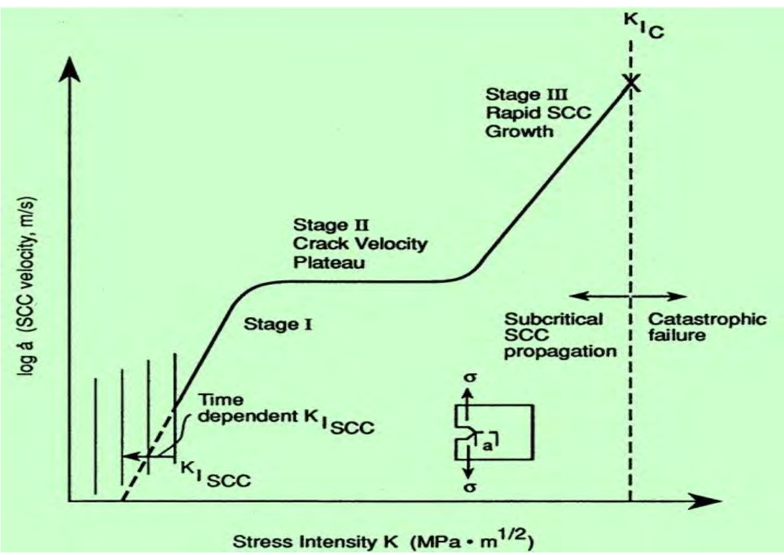


Planned Tests on statically loaded pre-cracked samples

- Fracture mechanics testing for SCC conducted with either :
  - a constant load or
  - with a fixed crack opening displacement,
- the *da/dt* is measured.
- The crack depth is determined as a function of time and the stress intensity.
- K_{1SCC} is the min. stress intensity below which SCC does not occur.



CT- specimen for fracture- mechanic-type testing where crack velocity vs. stress intensity is obtained



Schematic plot of data from fracture- fracture-type Testing. K_{ISCC} is shown to

Conclusions

- Reliability models for Corrosion-Fatigue has been developed, verified and demonstrated
- Pitting corrosion is nearly completed with models developed for pitting depth and density
- Literature search for creep models is completed, model developed and validation to follow
- SCC modeling will start in the future--Preliminary test planning is performed