ON THE MODELING OF PRIMARY WATER STRESS CORROSION CRACKING AT CONTROL ROD DRIVE MECHANISM NOZZLES OF PRESSURIZED WATER REACTORS

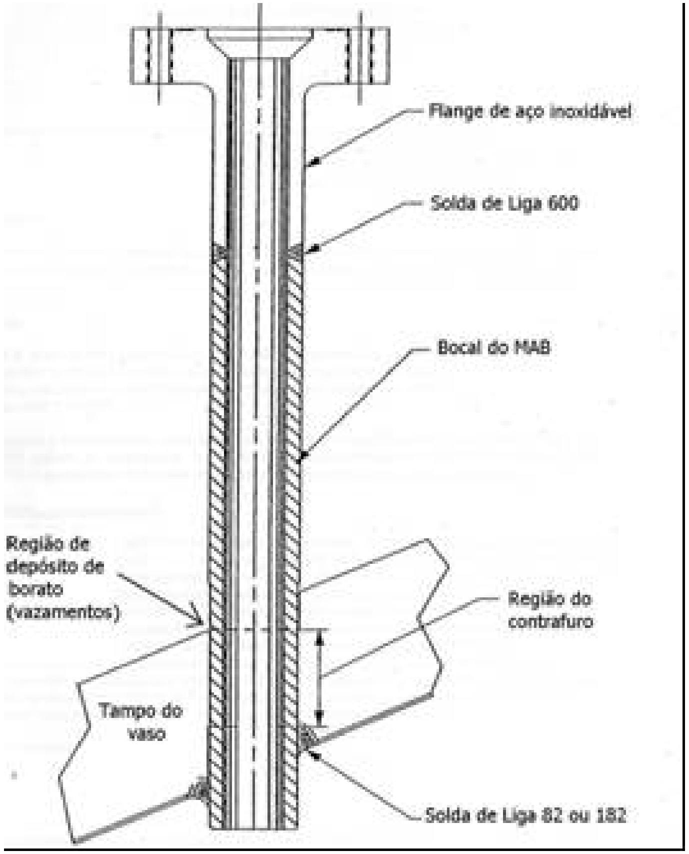
Omar F. Aly[1]
Arnaldo H.P. de Andrade[1]
Miguel Mattar Neto[1]
Mônica M.A.M. Schvartzman[2]

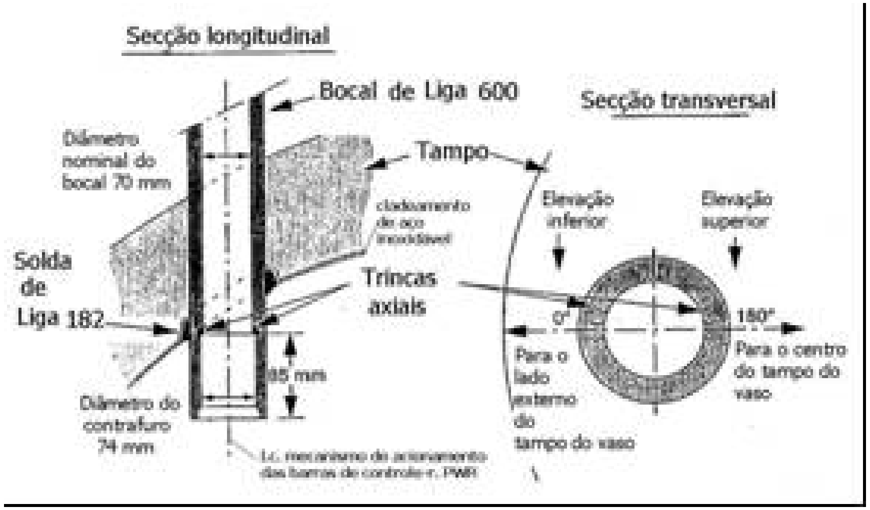
[1] CNEN-IPEN/SP - Nuclear and Energy Research Institute
[2] CNEN-CDTN/MG - Center of Nuclear Technology Development

OUTLINE

PWR CRDM NOZZLE
SCC FACTORS
SCC PROCESSES
PWSCC DIAGRAMS
PWSCC MODELLING
PWSCC POURBAIX DIAGRAM
SEMI-EMPIRICAL–PROBABILISTIC MODEL
SIMPLIFIED STRAIN RATE DAMAGE MODEL
EXPERIMENTAL DATA
RESULTS
CONCLUSIONS

PWR CRDM NOZZLE





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, $\boldsymbol{\sigma}_{YS}$.

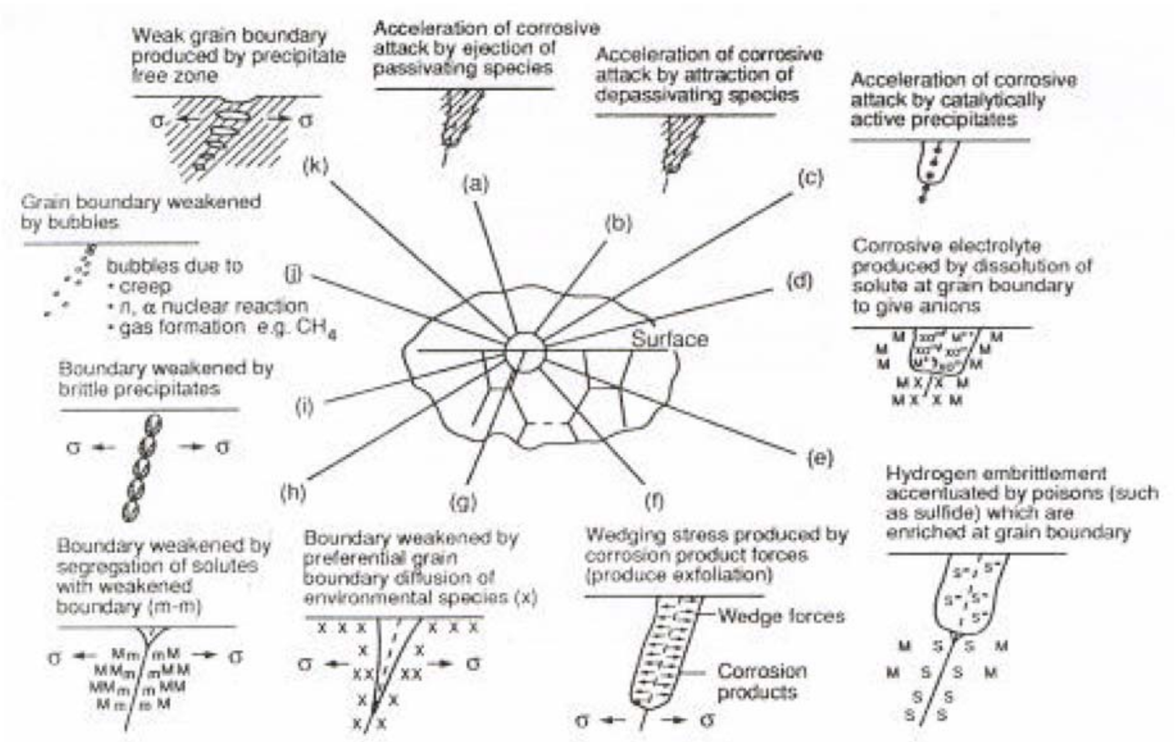
Mechanical variables are: (i) residual stress, $\boldsymbol{\sigma}_r$; (ii) applied stress, $\boldsymbol{\sigma}_a$ (a tensile stress and geometry can be summarized as a stress intensity factor, K_I); and (iii) strain $\boldsymbol{\varepsilon}$ and strain rate $\dot{\varepsilon}$

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

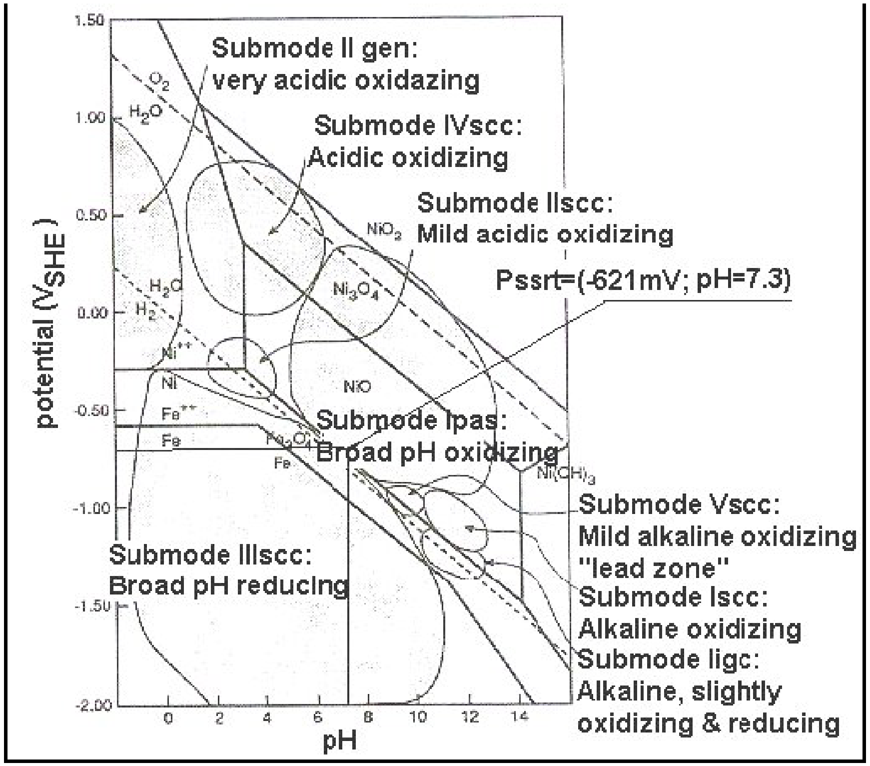
There are several processes by which above conditions at grain boundaries can be lead to SCC:

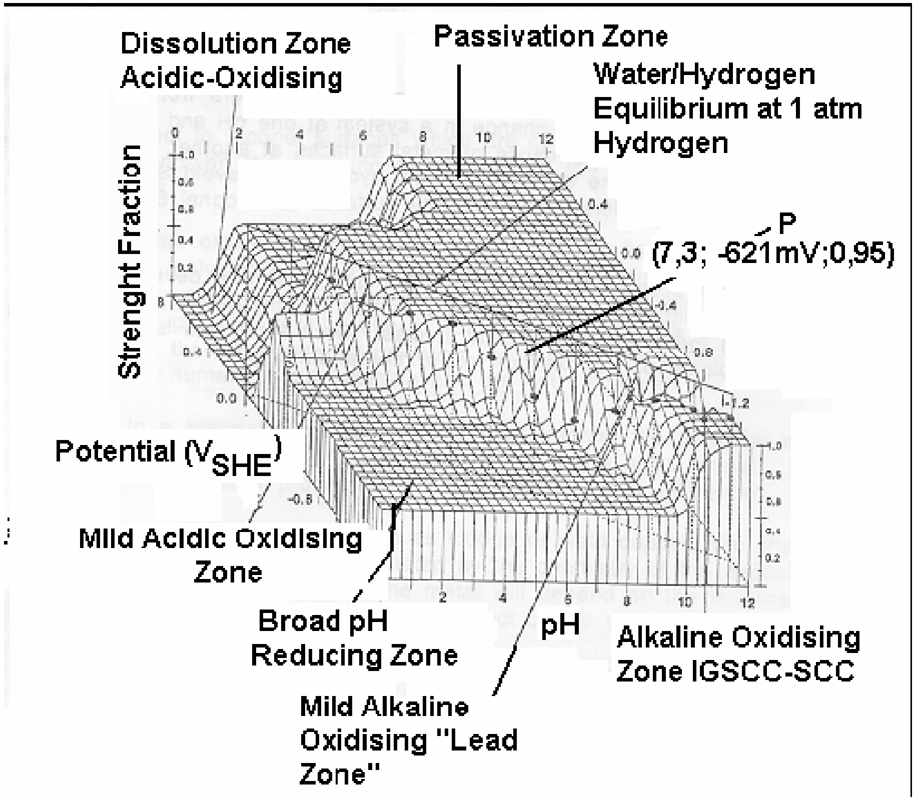
- Depassivation caused by film rupture
- Pitting starting SCC process
- Grain boundaries weakened by bubbles and creep
- Hydrogen embrittlement
- Others

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 DIAGRAMS

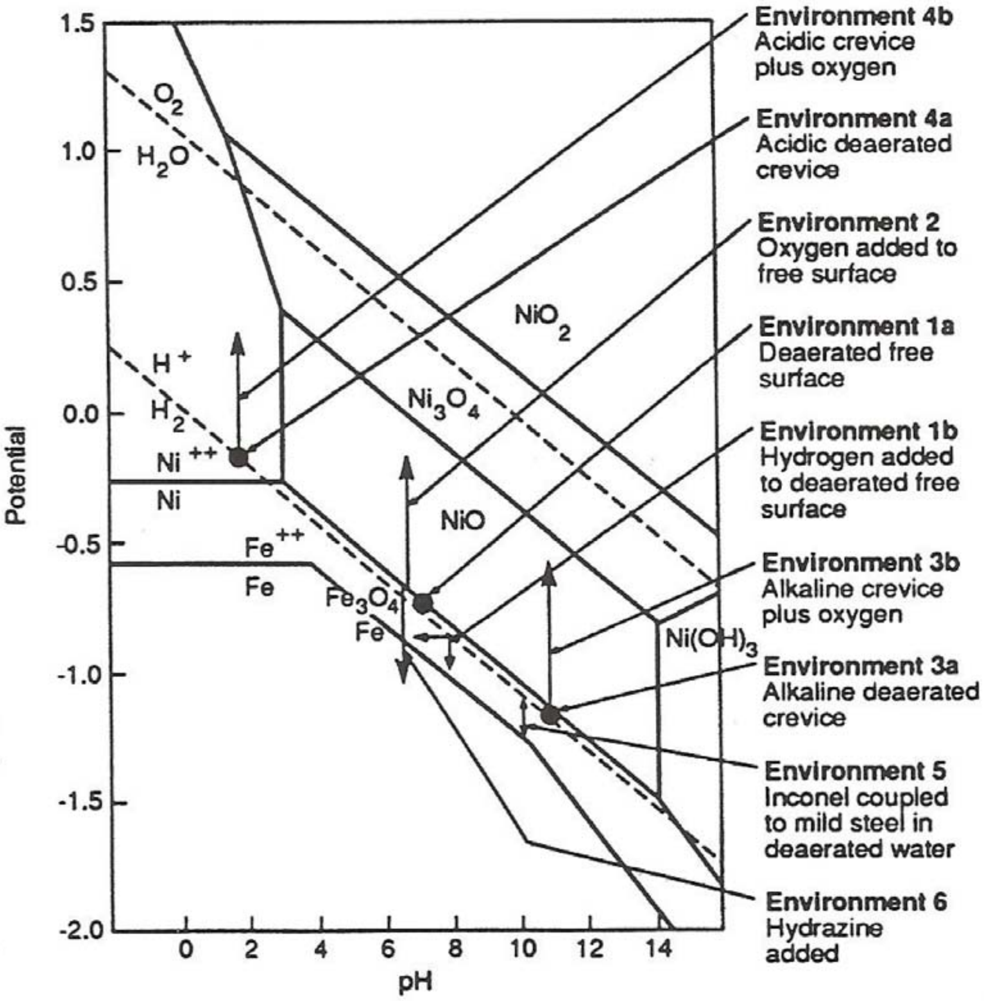




Bidimensional diagram base, the Pourbaix pH x potential VSHE

Tridimensional diagram: PWSCC strength fraction x pH x potential VSHE

PWSCC POURBAIX DIAGRAM



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

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 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

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.

STRAIN RATE DAMAGE MODEL

The strain rate damage model is essentially a semi-empirical model theory of stress corrosion cracking, where strain rate rather than stress is considered to be the main mechanical variable.

Strain rate is the driving force to initiate and propagate the crack. The main parameter of this model is the damage parameter *D* defined by

$$D = \int_0^t A[\dot{e}(t)]^p . dt$$

Where t = time; $\dot{e}(t)$ = total strain rate; A and p = parameters, which depend on material–environment combination.

The strain rate is the driving factor in the damage model that allows quantitative predictions on serviceable life that depends on SCC. A damage function is defined as linked mode to a component submitted to a strain rate history. When this damage function reaches a critical value, the SCC is predicted. The critical value of this damage function depends on the concerned material and environment.

SIMPLIFIED STRAIN RATE DAMAGE MODEL

Concerning the Strain Rate Damage Model, there is a simplified one relating the initiation time of the crack with material activation energy and the material yield strength/ tensile strength ratio, developed to best describe the predictions based on the results of simulation of tube under uniform axial stress, σ, for time to initiation. The failure of a thin-wall tube is reached on time t_i according with

$$t_i = \alpha_i \exp (Q_i /RT).\ln[A(\sigma_y/\sigma)]$$

where t_i =initiation time, α_i = SCC resistance parameter (dimension of time); Q_i = apparent activation energy; R=universal gas constant (1,987 cal/mol); T= absolute temperature in K; A= parameter depending on material environment interaction; σ_{YS}=yield strenght of material at room temperature and σ = uniform axial stress.

These parameters were found for four conditions of Alloy 600: low temperature mill annealed, high temperature mill annealed, thermally treated at about 7100C and cold worked.

This model is based on assumption of a localized break of passivation film following with repassivation, and interacting with local strain that through the strain rate increases the SCC damage.

EXPERIMENTAL DATA

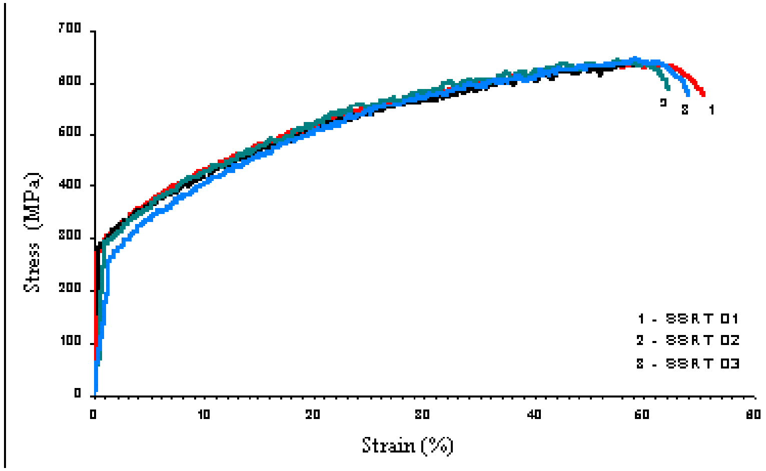
The used experimental data to calibration and check the models were obtained from CDTN through SSRT (Slow Strain Rate Tests)

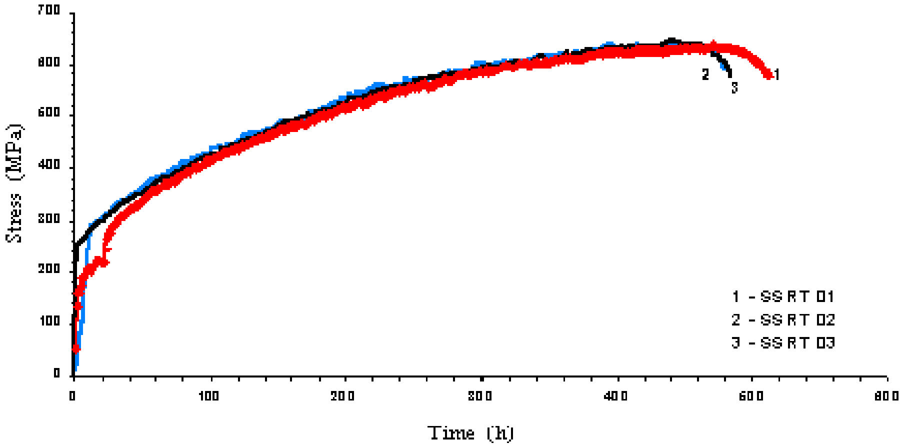
In the slow strain rate test (SSRT) it is imposed to the specimen a slow strain rate through external force over a monitored section, or over a notched region of this specimen, or over a fatigue pre-cracked for SCC material resistance assessment. The imposed slow strain rate is normally between 10^{-4} and 10^{-7} s^{-1}. The local strain rate should be slow enough to make time to occur corrosion processes, and quick enough to cause cracks or damage in a specimen during a reasonable time

Not pre-cracked Alloy 600 MA specimens were used

The tests were conducted according the standard ASTM G-129-00. Three tests were performed with strain rate $\dot{e}= 3.\ 10^{-7}\ s^{-1}$, velocity $v_T= 33$ μm/h, one of them in neutral environment (N_2).

EXPERIMENTAL DATA





Alloy 600 MA specimens stress-strain curves. SSRT 01 (neutral environment of N_2), SSRT 02 and 03 (PW environment at 303 ºC and 10 MPa). Initial strain rate of $3{,}0\times10^{-7}s^{-1}$

Alloy 600 MA specimens stress-time curves. SSRT 01 (neutral environment of N_2), SSRT 02 and 03 (PW environment at 303 ºC and 10 MPa). Initial strain rate of $3{,}0\times10^{-7}s^{-1}$

RESULTS

Concerning the Semi-Empirical-Probabilistic Model

Based on experimental results (initiation time of 482.4 h, and 494.4 h, in two tests with primary water environment) the empirical part of the model was obtained.

From the average between the tests results

$$t_i = 1{,}45.\ 10^{-13}.\ \sigma^{-4}.\ \exp\ (32882{,}35/T)$$

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)

RESULTS

Concerning the Simplified Strain Rate Damage Model

From the average between the tests results

$$t_i = 4{,}88.\ 10^{-23}.\ \exp\ (32822,\ 35/T).\ \ln\ [1{,}79\ (278{,}5/\sigma)]$$

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)

CONCLUSIONS

It is possible to use SSRT to model Alloy 600 PWSCC, departing from some selected models: semi-empirical-probabilistic (only the deterministic part) and simplified strain rate damage,

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.