Study for Improving and Generalization of Modeling of Stress Corrosion Cracking at Pressurized Water Reactors

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OUTLINE

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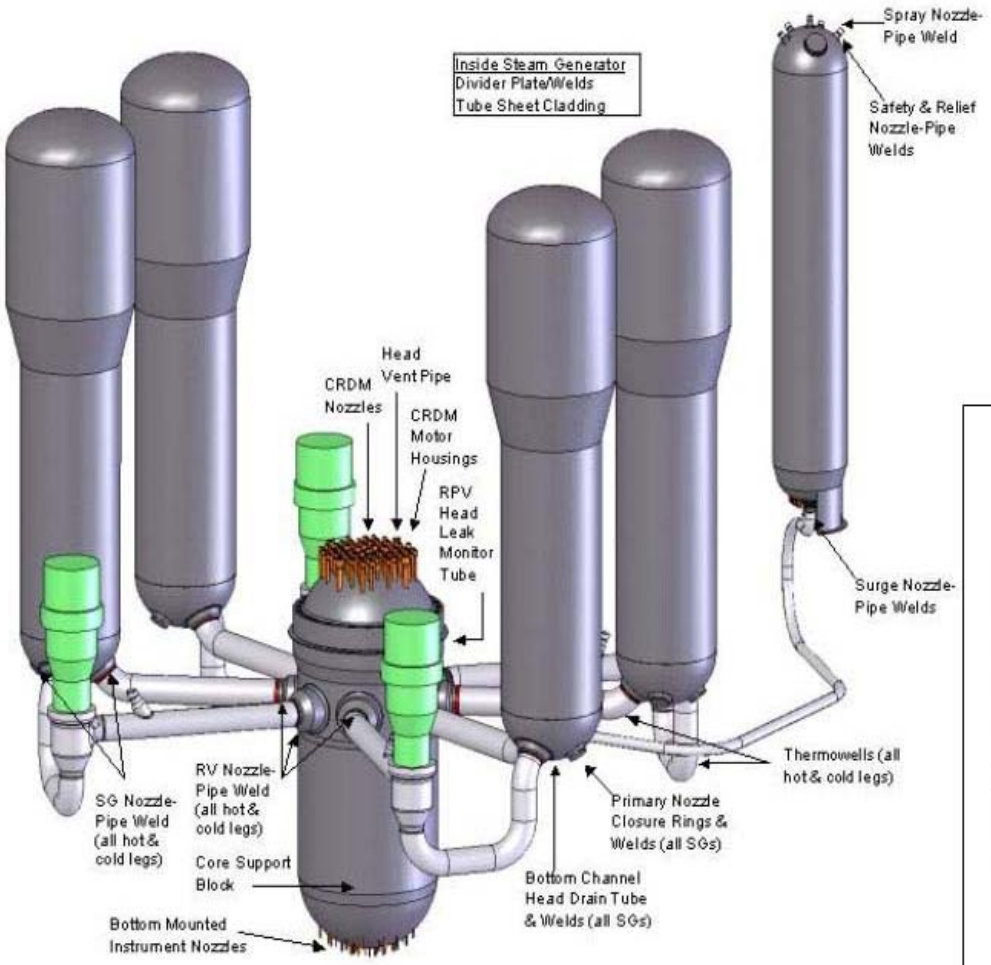
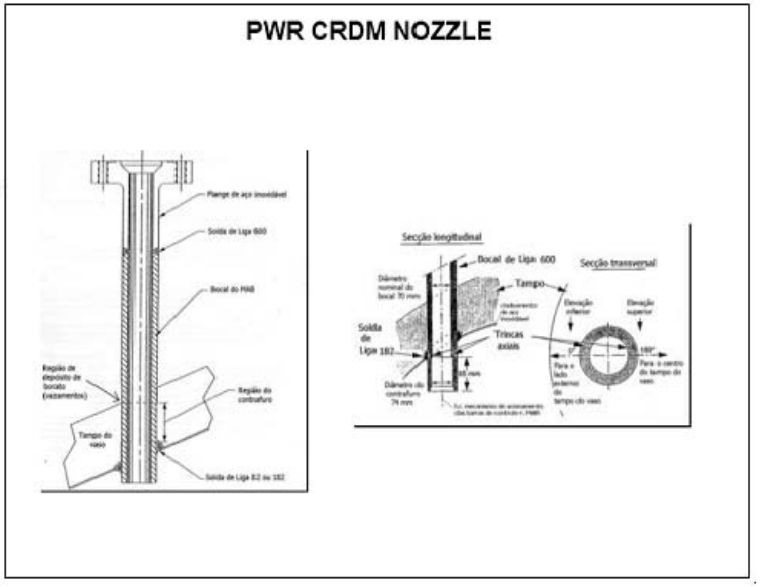
SUMMARY(1)

This research aims to improve and to generalize the results obtained in our doctorate thesis upheld at June 2006 on IPEN (Brazilian Energy and Nuclear Research Institute located at São Paulo), "Modeling of Primary Water Stress Corrosion Cracking at Control Rod Drive Mechanism Nozzles of Pressurized Water Reactors".

SUMMARY (2)


Spray Nozzle-Pipe Weld
Inside Steam Generator
Divider Plate/Welds
Tube Sheet Cladding
Safety & Relief Nozzle-Pipe Welds
Head Vent Pipe
CRDM Nozzles
CRDM Motor Housings
RPV Head Leak Monitor Tube
Surge Nozzle-Pipe Welds
Thermowells (all hot & cold legs)
RV Nozzle-Pipe Weld (all hot & cold legs)
SG Nozzle-Pipe Weld (all hot & cold legs)
Primary Nozzle Closure Rings & Welds (all SGs)
Core Support Block
Bottom Channel Head Drain Tube & Welds (all SGs)
Bottom Mounted Instrument Nozzles


PWR CRDM NOZZLE

SUMMARY (3)

The environmental assisted cracking study including those by stress corrosion, is one of the main fields of engineering and materials science since the 1940's. The structural materials degradation during operation, including that by stress corrosion, represents one of the main technical parameters which can restrain safety, reliability, and efficiency of plants, thermonuclear, thermal, petrochemical, and generally industrial.

SUMMARY (4)

It had been obtained some stress corrosion modelings in the referred thesis, and also to a methodology which allows to expanding, to improve, and to generalize these modelings. Thus it represents a contribuition which may be meaningful to industry, mainly in the field of equipments life extension.

SUMMARY (5)

This study is strongly interdisciplinary, involving Fracture Mechanics, Materials Science, Eletrochemistry, and others. It will be used basically tests realized through the Constant Extension Rate/Slow Strain Rate Testing machines (CERT/SSRT) installed in CDTN - Centro de Desenvolvimento da Tecnologia Nuclear (Brazilian Nuclear Technology Development Center).

SCC FACTORS

SCC nucleation and propagation are very complex phenomena. SCC is one modality of environment-assisted cracking (EAC) besides corrosion fatigue and hydrogen embrittlement, depending on several variables that can be classified in microstructural, mechanical, and environmental terms.

Microstructural variables are: (i) grain boundary microchemistry and segregation, **M**; (ii) thermal treatment, **TT**, that can cause intragranular and intergranular metallic carbide distribution; and (iii) grain size , **gs**, and cold work, **CW**, or plastic deformation. The second two variables fix another variable such as the yield stress, σ_{YS}.

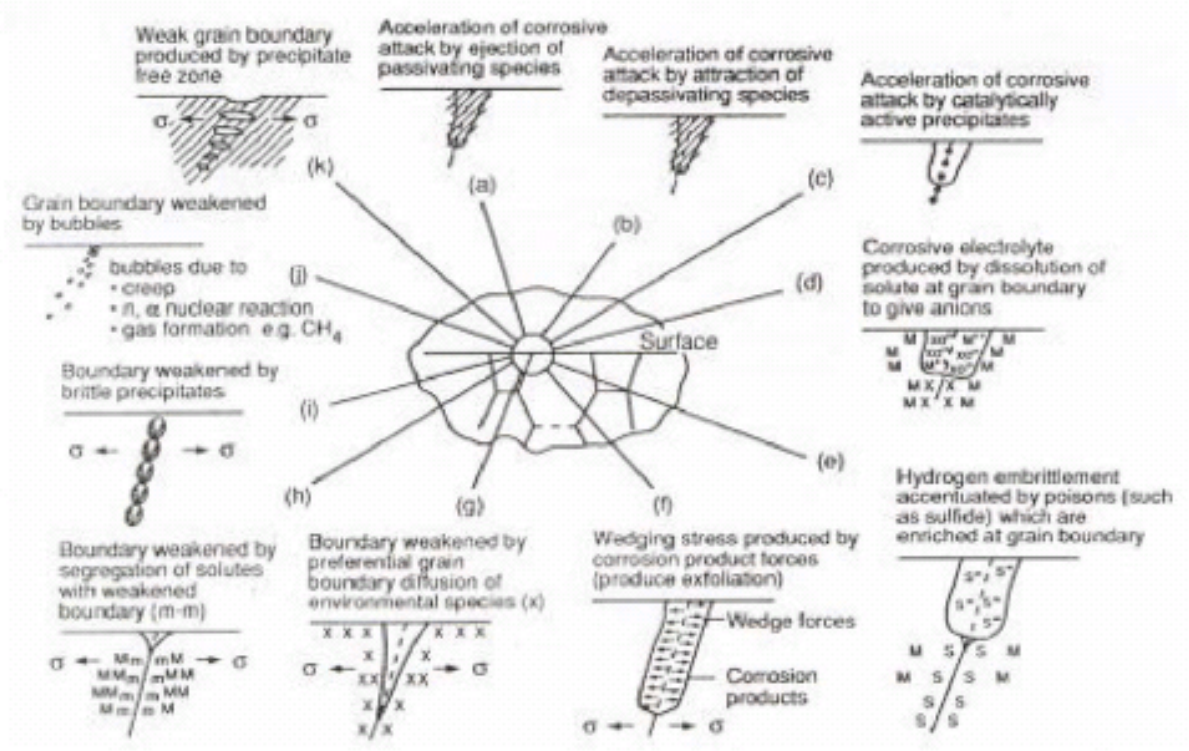
Mechanical variables are: (i) residual stress, σ_r; (ii) applied stress, σ_a (a tensile stress and geometry can be summarized as a stress intensity factor, K_I); and (iii) strain ε and strain rate $\dot{\varepsilon}$

Environmental variables include: (i) temperature, **T**; (ii) [H]+ or **pH**; (iii) solution or water chemistry, **SC**; (iv) inhibitors or pollutants in solution; (v) electrochemical potential, **V**; and (vi) partial pressure of hydrogen, p_{H2}.

Environmental cracking susceptibility can be expressed as:

$$\mathrm{SCC} = \mathrm{f}\,(\mathrm{M}, \mathrm{TT}, \mathrm{gs}, \mathrm{CW}, K_{\mathrm{I}}, \varepsilon, \dot{\varepsilon}, \mathrm{T}, \mathrm{pH}, \mathrm{SC}, V, p_{\mathrm{H2}})$$

SCC PROCESSES



The processes starting from (a) to (k) range from the mostly chemical to the mostly mechanical (from R.W. Staehle, Combining design and corrosion for predicting life, in: R.N. Parkins (Ed.), Life Prediction of Corrodible Structures, vol. 1, NACE International, Houston, 1994, pp. 138–291)

SCC PROCESSES

There are several processes by which above conditions at grain boundaries can be lead to SCC:

- Depassivation caused by film rupture
- Pitting starting SCC process
- Grain boundaries weakened by bubbles and creep
- Hydrogen embrittlement
- Others

Thus, there are several approaches to mathematically express these phenomena such as:

- The slip dissolution / film rupture model
- The enhanced surface mobility theory
- The coupled environment fracture model
- The internal oxidation mechanism
- Hydrogen induced cracking models

PWSCC MODELLING

Proposed Modelling

Based on a three-dimensional diagram that shows the thermodynamic conditions to occur the modes of PWSCC in Alloy 600.

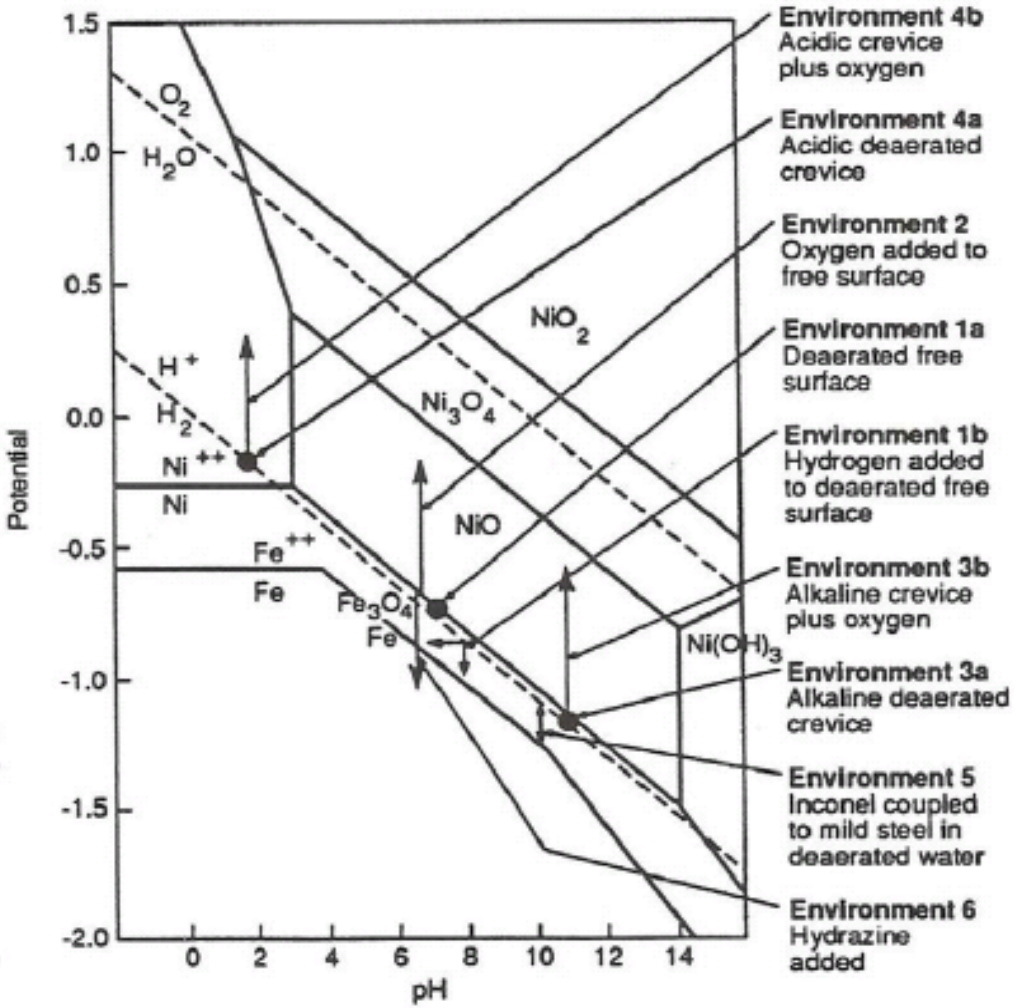
The base is a two-dimensional one, the potential x pH or Pourbaix diagram for this material in primary water at high temperature (300 to 350 °C).

Then, using literature experimental data, the corrosion submodes are superimposed over this diagram.

Submodes are determined by regions of potential where the different modes of surface material-environment interactions can occur, like stress corrosion, pitting, generalized corrosion or passivation.

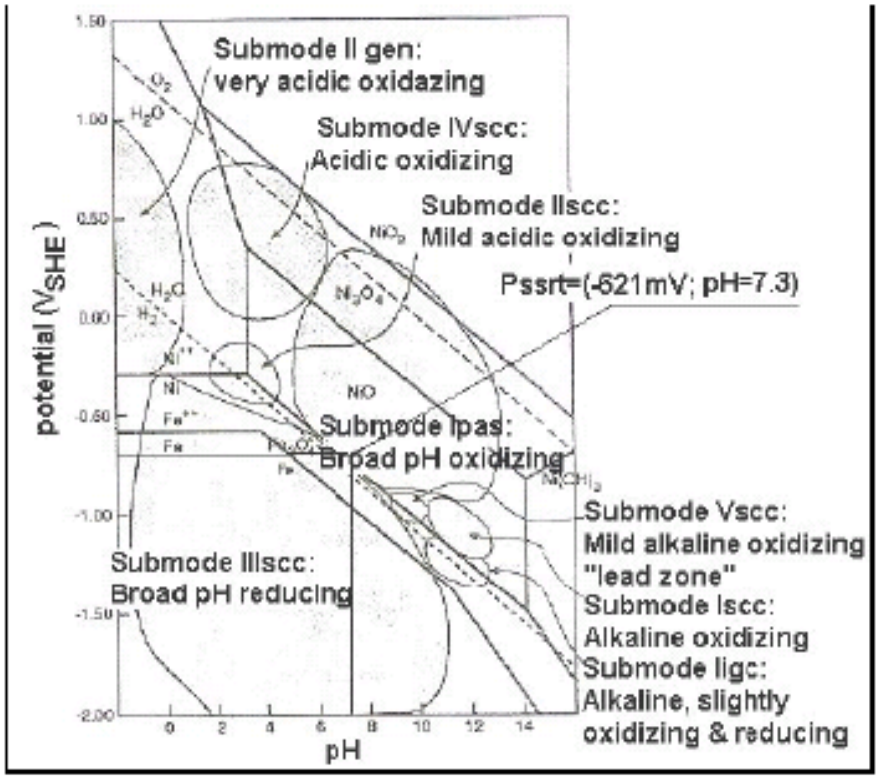
The third dimension is the “SCC useful strength fraction” of the material as affected by the environment at that point. This third variable could be replaced by another one such as crack velocity for the vertical coordinate, instead of the strength fraction because the data are sparse and the component testing with reference to this diagram used different methods of loading states and handling the data.

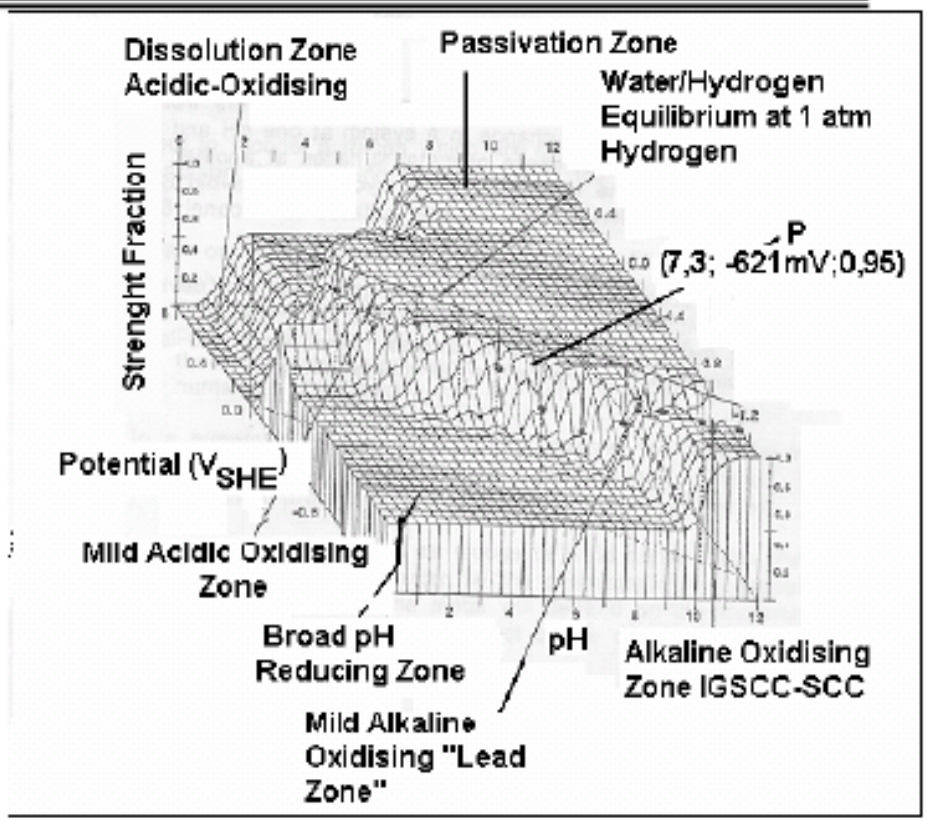
PWSCC POURBAIX DIAGRAM



Pourbaix diagram V × pH for Alloy 600 in the range of 300°C

PWSCC DIAGRAMS





Bidimensional diagram base, the Pourbaix pH x potential VSHE

Tridimensional diagram: PWSCC strength fraction x pH x potential VSHE

PWSCC MODELLING

It was chosen the following kinetic models to be composed with the referred potential x pH diagram:

- The semi-empirical–probabilistic
- The simplified strain rate damage model

1) Some results already presented at SCC Workshop, Vera Cruz, Mexico, 2008.

2) This presentation concerns the following research to extend and to improve SCC modelling methodology.

-New data from CDTN for Alloy 182.

-Methodology improvement includes: tests accuracy, screening data, a clear distinction between time to initiation and time to failure, to establish a fixed procedure to tests, evaluation of cracking growth rates, to introduce an auxiliary model to includes probabilistic uncertainty of inspections.

-Using and comparing new models

SEMI-EMPIRICAL–PROBABILISTIC MODEL

The semi-empirical–probabilistic follows the equations

$$t_f = A\, t_{ref} \left(\frac{\sigma}{\sigma_{ref}}\right)^n \exp\left[\left(\frac{Q}{R}\right)\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]$$

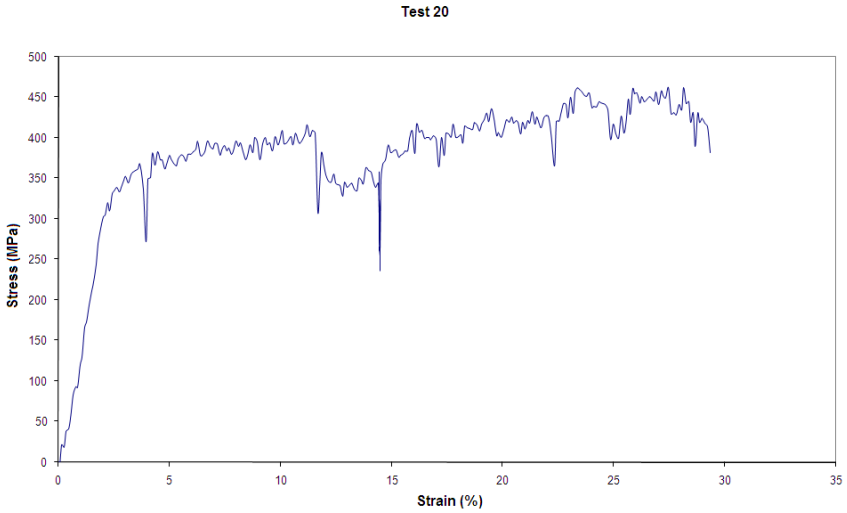
Where t_f = time to failure; A = non-dimensional material constant that reflects the effect of material properties on time to 1% PWSCC; σ = tensile stress; n = exponent of stress; t_{ref} = time to selected fraction of PWSCC for a reference case; σ_{ref} = reference value of stress; Q = thermal activation energy; T = absolute temperature; R = gas constant; T_{ref} = reference value of temperature.

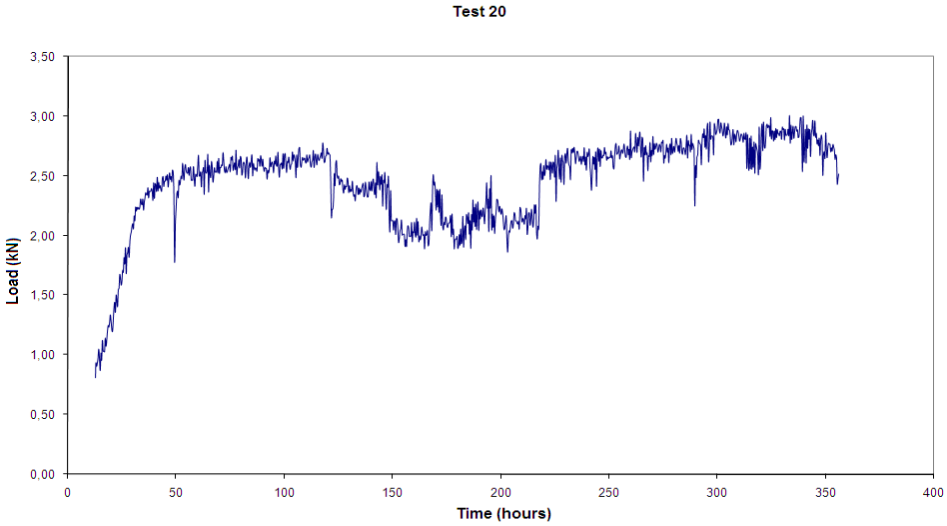
$$F = 1 - \exp\left[-0{,}0101\left(\frac{t}{t_{1\%}}\right)^b\right]$$

The two-parameter Weibull statistical distribution describes the variation of PWSCC as time function where F = fraction of population of components under consideration, all susceptible to the same failure mode that experiences PWSCC; t = time normally given in Effective Full Power Years (EFPY); b = Weibull slope, a fitted parameter determined by analysis of failure data

The value of t_{ref}, together with an appropriate value for the Weibull slope *b*, determines the complete prediction for PWSCC as time function.

EXPERIMENTAL DATA





Alloy 182 specimen stress - strain curve.

SSRT at 303ºC and 10 MPa.

Initial strain rate of 3.0 x 10^{-7} s^{-1}

Alloy 182 specimen load-time curve.

SSRT at 303ºC and 10 MPa.

Initial strain rate of 3.0 x 10^{-7} s^{-1}

RESULTS (EXTRACT)

Concerning the Simplified Strain Rate Damage Model **for Alloy 182**

From the average between the tests results

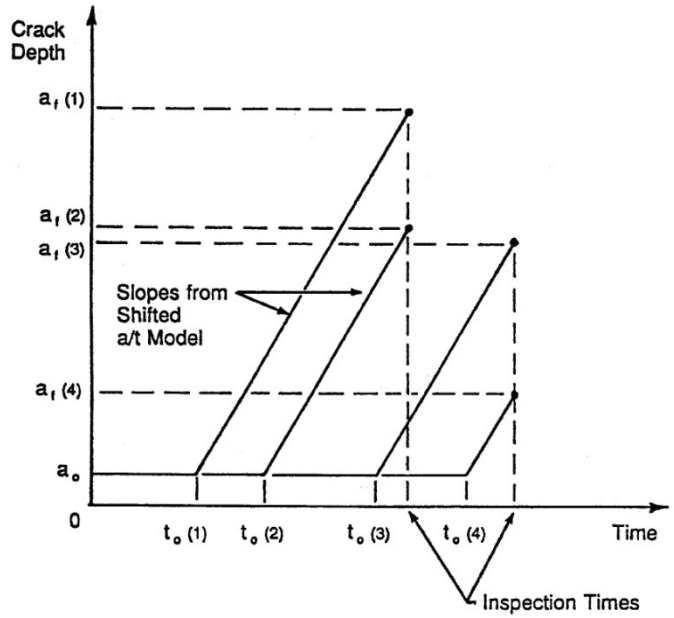
$$t_i^{A182} = 92176093{,}62 \cdot \sigma^{-7} \cdot \exp(15601{,}41/T)$$

with t_i = initiation time in days; σ= stress in MPa and T=absolute temperature in K. (Other non experimental values were collected from the literature)

METHODOLOGY IMPROVEMENTS

-Methodology improvement includes: tests accuracy, screening data, a clear distinction between time to initiation and time to failure, to establish a fixed procedure to tests, evaluation of cracking growth rates, to introduce an auxiliary model to includes probabilistic uncertainty of inspections.

METHODOLOGY IMPROVEMENTS



(EXAMPLE)

Schematic procedure to estimate time to initiation. From Pathania et al [8].

$$t_0 = t_f - (a_f - a_0)/(a/t)$$

with: t_0 = initiation time, t_f = failure time a_f = crack length at failure time, a_0 = crack length at initiation time, a/t= average rate of estimating crack growth considering standard deviation $+2S_e$.

CONCLUSIONS

It is possible to use SSRT to extend modelling of Ni-Alloys (A600 to A182) PWSCC, departing from selected models like the semi-empirical-probabilistic.

The use of Pourbaix diagram (potential x pH) may be used to determine the thermodynamics conditions to occur various corrosion submodes, combined with kinetic models of crack initiation and growth.

This has the potential advantages to do better predictions of the very complex PWSCC, and also to give a research methodology for this kind of cracking.

It is necessary to do more tests to confirm obtained results and to improve modelling.

It is necessary to improve methodology according exposed issues.