PVP-Vol. 241

FATIGUE, FRACTURE, AND RISK

— 1992 —

EDITED BY
W. H. BAMFORD
H. MEHTA
B. A. BISHOP
J. H. PHILLIPS
F. W. BRUST

PVP-Vol. 241

FATIGUE, FRACTURE, AND RISK
– 1992 –

presented at
THE 1992 PRESSURE VESSELS AND PIPING CONFERENCE
NEW ORLEANS, LOUISIANA
JUNE 21–25, 1992

sponsored by
THE PRESSURE VESSELS AND PIPING DIVISION, ASME

principal editor
W. H. BAMFORD
WESTINGHOUSE ENERGY SYSTEMS

contributing editors
H. MEHTA
GENERAL ELECTRIC NUCLEAR ENERGY
B. A. BISHOP
WESTINGHOUSE ENERGY SYSTEMS
J. H. PHILLIPS
EG&G IDAHO
F.W. BRUST
BATELLE COLUMBUS LABORATORIES

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 East 47th Street ○ ○ United Engineering Center ○ ○ New York, N.Y. 10017

ISBN No. 0-7918-0782-7

Library of Congress
Catalog Number 91-55428

FOREWORD

Environmental effects are an important element in assessing the fitness for service of nuclear power plant components. Such effects may be accounted for at the design stage in the ASME Code fatigue analysis, and during the component service, when inspection may reveal cracking, by a fracture mechanics based evaluation.

Three papers presented in this section treat different aspects of the environmental effects; "A Review and Further Applications of the Incremental Damage Approach for SCC Assessments," addresses the development and application of incremental damage approach to steam generator tubing. "Use of Fundamental Modeling of Environmental Cracking for Improved Design and Lifetime Evaluation," describes the application of slip dissolution/film rupture model for environmentally assisted crack growth to stainless steels, nickel alloys, and low alloy steels in high temperature water systems. "An Environmental Fatigue Stress Rule for Carbon Steel Reactor Piping," reports on a proposed method to account for the environmental effects in the ASME Code stress analysis.

H. S. Mehta

CONTENTS

PVP-Vol. 241, Fatigue, Fracture, and Risk
ASME 1992

A REVIEW AND FURTHER APPLICATIONS OF THE INCREMENTAL DAMAGE APPROACH FOR SCC ASSESSMENTS

Y. S. Garud
S. Levy Incorporated
Campbell, California

ABSTRACT

*Stress corrosion cracking (SCC) of normally ductile materials under aqueous environments continues to be a dominant mechanism of degradation of many load-bearing components in the existing power generation systems. SCC has also been identified as the primary (life-limiting) mode of failure in a number of key components critical to the success of plant life extension programs. In an effort to provide a critical and quantitative assessment of this degradation mechanism the author had recently developed and applied a new in*cremental damage approach *which offers some unique and alternative prediction capabilities.*

The approach explicitly accounts for the material creep deformation and its interaction with the extent and growth rate of SCC. An arbitrary definition of crack initiation *is not needed since the approach does not require that the initiation and propagation phases be treated separately; nor is it a requirement that a crack-like defect should exist for SCC to occur. The predictive capabilities for crack growth rate estimations and for consistent inter-relation between accelerated tests data and service conditions are demonstrated.*

The objectives of work presented in this paper are (a) to critically review and summarize the incremental damage approach, (b) to discuss earlier applications, and (c) to present results of further applications. In particular, an alternative interpretation is offered for the so-called short-crack behavior *and, at the other end of the crack response spectrum, the model is also applied to explore the possibility of* crack arrest and/or crack growth rate retardation. *Furthermore, although the model is based on a strain-rate interpretation of the film-rupture mechanism of SCC, the resulting characteristics and predictions are re-evaluated in terms of the fracture mechanics parameters. This evaluation offers a new perspective on the model application and a more explicit comparison of the linear elastic fracture mechanics (LEFM) stress intensity method and the incremental damage approach.*

INTRODUCTION & BACKGROUND

The stress corrosion cracking (SCC) of pressure retaining components is one of the significant mechanisms of sub-critical crack growth, especially under aqueous environments. SCC and the related mechanism of corrosion fatigue (CF) under cyclic loads have been recognized as the primary (life-limiting) forms of degradation affecting several components critical to the success of plant life extension of light water reactor (LWR) power generating systems.

Both, the significance of safety implications on the one hand and the desirability of longer term continued operation of unflawed or possibly flawed components on the other hand, call for a more accurate and comprehensive evaluation of the cracking response characteristics (under the influence of localized corrosion). Various methods and concepts available for such an evaluation were examined in a recent survey [1] which suggested some merits in utilizing the framework of nonlinear damage accumulation methods, especially if the key factors affecting the cracking mechanism are known and can form a consistent basis. This is particularly applicable for SCC and CF in which the (local) interactions between mechanical and (environmental) electrochemical factors need to be adequately represented and in which these factors can change with time and the extent of damage significantly affecting the local response.

The suggested approach was formulated and applied [2] with reference to the intergranular stress corrosion cracking (IGSCC) response of Ni-Cr-Fe Alloy 600 tubing used in the steam generators. This formulation is summarized in the following with a review of the results of subsequent applications; the predictive capabilities and characteristics of the quantitative model are demonstrated and discussed in terms of the crack growth (da/dt) aspects of test specimen geometries and service components. These model predictions and characteristics are evaluated using the linear elastic fracture mechanics (LEFM) stress intensity factor (K_I); notwithstanding the approximations involved, this evaluation offers a more explicit comparison of the results of damage mechanics formulation with the $da/dt - K_I$ method. The paper is concluded with some implications and discussion of the presented developments and suggestions for further work in the application to better quantify the environmentally influenced sub-critical crack growth.

INCREMENTAL DAMAGE FORMULATION

In the new approach, for the purpose of quantitative evaluation, the environmentally assisted crack growth process is treated incrementally in the space–time continuum so as to account for the essential changes in both the mechanical and environmental factors known (or presumed) to govern the cracking mechanism. For example, one basic concept is that as the microcracking under the joint load–environment action continues with time, the effective load-bearing area decreases, thereby increasing the mechanical driving force; similarly, the environmental influence will also change. With regard to the process of SCC of ductile alloys in aqueous environments one of the significant factors appears to be the local strain rate which relates well with at least the (corrosion or oxide) film rupture mechanism. With the progressive action of microcracking, the effective strain rate will also depend on the extent and the speed of crack growth. Thus, a number of inter-related and inter-dependent factors are affecting the SCC. These are conveniently integrated in the incremental treatment of SCC evaluation as shown in the logic diagram of *Figure 1*.

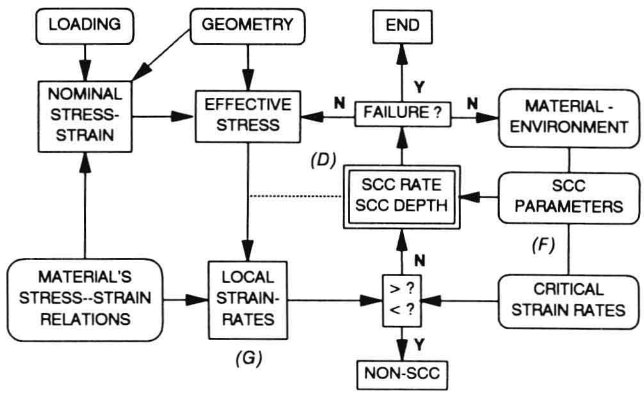

Fig. 1: **Incremental damage approach for crack growth prediction under IGSCC (schematic).**

Analytically, the formulation can be expressed as follows [1, 2]:

$$\dot{D} = F(\dot{\epsilon}, D, T) \quad (1)$$

$$\dot{\epsilon} = G(\sigma(D), \epsilon, D, \dot{D}, T) \quad (2)$$

where $\sigma(D)$ represents the *effective* stress dependent on the accumulated damage D, T is the temperature, $\dot{\epsilon}$ is the *local* strain-rate, and F and G denote the functional relations between the respective factors. The function F represents the localized SCC damage rate and contains the main corrosion related parameters dependent on the material–environment conditions. The function G describes the local stress–strain behavior and it is determined mainly by the material constitutive relations.

The effective stress $\sigma(D)$ relates the nominal deformation response (in the absence of any damage) to the local response by the following relation:

$$\dot{\sigma}(D) = g_1[D] \cdot \dot{\sigma}_{nom} + g_2[D] \cdot \sigma_{nom} \cdot \dot{D} \quad (3)$$

where 'g_1' and 'g_2' are geometry dependent functions of D, and σ_{nom} is the *nominal* stress.

The specific functions (F, G, g_1, and g_2) and model parameters are summarized in the Appendix for the applications discussed below. Thus, in brief, the IGSCC model considered in this work consists of three sets of relations: (1) the damage rate expression that describes the local rate of SCC in terms of the local strain rate and environment–material specific parameters, (2) an effective stress, which accounts for the extent and growth rate of SCC, relating the local strain rate to the nominal stress–strain values, and (3) the material constitutive relations which relate the external loads to the nominal stresses and deformations. Any particular load–geometric combination is then analyzed by numerical solution (computer simulation) of the appropriate set of model equations.

RESULTS OF MODEL APPLICATIONS

In the following, unless otherwise indicated, the term *damage* is used to represent the (uniform) depth of IGSCC; also the specific model predictions and data correlations considered in this paper deal with the Ni-Cr-Fe Alloy 600 in de-ionized, de-oxygenated, lithium–borated water in the temperature range of 290 °C to 370 °C—conditions typical of the primary side of pressurized water reactor steam generators.

Since the SCC damage model emphasizes the role of strain rate and also claims to address the crack growth starting from a practically smooth (unflawed) surface, the first natural application is to evaluate the slow strain rate test (SSRT). This was considered in detail in the earlier work [2] in which a flat, uncracked specimen with rectangular cross section was analyzed for IGSCC; the minimum dimension was 1.252 mm (50 mils) typical for the wall thickness of steam generator tubes. The following significant observations were shown to be correctly predicted by the model: With the lowering of the applied strain rate (1) the apparent ductility is reduced, (2) the sustained maximum load before failure is lowered, and (3) the extent (area) of cross section affected by IGSCC is increased. These are also the more generally observed effects in many other IGSCC-prone material–environment systems.

Two other unique SSRT predictions of the model, supported by experimental observations [3–5], are as follows: (1) To produce measurable IGSCC under a typical SSRT (at least for the examined material and environment system) lower and lower strain rates are needed as the test temperature is lowered; this result is illustrated in *Figure 2* where model predictions (solid lines) show the strain rate and temperature combinations needed for the two low values of the IGSCC depth. (2) The applied nominal strain must exceed at least a few percent, even at the lower strain rates, before the measurable extent of IGSCC can accrue.

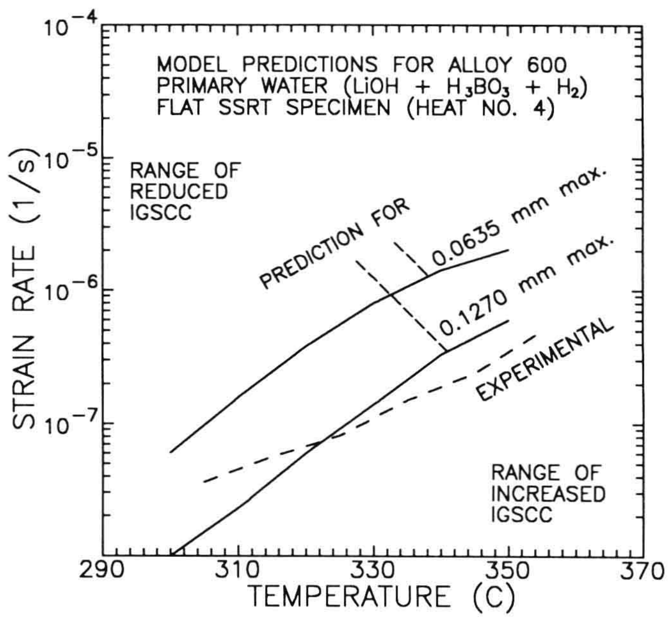

Fig. 2: The strain rate and temperature dependence of the propensity to induce IGSCC; comparison of the model predictions (solid lines) with the experimental observations (for non-detection of IGSCC) under slow strain rate tests.

Figure 3 shows the model predictions for the *average* crack growth rate as dependent on the temperature and the *nominal* strain rate in SSRT;[1] here the average crack growth rate is calculated from the predicted IGSCC depth and the simulation time taken to reach that depth. It may be of interest to note that the slopes of prediction lines range from about 0.36 (at 365 °C) to 0.47 (at 300 °C) which differ from the exponent 0.5 (used in the damage law, Equation 4, relating the respective *instantaneous* rates).

[1]The author would like to note a correction in an earlier paper [2]: the strain rate labels in *Figure 3* of that paper should be interchanged with reference to the model prediction lines.

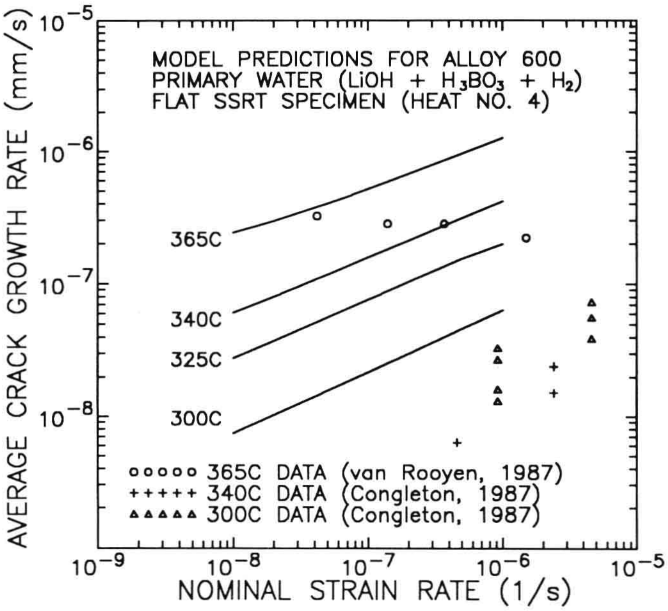

Fig. 3: Average crack growth rate characteristics under slow strain rate tests.

Also shown in the same figure are the data values as quoted in two experimental investigations [3, 5] under somewhat similar conditions of interest; both the sources expressed difficulties in accurately determining these numbers and noted that the values are generally underestimated (due to the use of total test time, not knowing well the actual period for which the IGSCC was active). Indeed, in one case [3] the quoted trend (at the highest temperature) even shows slight inverse relation; on the other hand, the data from the other source [5] appear to show very little temperature sensitivity at the two lower temperatures. Clearly, it is difficult to rationalize the data trend as shown—suggesting, not surprisingly, that the average growth rate may not be very usable for detail correlation in certain cases.

The model application to predict the IGSCC life under constant nominal stress was considered in the subsequent work [6] for the same material, environment, and initially uncracked geometry as in the above SSRT investigation; both the stress dependence and the temperature dependence were shown to be in reasonably good agreement with the test data. Also, for the idealized conditions examined, the model suggested relatively sharp increase in failure times for stress levels below the yield stress and below a critical temperature of about 330 °C (603 °K); however, the affected area of IGSCC was predicted to be large and growing at very slow rate. This also implied that a wide variation in the failure times is to be expected at the current operating temperatures of 325 °C (598 °K) and for the near-yield stress levels typical of certain roll transition zones of some steam generator tubes.

One of the significant and unique aspects of the results of model application under constant stress condition was that the instantaneous crack growth rate characteristics showed four regions: (1) an initial short period when no IGSCC takes place (since the strain rate is too high), (2) a period of decreasing crack growth rate as the small crack size is increasing (due to the dominant strain hardening contribution to the reduced local strain rates), (3) an interim period where the IGSCC rate creeps back up to a high value (as the crack size and its growth rate begin to influence the local strain rate), and (4) the final phase where the growth rate is mostly under non-IGSCC conditions.

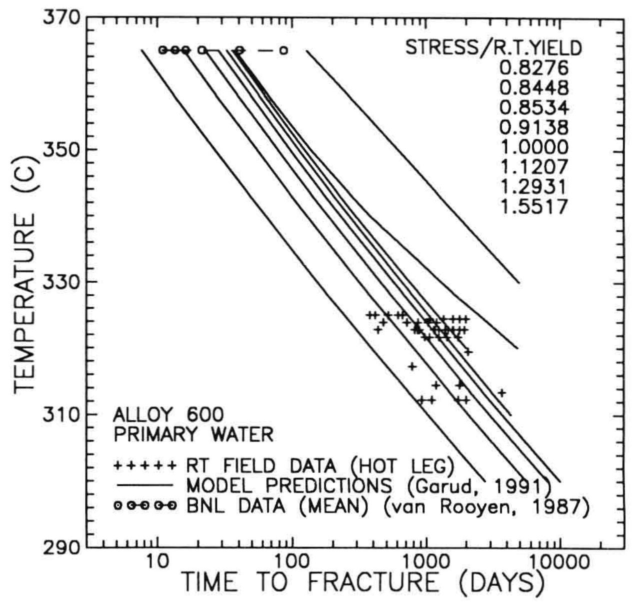

Fig. 4: Model predictions and data for IGSCC under constant stress conditions and temperature effects.

Figure 4 illustrates the results of model application to predict the life of steam generator tubing (19.05 mm diameter and 1.092 mm wall thickness) by considering the formation and growth of a part-through circumferential crack under constant axial stress. The predicted temperature dependence is shown for various stress levels indicated by the respective values normalized by the room temperature yield stress. The high temperature test data as well as the field observations of tube failures [7] in the hot leg roll transition zones from (the primary side of) various steam generators are also shown for comparison purposes. In these zones the total stress levels are expected to be in the same range but with some through-wall gradients not accounted in the analysis; also, the field failure data is likely to represent the cases of highly stressed tubes from the more susceptible heats of material.

LEFM INTERPRETATIONS

As emphasized earlier the incremental damage formulation was developed mainly with the explicit goal of being able to analyze the crack growth aspects under environmentally assisted cracking (EAC) conditions (in particular, SCC and CF) while accounting for the local creep strain rate and its interaction with the crack size as well as EAC growth rate. However, it may be of some interest to present and discuss the above results in terms of the linear elastic fracture mechanics (LEFM) factors commonly used in the engineering analysis.

From the above model predictions the instantaneous value of LEFM stress intensity factor, K_I, was calculated using the nominal (remote) stress, σ, and the IGSCC depth, D, for the two geometries: (1) For the flat plate SSRT (double edge-crack tension) specimen the following expression was used:

$$K_I = \sigma\sqrt{\pi D} \cdot \left[1 + 0.122\cos^2(\lambda)\sqrt{(1/\lambda)\ \tan(\lambda)}\right]$$

where $\lambda = \pi D/h$ and h is the plate thickness dimension (into which the crack is growing). (2) For the tube under constant stress (with part-through fully circumferential crack under remote tension) the stress intensity factor was given by:

$$K_I = 1.122\,\sigma\sqrt{\pi D/(1 - D/t)}$$

where t is the tube wall thickness.

Figure 5 shows the model characteristics relating the da/dt and K_I for five nominal (constant) strain rates under SSRT at two temperatures. First, it should be noted that the load-geometric conditions analyzed in the above application of the model to SSRT are such that considerable inelastic deformations are present for the most part (although less so at the lowest applied strain rates); therefore, any interpretation based on the LEFM stress intensity factor may not be strictly valid. However, certain aspects of the SCC growth rate can be illustrated without loss of generality.

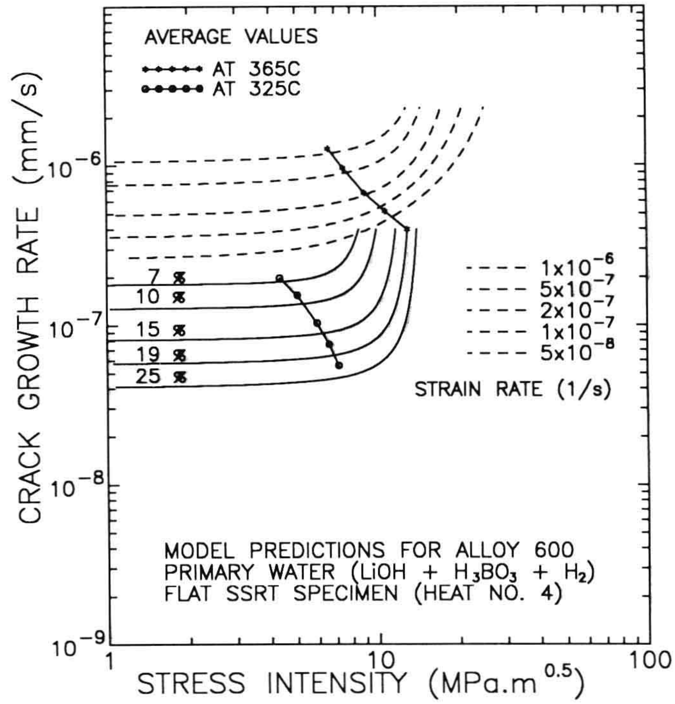

Fig. 5: Model predictions for $da/dt - K_I$ characteristics under slow strain rate tests.

For example, even if one were to use plasticity based fracture mechanics parameter such as the J integral (to represent the loading severity), the $da/dt - K$ lines (*Figure 5*) would only stretch or shift to the right and would not collapse into one relation. Thus, under the applied strain rate conditions, the model predicts a very weak dependence on the stress intensity factor and shows that the plateau crack velocities are dependent on the strain rate. These are analogous to the observations under corrosion fatigue when the conditions are present for most severe EAC to occur. The commonly observed frequency effect—namely, the higher the loading rate (frequency) the slower is the CF crack growth—may appear to contradict the strain rate dependence shown in *Figure 5*; however, if the plateau EAC rates are converted into per-cycle-rates then the trend is consistent.

The $da/dt - K$ response under constant remote stress condition as predicted by the model is shown in *Figure 6* for five stress levels (at 325 °C). As may be expected, the IGSCC growth rates are nearly an order of magnitude slower than under SSRT (for the same K_I) (see *Figure 5* for 325 °C). Also, the time dependent strain hardening effect in the very early stage of crack growth (noted in the preceding section) is reflected in the *bath tub* shape of $da/dt - K$ response. Interestingly, for the analyzed case of load–geometry combinations, in the latter stage of crack growth the curves for different stress levels seem to converge.

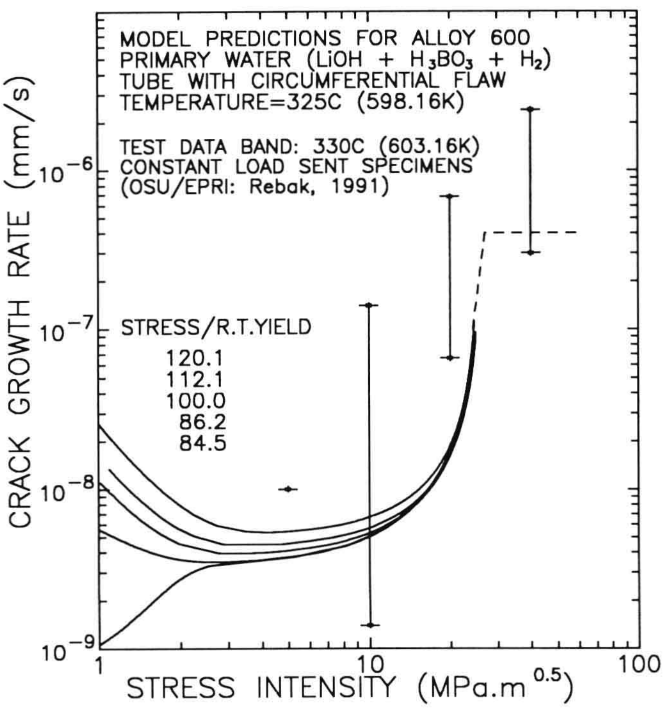

Fig. 6: Model predictions for $da/dt - K_I$ characteristics under constant stress condition.

For the purpose of comparison, recently published test data for similar material–environment system are shown by the vertical band lines [8]; these tests were performed at 330 °C on fatigue pre-cracked flat plate (25.4 mm wide single edge notched tensile) specimens with the initial crack depth of 10.16 mm.

IMPLICATIONS AND DISCUSSION

The $da/dt - K$ characteristics as predicted by the incremental damage formulation, shown to be consistent with several related EAC observations, reflect the time- and load-history dependence of the EAC growth rate essentially implying the non-uniqueness of $da/dt - K$ relation.

One of the important implications (of the strain rate based model) is that high stress and high K don't necessarily result in severe EAC—i.e., although the SCC *growth rate* may be higher under these conditions, the *extent* to which sectional area or depth is affected can be substantially less than that possible under low stress and low K. This is somewhat similar to the general observation (and to predictions as shown in *Figure 5* where the percent areas affected by IGSCC, just before the non-IGSCC conditions set in, are noted) that SSRT is a more severe test in the sense of producing SCC in short time but not necessarily in terms of large area of SCC; note that at the lower strain rate the nominal stress levels are much lower than at the higher strain rates.

There are indications that the influence of environmental (high growth rate) conditions is likely to be more surface bound; this is related not only to the mechanical factors emphasized in this paper but to possible changes in the electrochemical and flow conditions for deeper cracks. The incremental damage approach provided an estimation of the time and extent of maximum SCC damage before the non-environmental conditions of crack growth start to dominate. In effect, this has implications with regard to the assumption of *self-similar* growth of a flaw (i.e., the crack aspect ratio). It is apparent that the expected high EAC growth rates near the surface will tend to drive the crack faster and to greater extents along the surface than through the wall.

The above aspects suggest the likelihood of crack growth rate reduction or crack arrest—because, high strain rate condition (e.g., with a larger flaw size) may not necessarily imply high *mechanical* crack growth rate while it would not allow the strain rate sensitive EAC mechanism, with its high crack growth rate, to be operative either. It is also likely that the environmental conditions at the crack-tip (pH, potential, concentrations or the ratio of anion to cation activities) will change and will depend on the depth of SCC; these changes may also contribute to the transition from EAC to non-EAC. The relative significance of these two actions (mechanical and environmental) is hard to judge without further detail work; *however, it may be of interest to note that the environmental effects and changes are expected to be less sensitive to the geometric dimensions and will be dominated by the* absolute *depth (or extent) of SCC, whereas the mechanical factors will be more sensitive to the geometric dimensions and the* relative *extent of SCC.* In any event, these changes can be directly integrated in the formulation in as much details as allowed by the need and understanding of the situation.

Also, as a consequence, it is to be expected that the sub-critical crack growth response will be affected by the physical dimensions (crack size and geometry) in a manner not quite well representable by the usual fracture mechanics parameters. For example, it seems that a thin wall section may be *relatively* easy to undergo large percent of SCC while for a thick section it may be very difficult to have sustained high growth rate of SCC (unless additional deformation rate transients occur to provide the necessary driving force).

CONCLUSIONS AND FUTURE WORK

The results of application of incremental damage formulation were presented for various loading and geometric conditions; these results were discussed in relation to the crack growth rates and flaw evaluations, especially from an initially defect-free, smooth surface. It was shown that with the alternative crack growth interpretation offered by the formulation significant quantitative information can be extracted from careful and systematic observations made in SSRTs. The results were shown to be consistent with general trends and stress- strain-rate- and temperature-dependencies observed under laboratory conditions and in the service.

The model predictions were interpreted in terms of the calculated da/dt versus K_I characteristics. This provided a more direct comparison of the strain rate based damage formulation and the LEFM based approach in dealing with, or representing, several peculiarities and significant aspects of the EAC (IGSCC in particular). The non-uniqueness of $da/dt - K_I$ resulting from the load-history and time dependent effects was shown to be a natural consequence of the incremental damage approach. Many other important implications regarding various aspects of sub-critical crack growth, which differ significantly from (or remain unaccounted in) the LEFM type approaches, were discussed indicating new areas of further investigation.

In this paper only one set of SCC damage parameters was developed and examined for a fixed condition of material and environment. In general, these parameters will depend upon the metallurgical and environmental conditions which can vary from one set of tests to another or from laboratory to service conditions. These details could not be explored at this time mainly due to the paucity of relevant test data and the correspondingly limited development effort for the examined application (primary side IGSCC of Alloy 600).

Although the model predictions and capabilities have shown considerable promise in the quantitative evaluation of EAC its application thus far has been limited to only a few cases of loads, geometries, and material–environment conditions. Further comprehensive and critical investigations can be very useful in enhancing the model capabilities and expanding its applicability. In particular, and of immediate interest, some items can be pointed out as follows:

The model implications for thin versus thick sections, static (SCC) versus dynamic (CF) loading conditions, short versus long cracks, and crack arrest or crack growth rate retardation, need to be explored more systematically since these can have significant impact on flaw evaluation, perhaps complimenting the current, simplified methods of analysis.

The feasibility of extending the incremental damage approach to investigate the role of irradiation in SCC should be examined as it appears to offer the possibility of integrating the influence of (prolonged) irradiation on the deformation response of materials of components critical to the plant life extension which are also likely to be susceptible to SCC or CF.

It should be noted that the model applications discussed in this paper dealt with an initially smooth surface geometry and relatively thin cross sections; as such, the implicit (and mostly conservative) assumption of crack growth being dominated by the environmental mechanism is valid. For better and more generally applicable evaluation it would be useful to incorporate the non-environmental crack growth response more explicitly, especially for large crack sizes (or large stress intensity factors).

Also, the existence of a lower cut-off strain rate for a specific material–environment system, if confirmed, may be included in the analysis to reduce the likely conservatism integral in the current form of the model which ignores this barrier (although, there is the inherently built-in *practical* limit due to the fact that the EAC rate at very low strain rates will be too slow to have any impact within the design life).

ACKNOWLEDGMENT

Most of the model development and application work was funded by the Steam Generator Projects Office of the Electric Power Research Institute (EPRI), Palo Alto, California. The author is thankful to Dr. A. R. McIlree of EPRI for his interest and support.

REFERENCES

1 Y. S. Garud, "Quantitative Evaluation of Environmentally Assisted Crack Initiation and Propagation: Modeling Concepts, Their Development and Engineering Application," *Predictive Capabilities in Environmentally Assisted Cracking*, PVP–Vol. 99, ed.: R. Rungta, ASME, New York, pp. 91–106 (1985).

Also, *Journal of Pressure Vessel and Technology*, Trans. of the ASME, Vol. 113, pp. 1–9 (1991).

2 Y. S. Garud, "An Alternative Interpretation of Smooth Specimen SCC Test Data and Its Implications for Analyzing the Environmental Crack Growth in Engineering Components," in *Proceedings of the 4th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems–Water Reactors*, ed.: D. Cubiciotti, NACE, Houston, Texas, pp. 4/12–4/25 (1990).

Also, *Corrosion*, Vol. 46, No. 12, pp. 968–974 (1990).

3 D. van Rooyen, "Update on SCC of Alloy 600 in High Temperature Water," 1985 Workshop on Primary-side Stress Corrosion Cracking of PWR Steam Generator Tubing, *EPRI NP-5158*, Paper No. 10, Electric Power Research Institute, Palo Alto, California (1987).

4 T. S. Bulischeck and D. van Rooyen, "Stress Corrosion Cracking of Alloy 600 Using the Constant Strain Rate Test," *Corrosion*, Vol. 37, No. 10, pp. 597–607 (1981).

5 J. Congleton and R. N. Parkins, "Stress Corrosion Cracking of Alloy 600 in High Temperature Water," *Nuclear Engineering and Design*, Vol. 103, pp. 301–311 (1987).

6 Y. S. Garud, "Incremental Damage Formulation and Its Application to Assess IGSCC Growth of Circumferential Cracks in a Tube," *Corrosion*, Vol. 47, No. 7, pp. 523–527 (1991).

7 Y. S. Garud, "Survey of Primary-side IGSCC Events in Westinghouse Steam Generators of Pressurized Water Reactors," *Report No. 8508*, S. Levy Incorporated (1985).

8 R. B. Rebak et al., "Effects of pH and Stress Intensity on Crack Growth Rate in Alloy 600 in Lithiated + Borated Water at High Temperatures," presented at the 5th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors, NACE/ANS/TMS–AIME, Monterey, California (1991).

9 Y. S. Garud, "Development of a Model for Predicting Intergranular Stress Corrosion Cracking of Alloy 600 Tubes in PWR Primary Water," *EPRI NP-3791*, Electric Power Research Institute, Palo Alto, California, January (1985).

10 Y. S. Garud and A. R. McIlree, "Intergranular Stress Corrosion Cracking Damage Model: An Approach and Its Development for Alloy 600 in High-purity Water," *Corrosion*, Vol. 42, No. 2, pp. 99–105 (1986).

11 S. R. Bodner and Y. Partom, "Constitutive Equations for Elastic-Viscoplastic Strain-Hardening Materials," *Journal of Applied Mechanics, Transactions of the ASME*, Vol. 42, pp. 385–389 (1975).

APPENDIX

SPECIFIC FORMS OF MODEL FUNCTIONS

For the case of IGSCC of Alloy 600 in high purity water the following relation (for the function F of Equation 1), between damage parameter D and the total net *local* strain-rate $\dot{\epsilon}_{net}$, was proposed [2]:

$$\dot{D} = \alpha_0 exp[-Q/RT](\dot{\epsilon}_{net})^{\phi} \text{ for } \dot{\epsilon}_{net} \leq \dot{\epsilon}_{ucr} \quad (4)$$

where α_0, Q, ϕ, and $\dot{\epsilon}_{ucr}$ are material-environment specific parameters to be determined from experimental data; R is the universal gas constant. $\dot{\epsilon}_{ucr}$ specifies the upper critical strain-rate that must not be exceeded if IGSCC is to occur. Here, the *Arrhenius* type of temperature dependence is limited to temperatures between 290 °C (563 °K) to 370 °C (643 °K).

The local strain-rate (function G of Equation 2) is determined by the material constitutive relations; these were derived [9, 10] using the deformation law, proposed by Bodner and Partom [11], which was found to adequately describe the visco-plastic strain rate response of Alloy 600 for the above temperatures:

$$\dot{\epsilon}_{net} = \dot{\sigma}_{net}/E + \dot{\epsilon}_{n,net} \quad (5)$$

$$\dot{\epsilon}_{n,net} = (2D_0/\sqrt{3})exp[-0.5(Z_{net}/\sigma_{net})^{2n}] \quad (6)$$

$$\dot{Z}_{net} = m(Z_1 - Z_{net})\dot{W}_{p,net} \quad (7)$$

$$\dot{W}_{p,net} = \sigma_{net} \cdot \dot{\epsilon}_{n,net} \quad (8)$$

where overhead dots denote the respective temporal rates, σ_{net}, ϵ_{net}, $\epsilon_{n,net}$ denote the local stress, strain, and non-elastic strain, respectively, $W_{p,net}$ and Z_{net} represent the corresponding *state variables* for the work of non-elastic deformation and the material hardness due to the deformation, respectively. E is the elastic modulus, D_0, Z_1, m, and n are material parameters. Similar set of equations is used to relate the nominal (uncracked) section stresses and strains due to the external loads.

Note that the *local* and the *nominal* stress–strain quantities are connected through the *effective* stress (Equation 3 of the main text), here equated with the net-section stress. The corresponding geometric functions (g_1 and g_2) are as follows:

(I) For the case of a flat plate, with same environment acting from both sides of the thickness dimension, with uniformly loaded cross-section (under remote tension) of minimum thickness h:

$$g_1[D] = 1/[1-2D/h] \quad (9)$$
$$g_2[D] = (2/h)/[1-2D/h]^2 \quad (10)$$

(II) In the case of a cylindrical tube, with environment acting on the inside surface, under (remote) uniform axial load:

$$g_1[D] = a_c/[a_c - D(D+d_i)] \quad (11)$$
$$g_2[D] = g_1 \cdot (2D+d_i)/[a_c - D(D+d_i)] \quad (12)$$

where $a_c = (d_o^2 - d_i^2)/4$ and d_i, d_o are the internal and external diameters of the tube, respectively.

MODEL PARAMETERS

The values of parameters for the material stress-strain (constitutive) relations (Equations 5–8) are summarized in *Table 1*; these were determined in an earlier work [9] based on the mechanical tensile tests data. Alloy 600 properties of the heat # 4.0 were used in the analysis of SSRTs (since this was considered to be close to the material used in SSRTs); the other heat (# 5.0 with higher carbon, higher yield strength) is more representative of tubes in service and is used in the analysis of constant stress condition on the tube geometry.

The SCC related model parameters were determined [2] by correlating the data [3, 4] which consisted of observations typically reported for SSRTs; these observations included the total time to failure, strain to failure, and the maximum load before failure. Equations 3 through 8 were numerically solved with parametric variations leading to the correlated parameters. The data set pertained to mill-annealed Ni-Cr-Fe Alloy 600 tubing material in simulated primary water (with 650 ppm of boron as H_3BO_3, 10^{-4}M LiOH and 103.435 kPa H_2). The estimated values of model parameters were as follows:

$$\phi = 0.5$$
$$\alpha_0 = 203844$$
$$Q = 138.07 \ (kJ/mol)$$
$$\dot{\epsilon}_{ucr} = 5 \times 10^{-6} \ (1/s)$$

when $\dot{D}$ is expressed in *m/s* and $\dot{\epsilon}$ is in *1/s*.

TABLE 1

Material constants for the visco-plastic (stress-strain) response of two mill-annealed heats of Ni-Cr-Fe Alloy 600 and the respective room–temperature yield strengths (S_y) [9].

Heat No.*	D_o (1/s)	Z_1 (MPa)	a (K)	m_o (1/MPa·K)	C_o (1/MPa)	m_1 (1/K)	C_1 –	S_y (MPa)
4.0	10	805.82	5950	1.0196×10^{-5}	1.942×10^{-2}	-1.635×10^{-4}	0.42481	280.14
5.0	10	998.05	7319	1.0486×10^{-5}	9.923×10^{-3}	-8.020×10^{-5}	0.45093	399.91

*with 0.019 and 0.029 weight percent of carbon content, respectively.

Note: $m = C_0 + m_0T$, $n = a/T$, $Z_{initial} = (m_1T + C_1)Z_1$,
$E = 259363 - 199.244T + 0.205857T^2 + 5.91521\times10^{-5}T^3 - 2.029\times10^{-7}T^4$,
where E is the Young's modulus of elasticity (MPa) and T is the temperature (K).

PVP-Vol. 241, Fatigue, Fracture, and Risk
ASME 1992

USE OF FUNDAMENTAL MODELING OF ENVIRONMENTAL CRACKING FOR IMPROVED DESIGN AND LIFETIME EVALUATION

Peter L. Andresen and F. Peter Ford
General Electric Corporate Research and Development Center
Schenectady, New York

ABSTRACT

This manuscript reviews an approach for improved design and lifetime evaluation for environmental cracking based on fundamental modeling of the underlying, operative processes in crack advance. In outlining this approach and its application in energy industries, the requirements for a life prediction methodology will be highlighted and the shortcomings of the existing design and lifetime evaluation codes will be discussed. Examples will be given of its development and application in a variety of *cracking systems*, such as environmental cracking of stainless steels and nickel alloys in hot water, and irradiation assisted stress corrosion cracking.

INTRODUCTION

Failure of structural components by stress corrosion or corrosion fatigue represents a possible life limiting factor in the operation of Light Water Reactors. A life prediction methodology for environmental cracking is needed for design purposes, for lifetime evaluation of components in which defects are found, and for plant life extension analyses. Essential ingredients to any comprehensive life prediction methodology include: • treatment of the continuum in material and condition, environment, and stress; • treatment of time dependent crack growth to encompass the continuum from static to cyclic loading; • unified approach for crack initiation and growth, which requires understanding of short crack behavior; • fracture mechanics and crack chemistry similitude for relevance to varying component geometries and loading conditions; • calculational approaches for complex service conditions which require accounting for the time and through-thickness variations in properties and the use of distributions in properties as well as probabilistic approaches; • integrated predictive modeling and monitoring of on-line system behavior; and, ideally • extensibility into related cracking systems.

By these standards, existing design and lifetime evaluation procedures are inadequate. The approach described in this paper incorporates these elements, and has involved identifying the mechanism of environmentally assisted crack advance, then independently evaluating the parameters of fundamental importance. On this basis, predicted subcritical crack growth rates are obtained for different combinations of environment (e.g., dissolved oxygen content, impurity concentration, radiation flux), material (e.g., thermal or radiation-induced sensitization, sulfur content), or stress, (e.g., static and cyclic load). Short crack studies address the transition between crack initiation and growth, as well as crack tip chemistry similitude issues. The complex variations of properties vs. time and thickness are accounted for using computer codes which incrementally integrated these effects over elapsed time and crack depth. Ranges in distributions (e.g., mean, upper, and lower limits) are easily input into the model, and a variety of approaches have been used for statistical and probabilistic treatment. Incorporation of direct measurements from system monitors has been used to fine-tune the model by providing improved characterization of specific system conditions, or calibrate the overall model prediction using in-situ, on-line measurements of crack growth in reference components or specimens. Finally, predictions have been compared with the observed data to evaluate the quantitative validity of the original working hypothesis and modeling algorithms.

MODEL FORMULATION AND QUANTIFICATION

The slip dissolution/film rupture mechanism of environmentally assisted cracking relates crack advance to dissolution reactions at the crack tip where a thermodynamically stable oxide is ruptured by increasing strain in the underlying matrix (Figure 1). (This mechanism is also applicable to chemical oxidation, where no electrochemical reactions occur). The periodicity of this film rupture event is related to the strain rate in the metal matrix and this, in turn, is controlled by either creep processes under constant load or applied strain rates under monotonically increasing or cyclic load conditions. Thus, the model is potentially applicable not only to stress corrosion (under constant stress) but also to corrosion fatigue over the range of stress amplitude, mean stress, frequency, etc. combinations. The average crack velocity, V_t, is related to the crack tip strain rate, $\dot{\varepsilon}_{ct}$, as follows:

$$\overline{V}_t = A\,(\dot{\varepsilon}_{ct})^n \qquad (1)$$

where A and n account for the material and environment compositions at the crack tip. One limit to the validity of this relationship (Figure 2) occurs at high crack tip strain rates ($\approx 10^{-2}\ s^{-1}$), where the environmental crack growth rate saturates because a bare surface is maintained continuously at the crack tip (dotted line in Figure 2). At low crack tip strain rates, changes in the parameters in Equation 1 can occur if, e.g., crack blunting occurs (i.e., when the corrosion rate of the crack sides approaches the oxidation rate at the crack tip), or the dynamic creep–crack growth processes which sustain crack advance under static loading are disrupted.

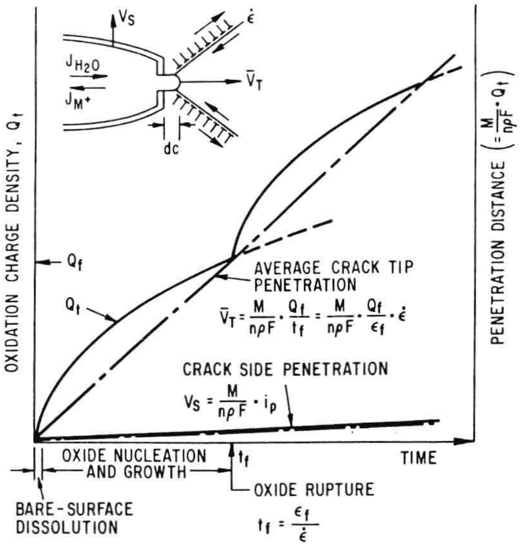

Figure 1. Schematic oxidation charge density/time relationships for a strained crack tip and unstrained crack sides.

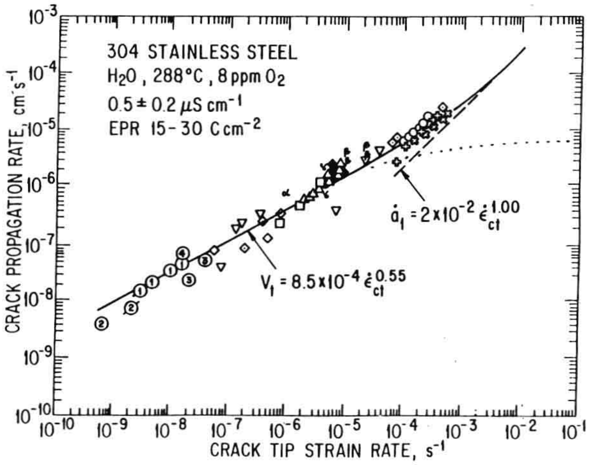

Figure 2. Observed and predicted crack growth rate vs. crack tip strain rate for type 304 stainless steel. The film rupture model predicts a maximum in crack velocity at crack tip high strain rates associated with the bare surface dissolution rate (dotted line). The dashed line shows the contribution of the inert fatigue crack growth rate.

Since Equation 1 expresses only the environmental component of crack advance, the contribution of the mechanical component of crack advance under cyclic loading must also be accounted for (dashed line in Figure 2).

The model was quantified by evaluating the following processes: (1) the steady state and transient compositions of the environment at the crack tip as a function of the conditions in the bulk (external) solution; (2) the oxidation rates for the material/environment system expected at a strained crack tip; and (3) the oxide fracture strain and the crack tip strain rate, defined in terms of engineering parameters such as K, ΔK, R, frequency, etc. These tasks have been discussed in detail elsewhere for stainless steels [1-4], low alloy and carbon steels [1-3,5-8], ductile nickel alloys [2-4,9-11], and irradiated stainless steels [3,12-15]. Additionally, short crack behavior and the transition to long crack behavior [16,17], concerns for crack chemistry similitude [16,17], treatment of thickness- and time-varying properties, and treatment of distributions in properties and statistical approaches [1-4,6-8,11-15] have also been addressed. This paper will illustrate the validity and practical use of a prediction model based on Equation 1.

EVALUATION OF CRACK GROWTH RATE PREDICTIONS

Observed crack growth rates for various combinations of stainless steel microstructure, dissolved oxygen content, solution purity and stressing mode have been compared with the values predicted by the slip dissolution/film rupture model via Equation 1. The correlation between observed and predicted crack velocity / strain rate relationships is shown in Figure 2 for furnace sensitized type 304 stainless steel in aerated water at 288°C under static, monotonically increasing, and cyclic loading conditions. Similar agreement is obtained for other environmental conditions associated, e.g., with the synergistic effects of corrosion potential (e.g., dissolved oxygen and radiation flux) and solution conductivity (or anionic activity) (Figure 3). The overall agreement between observation and prediction for the stainless steel/water system is illustrated in Figure 4 as the ratio of the (predicted divided by observed) crack growth rates over a wide range of material, environment, and loading conditions. The mean value of this ratio is 1.17, and the variance in the distribution can be correlated with the uncertainty in the system definition [1-4]. Similar predictive accuracy has been obtained for low alloy steels] [1-3,6-8], ductile nickel alloys [2,3,9-11], and irradiated stainless steel [12-15].

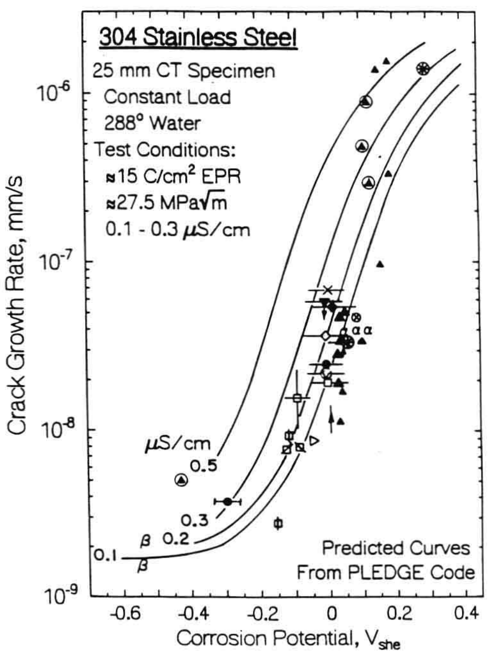

Figure 3. Comparison of observed vs. predicted crack growth rate as a function of corrosion potential for sensitized type 304 stainless steel at constant load. Data points at elevated corrosion potentials and growth rates correspond to irradiated water chemistry conditions in test or commercial reactors [1-4].

APPLICATIONS OF PREDICTIVE MODELING

The ability to predict environmentally assisted crack growth rates in high temperature water with reasonable accuracy has considerable practical impact. For example, it provides a methodology for evaluating the quantitative benefit and overall validity of empirically derived remedies, often based on accelerated test data. Also, it provides the ability to optim-