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PRELIMINARY STUDY FOR EXTENSION AND IMPROVEMENT ON MODELING OF PRIMARY WATER STRESS CORROSION CRACKING AT CONTROL ROD DRIVE MECHANISM NOZZLES OF PRESSURIZED WATER REACTORS

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ABSTRACT

This study is for to extend, to improve the existing models, and to propose a local approach to assess the primary water stress corrosion cracking in nickel-based components. It is includes a modeling of new data for Alloy 182 and new considerations about initiation and crack growth according a developing method based on EPRI-MRP-115 (2004), and USNRC NUREG/CR-6964 (2008). The experimental data is obtained from CDTN-Brazilian Nuclear Technology Development Center, by tests through slow strain rate test (SSRT) equipments.

The model conception assumed is a built diagram which indicates a thermodynamic condition for the occurrence of corrosion submodes in essayed materials, through Pourbaix diagrams, for Nickel Alloys in high temperature primary water. Over them, are superimposed different models, including a semi-empiric-probabilistic one to quantify the primary water stress corrosion cracking susceptibility, and a crack growth model. These constructed models shall be validated with the experimental data.

This development aims to extent some of the models obtained to weld metals like the Alloy 182, and to improve the originals obtained according methodologies exposed in above referred reports. These methodologies comprise laboratory testing procedures, data collecting, data screening, modeling procedures, assembling of data from some laboratories in the world, plotting of results, compared analysis and discussion of these results. Preliminary results for Alloy 182 will be presented.

1. INTRODUCTION

One of the main failure mechanisms that cause risks to pressurized water reactors (PWR) is the primary water stress corrosion cracking (PWSCC) occurring in nickel superalloys materials like the Alloy 600 (75Ni-15Cr-9Fe), or weld material Alloy 182 (67Ni-15Cr-8Fe). It can be located, besides other places, at the control rod drive mechanism (CRDM) nozzles. It is caused by the joint effect of tensile stress, temperature, susceptible metallurgical microstructure, and environmental conditions of the primary water. These cracks can cause problems that reduce nuclear safety by blocking the displacement of the control rods, and may cause leakage of primary water that requires repair or replacement of the reactor pressure vessel head.

In an earlier work, concerning a Doctoring Thesis, it was performed a study of the existing models and proposed a new approach to assess the PWSCC in nickel-based Alloy 600 CRDM nozzles. The proposed model is obtained from the superimposition of electrochemical and fracture mechanics models, and validated using experimental and literature data. The experimental data were obtained from CDTN-Brazilian Nuclear Technology Development Center, in SSRT equipments [1],[2].

This study aims to extend some obtained models to weld metals like the Alloy 182, and to improve the originals for Alloy 600, according with a revised methodology. It is includes a modeling proposal for new data for Alloy 182 and Alloy 600 initiation and crack growth, according with a method based on Electric Power Research Institute-MRP-115 [3], and United States National Regulatory Comission-NUREG/CR-6964 [4]. The new experimental data also will be obtained from CDTN.

In this paper is presented an improved methodology for modeling of Alloy 182, and Alloy 600 data.

2. METHODOLOGY

Most of the western PWR have CRDM penetration in the pressure vessel head made of stainless steel and Alloy 600. Its nominal composition is in Table 1. The yield strength of this material varies between 213 and 517 MPa. Normally this material is mill annealed at 885^{0}C, final anneal for 4 to 6 hours followed by air cooling. Nevertheless this treatment could to be subject to vary, depending of vendors. This material works with some variation at 315^{0}C and 15.5 MPa in pure water. PWSCC appears in the lower part of each nozzle which is fabricated in Alloy 600 and welded to the internal vessel head surface with dissimilar material Alloy 182 (Table 1). There are typically 40 to 90 penetrations per vessel that may include some spare penetrations which are not fitted with CRDM or through core instrumentation of PWR [1].

Table 1. Main chemical composition (weight %) of nickel alloys [2], [3]

Alloy	Ni %	Cr %	Fe %	Mn %	Nb %	Ti %
182	67.0	15.0	8.0	7.0	1.8	0.5
600	75.0	15.6	8.8	0.2	0.2	0.2

The result of the earlier work, based on CDTN data, has generated four distincts modelings [1], [2]. One of these is showed in Figure 1, and Eq. (1): it is a semi-empirical one, with only a deterministic part, and superimposed at point P_{ssrt} [1], [2].

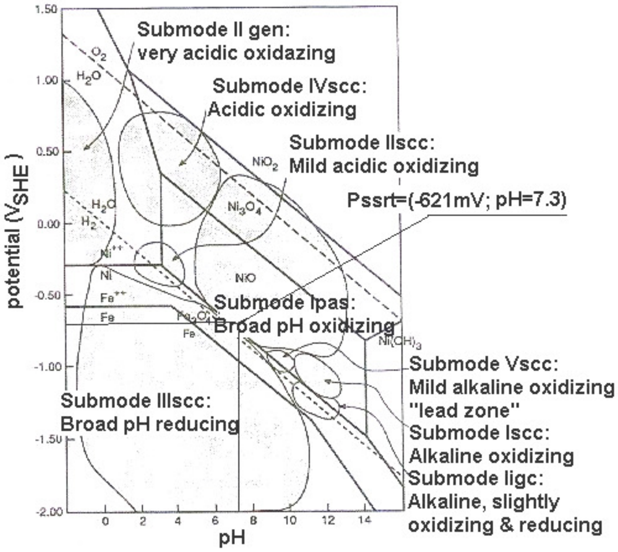

Figure 1. (a) Bi-dimensional diagram base, the Pourbaix pH x potential V_{SHE}; point marked P_{ssrt} was obtained through CDTN tests: V=-621mV; pH=7.3. Based diagram marked with corrosion submodes is from reference [5]. From Aly et al. [2]

$$t_i = 1.45.\ 10^{-13}.\ \sigma^{-4}.\ \exp\ (32882.35/T) \qquad (1)$$

with t_i = initiation time in days; σ= stress in MPa and T=absolute temperature in K; the not experimental parameters of modeling were taken off reference [6].

The study considered in this paper is for to extend the existing modeling for Alloy 600 to other nickel superalloys, like Alloy 182, and to propose a local approach to assess the primary water stress corrosion cracking in nickel-based components. It is includes a modeling proposal for new data for Alloy 182 and Alloy 600 initiation and crack growth. For this study, the same method will be used, but it needs data concerning Alloy 182, more data concerning Alloy 600, and also a reviewed methodology.

3. REVIEWED PROPOSED METHODOLOGY

The first methodology stage is to improve tests accuracy through rigorously classify them in about 50 -100 “microprocesses” of stress corrosion according Staehle [7]: in Figure 2 is showed the main necessary parameters to be found, before the tests initiation. A proper formulary can be used to help this identification.

The second methodology stage is to screen the tests data, according with a criterion suggested in MRP-115 [3]. In Table 2 is showed some factors to screening data.

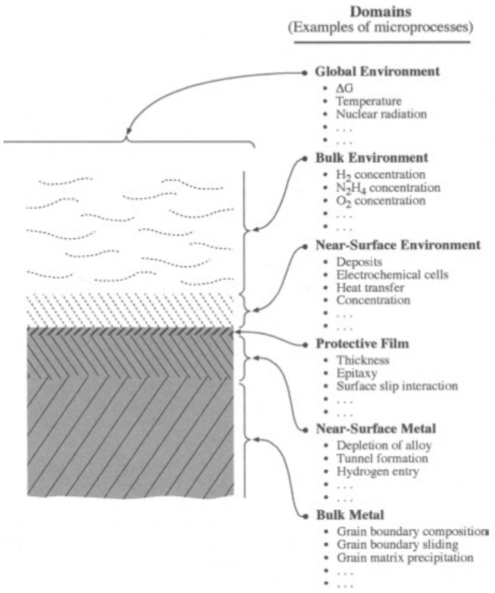

Figure 2. Scheme of six domains for quantifying microprocesses relating to the continuity from a global environment through the bulk metal: examples of these are indicated. From Staehle[7].

Table 2. Key factors for consideration in tests and data reporting. Extract from [3].

1	Material within specifications including composition/condition/heat treatment
2	Mechanical strength properties
3	ASTM specimen size criteria and degree of plastic constraint
4	Pre-cracking technique (including straightness criteria, plastic zone size, crack morphology)
5	Special requirements for testing welds (e.g. pre-crack location, residual stresses/strains)
6	Environment (chemistry, temperature, electrochemical potential (ECP), flow rate at specimen, neutron/gamma flux)
7	Loop configuration (e.g., once-through, refreshed, static autoclave)
8	Water chemistry confirmation by analysis (e.g., Cl, SO_4, O_2, Cr, total organic carbon (TOC), conductivity)
9	Active constant or cyclic loading versus constant displacement loading (e.g., using wedge)
10	On-line measurement of crack length versus time during test (including precision)
11	Actual crack length confirmed by destructive examination (assessment method/mapping)
12	Appropriateness of crack characteristics (fraction SCC along crack front, uniformity, adequate SCC increment, transgranular portions within IGSCC fracture surface, etc.)
13	Possible effects of changes in loading or chemistry conditions during a test (including heat up and cool down)
14	Calculation and reporting of K or ΔK values

The third methodology stage is to establish a clear distinction between time to initiation and time to failure, an important stage seldom treated in literature. Pathania et al [8] present a method to distinct them according a linear Eq. (2).

$$t_0 = t_f - (a_f - a_0)/(a/t) \qquad (2)$$

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 $+2S_e$.

The initiation time t_0 is considering for $a_0=20\mu m$, that according with authors is the minimum crack lenght to distinguish between intergranular attack and SCC. Another authors consider $a_0=10\mu m$. In Figure 3 is showed a schematic procedure to estimate time to initiation.

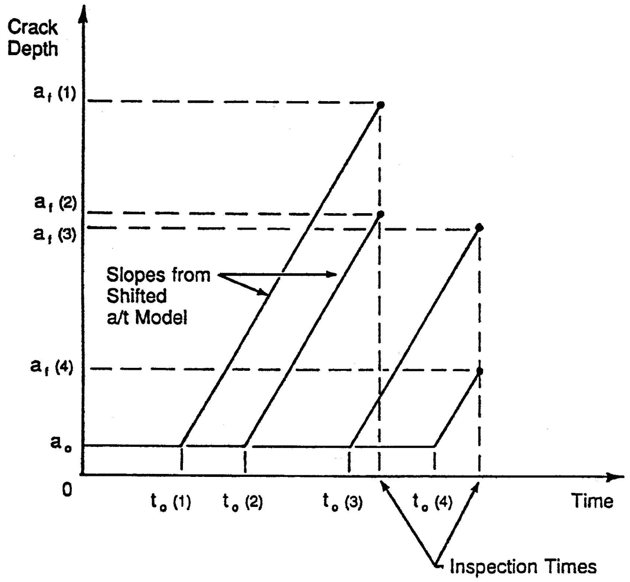

Figure 3. Schematic procedure to estimate time to initiation. From Pathania et al [8].

The fourth methodology stage is to establish a fixed procedure to tests, not only concerning SSRT, but looking at details like using the same type of specimen uniformly manufacturated (specially important in the case of Alloy 182 welded specimens because the scattering data tendency due to factors like weld dendrites structures with different directions, welding procedures inequalities, and so on), to test enough specimen number, to allow statistic regression (e.g. according Weibull distribution, minimum recommended number in each test in the same conditions is 7). Another point is to research enough literature data in case of scarce data as for time to initiation of Alloy 182.

The fifth methodology stage is to establish a procedure to tests for evaluation of crack growth rates, both for Alloy 600, and Alloy 182. The basic guideline for this stage is available on the work by Alexandreanu et al. [4]: it presents very completely the test facilities, test procedure, analysis of crack growth rate data, microstructural characterization of specimens, determination of values and discussion of activation energy for SCC crack growth, cycling effects and fatigue superimposed with SCC, and practical results like Davis Besse and V.C.Summer Nuclear Power Plants specimen analysis. It follows, as example, some interesting points of this work, a true guideline for crack growth rate tests:

a) For Alloy 600, SCC crack growth rate (m/s) is done by White, Hickling, and Mathews equation (Eq. 3).

$$\dot{a}_{A600} = \alpha \exp\left[-\frac{Q}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right](K-K_{th})^{\beta} \qquad (3)$$

with: Q = activation energy for crack growth =130 kJ/mole, R = universal gas constant = 8.314 x 10^{-3} kJ/mole K, T = absolute operating temperature (K), T_{ref} = absolute reference temperature used to normalize crack growth rate data = 598K, α= crack growth amplitude (2.67 x 10^{-12} at 325°C), K = crack tip stress intensity factor (MPa.$m^{1/2}$), K_{th} = crack tip stress intensity factor threshold (9 MPa.$m^{1/2}$) and β = exponent 1.16.

b) For Nickel Alloys welds, like Alloy 182, Eq. (3) has been modified to Eq. (4). It shall be noted that for these alloys, there is not crack tip stress intensity factor threshold.

$$\dot{a}_{Ni-weld} = \alpha \exp\left[-\frac{Q}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]K^{\beta} \qquad (4)$$

with Q, R, T, and T_{ref} the same as Eq. 3; α= crack growth amplitude (1.5 x 10^{-12} at 325°C), and β = exponent 1.6.

The sixth methodology stage is to introduce an auxiliary model, besides the main model of stress corrosion cracking initiation and/or propagation, to consider on final results, the probabilistic uncertainty on inspection techniques, like to evaluate properly the found cracking length: the available procedures and models are contained in reference [9].

4. SOME PRELIMINARY RESULTS

Some preliminary results, based on CDTN data and additional references [10],[11] and using original methodology, was obtained for a semi-empirical model for Alloy 182. The model is according Eq. (5), and is being evaluate. In the report [11] is detailed the general used methodology, data deviation between tests and model, an essay to probabilistic evaluation, and another details.

$$\mathbf{t_i^{A182} = 92176093{,}62.\ \sigma^{-7}.\ exp(15601{,}41/T)} \qquad (5)$$

with t_i = initiation time in days; σ= stress in MPa and T=absolute temperature in K; the not experimental parameters of modeling were taken off reference [10] and others in reference [11].

5. CONCLUSIONS

According with the points explained in this paper, and based on our previous experience, it can be possible to outline an own improved and extended methodology for modeling of primary water stress corrosion cracking at control rod drive mechanism nozzles of pressurized water reactors, adjusted to our actual laboratories, and work facilities. Preliminary results are concerning the extending of stress corrosion cracking initiation model for Alloy 182, and is being evaluated. Also, the reviewed proposed methodology shall be implanted.

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