FRACTURE MECHANICS AND FATIGUE EVALUATION OF NUCLEAR REACTOR COMPONENTS

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1. INTRODUCTION

Fatigue has been a major consideration in the design of the nuclear plant pressure vessel and piping components. Fluctuating thermal and mechanical loads, such as service pressure and temperature transients, earthquakes, and rotating machinery are primary sources to cause low and high cycles fatigue damage.

When the design loads are considered, the fatigue evaluation for the nuclear plants is currently based on the rules presented in the ASME Code Section III, [1]. The *S-N* fatigue curves (alternating stress - cycles to failure) were generated experimentally, using technology developed in the 60's. To evaluate the components under the actual operating loads, it is necessary to conduct an analysis to estimate the crack growth rates as a function of the range of stress intensity factors, using *da/dN* - ΔK curves generated in the 70's, and presented in the ASME Code Section XI, [2].

A variety of tests to evaluate the influence of the aggressive environment in the lifetime of components were conducted in the last decade. References [3-6] have shown that such effect is more deleterious than those predicted by the current *S-N* and *da/dN* ASME curves. The main reason for the life reduction is that the material under an actual operating condition is subjected to a new degradation mechanism, named corrosion-fatigue, which produces an increase in the crack growth rate. The corrosion-fatigue phenomenon is a result of interaction among several factors, such as loading characteristics (stress ratio, residual stress), material (microstructure, chemical composition, heat treatment), and environment (dissolved oxygen in the water, temperature, flow).

Another conclusion from fatigue data is that the ASME *S-N* design curves characterize the three phases of fatigue: crack initiation, crack propagation and fracture, [7]. In opposition to the high-cycles experiments, during low-cycles tests the crack initiation occurs early and most of the specimens life is consumed in crack propagation in the low-and medium-cycle, [8].

One can conclude that the reliable prediction of the nuclear reactor components lifetime may be reached with changes in the current ASME approach for fatigue evaluation. Those changes are necessary for the design of new reactors and in the life extension of the operating ones, and should incorporate factors not predicted when the *S-N* and *da/dN* curves were generated; besides, the addition of recent advances in the technologies are used to eliminate unnecessary conservatism, [9].

This paper presents a theoretical study available in the literature to evaluate the environmental effect on the lifetime of nuclear power plant components. The authors' motivation is to provide some technical tools to identify what research development could be done in this area.

2. CURRENT APPROACH - ASME *S-N* AND *da/dN* FATIGUE CURVES

The *S-N* fatigue design curves for nuclear reactor components given in the ASME Code Section III are material dependent, and were generated using unnotched small diameter polished specimens, tested in the air at room temperature. The experiments were conducted under completely-reversed strain amplitude, being these values converted to a fictitious stress by multiplying the strain by the elastic modulus; the results are plotted against the number of cycles required to failure the specimens, [10]. To take into account the differences among specimens and actual components (geometry effect, environment, surface finish, and loading) the best-fit of the experimental data are adjusted by reduction factors (two on stress or twenty on cycles). The *S-N* design fatigue curve for carbon and low-alloy steels given in the ASME Code Section III is shown in Figure 1.

The *da/dN* crack growth rate curves are employed to evaluate the components performance under actual service loads. These data, showed in the Figure 2, are available in the ASME Code Section XI. The curves were obtained from tension compact specimens, tested under constant amplitude loading in both air and aqueous reactor environments. The experiments were conducted for different stress ratio *R* (minimum to maximum stress ratio), in a frequency that gives the highest crack growth rate (1 cycle/min.), [5]. The *da/dN* versus ΔK data were generated using concepts taken from linear elastic fracture mechanics.

3. ENVIRONMENTALLY-ASSISTED FATIGUE

Experimental data recently published have shown the influence of different variables in the fatigue life of materials under a severe service environment. Higuchi and Iida, [3], conducted strain-controlled fatigue tests on carbon and low-alloy steels in high-temperature water (290°C), in order to quantify the reduction of fatigue strength due to factors such as strain rate, temperature, and amount of dissolved oxygen content. The result for carbon steel, presented in terms of the relation between applied strain amplitude and cycles to failure, is shown in Figure 3. It is observed that the original safety margins defined in the *S-N* design curves of the ASME III have been completely eroded. Besides, the fatigue lifetime reduction is accentuated with the increasing water temperature and with decreasing strain rate.

The main conclusions pointed out by Higuchi e Iida are confirmed by Majundar et al., [4]. This reference shows results from fatigue tests in carbon, low-alloy and stainless steels subjected to hostile environment. The tests were conducted at General Electric, Babcock & Wilcox, and Electric Power Research Institute, being the results presented in terms of a set of interim *S-N* fatigue curves which take into account the strain rate, temperature, dissolved oxygen and sulfur content in the material.

In conjunction with the *S-N* tests, several laboratories performed experiments to evaluate which variables are important for fatigue crack propagation on pressure vessel steel in light water reactor environment. Der Sluys and Emanuelson, [6], have shown the influence of the sulfur level in SA508 Cl-2 steel. From their results it is concluded that a material with a bulk sulfur contents greater than 0.012% may be susceptible to a phenomenon called EAC (environmentally-assisted cracking), characterized by crack propagation rates up to two orders of magnitude faster than the corresponding rates in air.

Eason et al., [5], based on results from fatigue crack propagation tests conducted in many laboratories worldwide, have proposed a new da/dN versus ΔK curve. These new data are to be included in future version of the ASME Section XI, where the primary improvements over the existing reference data are load rise time and sulfur content effect. Figure 4 shows the proposed da/dN - ΔK curve for 288°C, stress ratio equal 0.25 and a variety of rise time T_R. It is noticed that for larger T_R the current ASME XI underestimate the crack propagation.

4. FATIGUE CURVES MODIFIED DUE TO ENVIRONMENTAL EFFECTS

An engineering approach developed by O'Donnell, [11], based on fracture mechanics concepts, should be employed to address analytically the environmental effect on the ASME *S-N* design curves. The use of these concepts is consistent because most of the cycles to failure in the *S-N* tests involve the propagation phase of cracks (90 % of total life of the specimen). The main advantage of this approach is that it is possible to overcome the difficulties to generate experimental fatigue data in hostile environments (high cost to perform experiments, corrosion-fatigue process demands a long period of time).

Current crack growth propagation rates from ASME XI are used to correct existing *S-N* design curves. However, from [11], *da/dN-ΔK* can not be applied directly, since the *S-N* fatigue data are obtained with stress and strain over the yield strength of the material, where the stress intensity parameter ΔK is not valid. Therefore, a formulation based on elastic-plastic fracture mechanic theory is necessary.

O'Donnell's approach defines a correlation between the crack propagation rates, *da/dN*, and *J*-integral for cyclic loads, ΔJ. Despite the ability of the ΔJ to characterize the fatigue crack growth be questionable (originally, *J*-integral concept was developed considering the deformation theory of plasticity, which is violated during unloading), there is experimental evidence to validate the correlation *da/dN* versus ΔJ, [7], [12], [13]. Figure 5 shows the results of tests conducted in fracture specimens under different loading and geometry configurations. As can be observed there is a good correlation in both elastic and plastic regimes, indicating that *J*-integral is an adequate parameter for correlating fatigue crack growth rates under elastic-plastic conditions.

In order to generate *S-N* fatigue curves including reactor water environment, the approach proposed by [11] establishes that: a) first, the current *da/dN* from ASME XI curves are plotted in terms of ΔJ; b) for each point in the ASME III *S-N* fatigue curve evaluate the crack length associated with the specimen failure; c) the *da/dN* expression for air is back-integrated to find the initial crack length; d) forward integration using the *da/dN* for aggressive environment relation between final/initial crack length is then performed to estimate the number of cycles to failure. Results from Figure 6, a plot of the modified and original *S-N* fatigue curve, indicate a reduction in the fatigue life when the aggressive environment is consideredby (by a factor of ten in the intermediate-cycle range).

An additional analytical contribution to investigate the influence of mechanical parameters on fatigue crack growth rates is due to O'Donnell and Rajagopal, [14]. Based on experimental evidences, [15], and considering that *S-N* fatigue design curve are generated using specimens tested under completely reversed loading (no mean stress), it is suggested that cracks may be closed during strain cycles tests. This has an important effect in the fatigue life of the actual components, since mean stresses, caused by residual or applied cyclic stress, open the cracks and produce a crack growth rates greater than those considered by the conventional fatigue experiments.

The crack closure/open effect is modeled in [14], and the results are shown in the Figure 7. It is evident the influence of no crack closure in the *S-N* curve when compared to the existing ASME III design curve. It is clear that if the effect due to aggressive environment is used, the fatigue life is drastically reduced.

5. FUTURE EFFORTS

The analytical work completed to date to predict fatigue life of structural components under hostile environment, could be extended to include new topics or to confirm ideas addressed previously in [11] and [14]. The following are examples of issues on which research could be done:

. Evaluate the fracture parameters K and J related to the standard fatigue specimen. The solution is obtained by three-dimensional finite element models. The K and J values are calculated at every point along the crack front using elastic-plastic analyses and energy approach, such as virtual crack extension method, [16], [17].

. Define a correlation between crack growth rates and J-integral for cyclic loading, taking into account the mean stress. The motivation of this study is to confirm the relationship used in [14], where the closure parameter U, defined by Elber in [15], is obtained by the extrapolation from the results presented in [18].

. Combine the effect of mean stress and the strain rate in the da/dN versus ΔJ equation. This dependence is important in corrosion-fatigue, since this mechanism induces the environmentally-assisted cracking at specific strain rate/mean stress values.

. Investigate the fatigue behavior of short cracks (dimensions that are on the order of the grain size). The goal is to consider the microstructural effect on the crack tip stress and on crack growth rate.

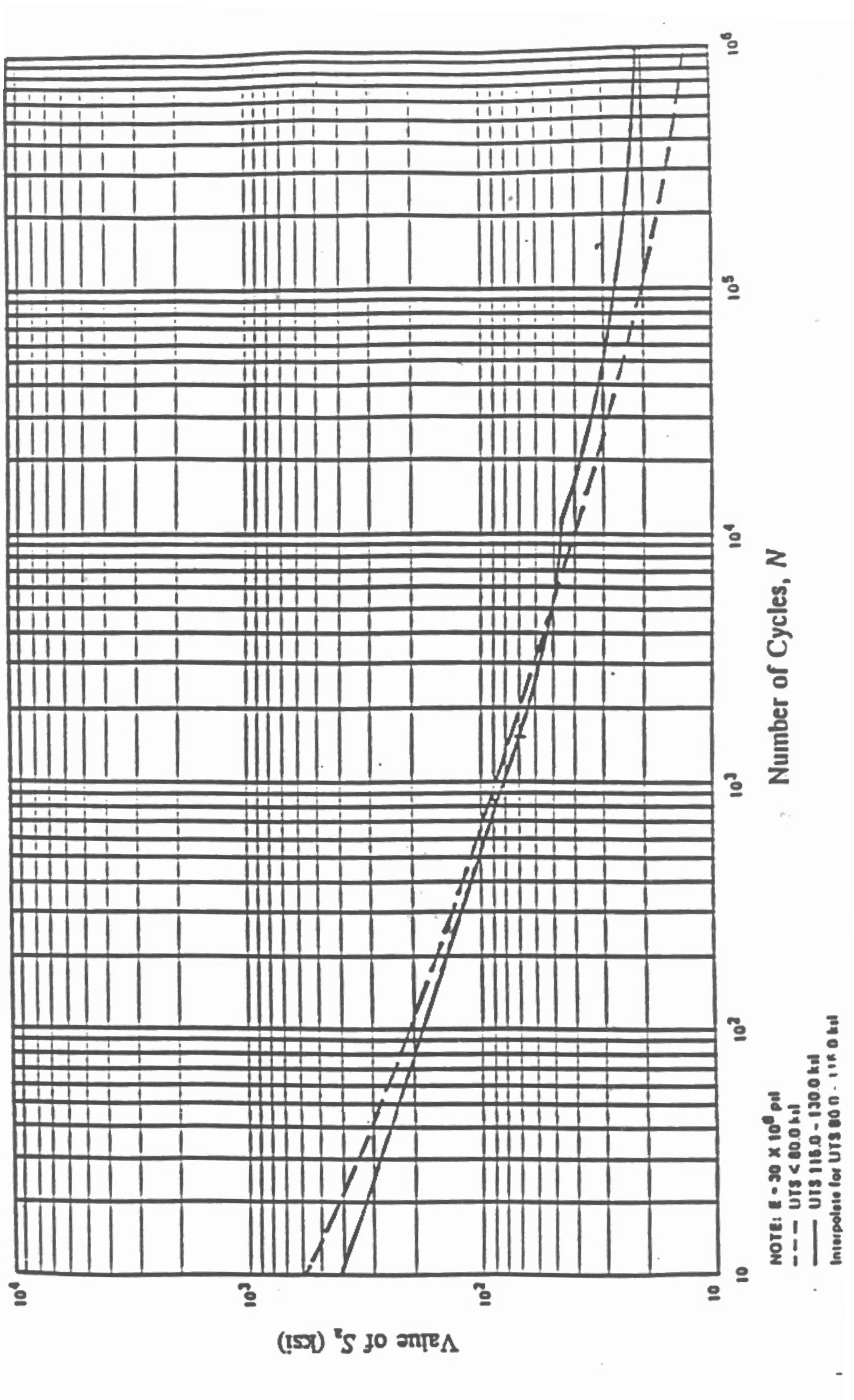

Figure 1 - ASME III S-N fatigue design curve for carbon and low-alloy steels

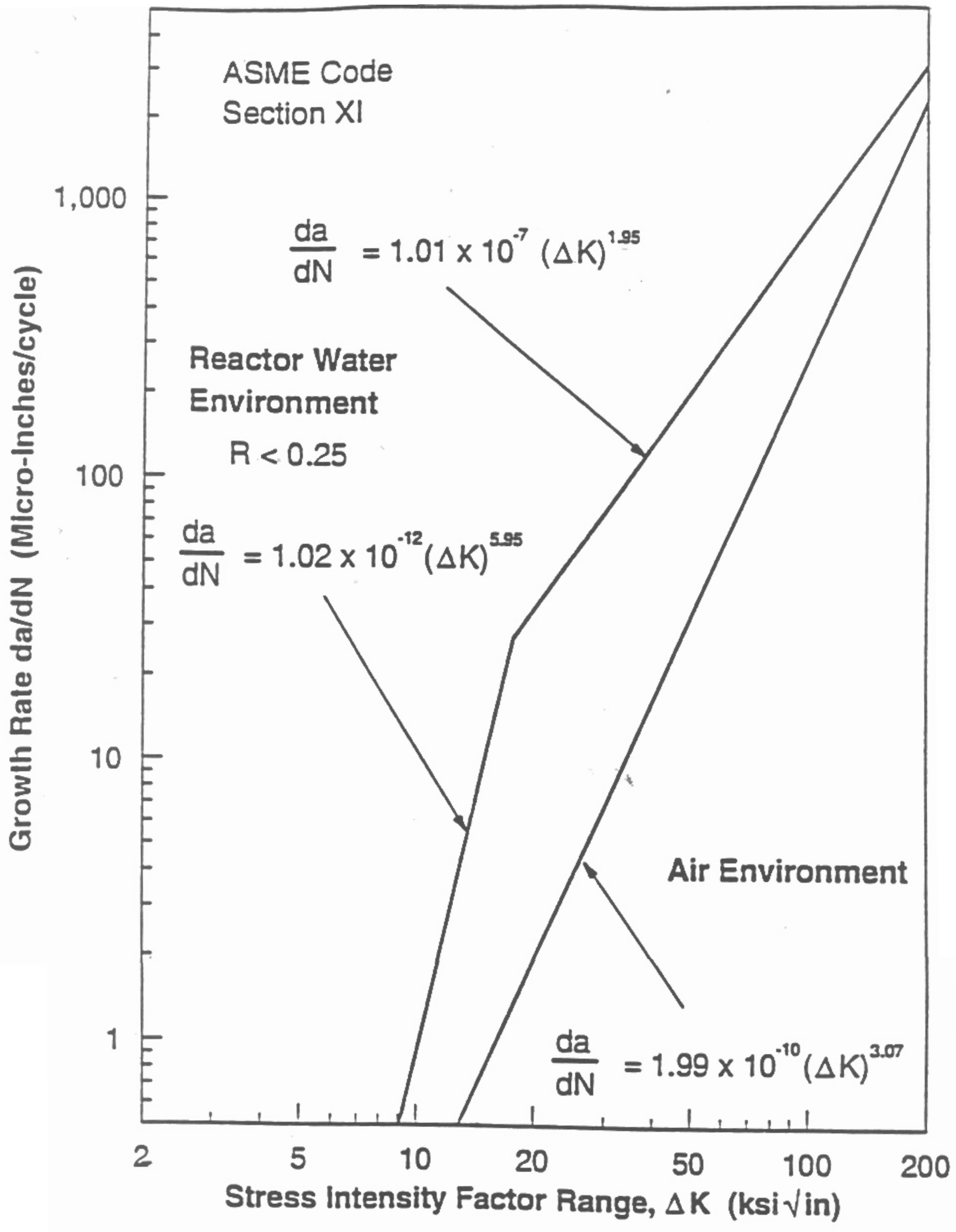

Figure 2 - ASME XI da/dN crack growth rates for carbon and ferritic steels

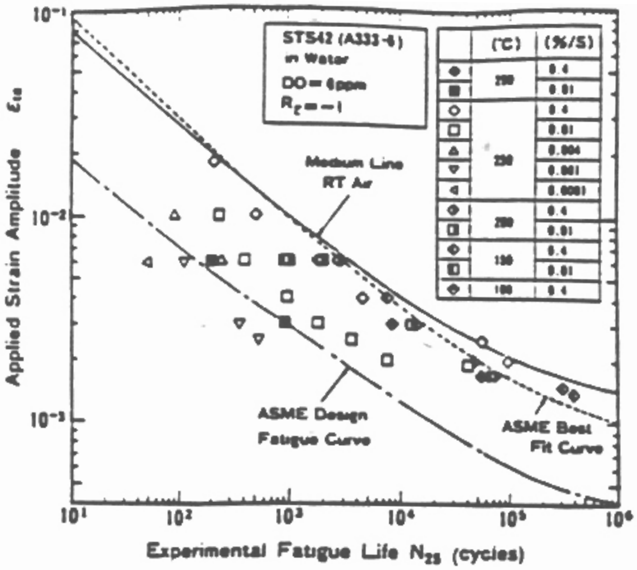

Figure 3 - Strain-cycles in aggressive environment for carbon steel (ref.[3])

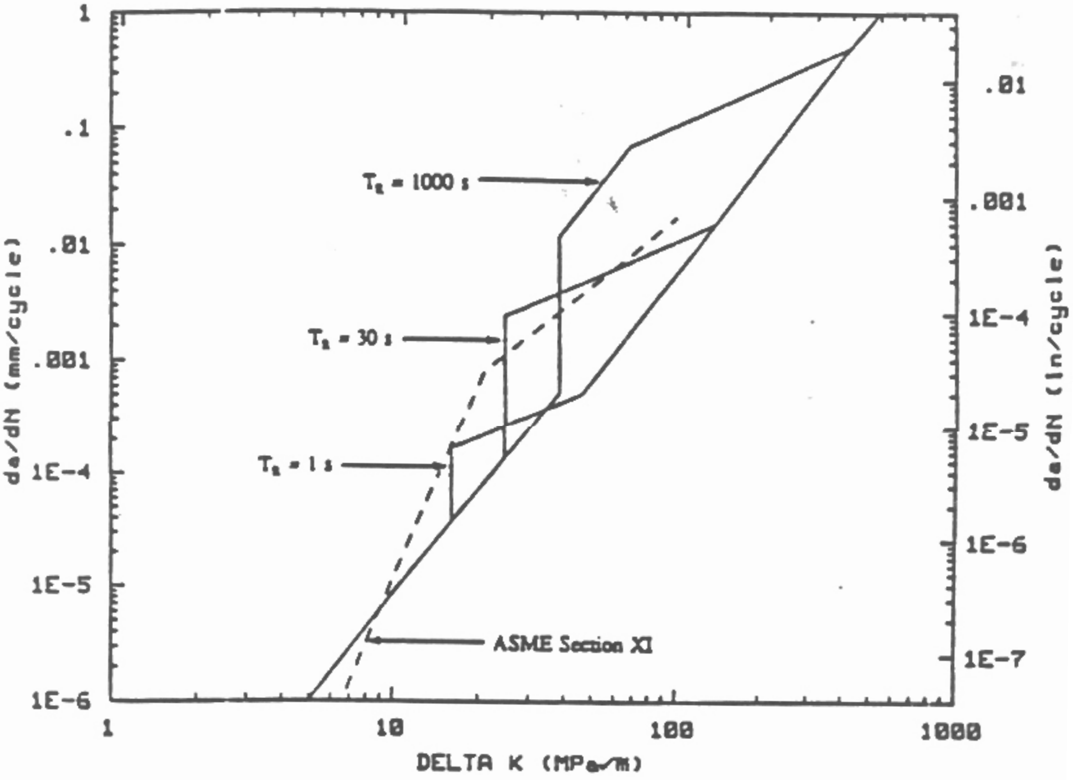

Figure 4 - Crack growth rate proposed in [5] versus current ASME XI data

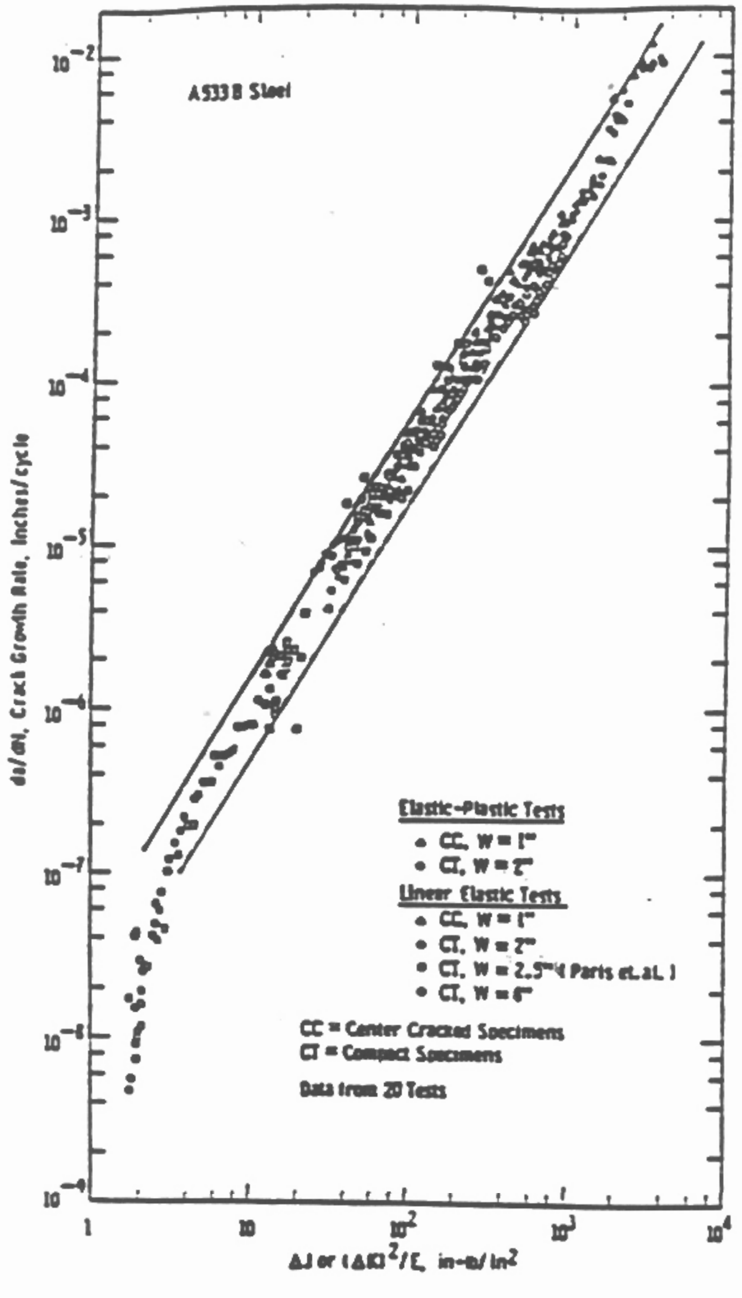

Figure 5 - Crack growth rate and *J*-integral for cyclic loading (ref.[7])

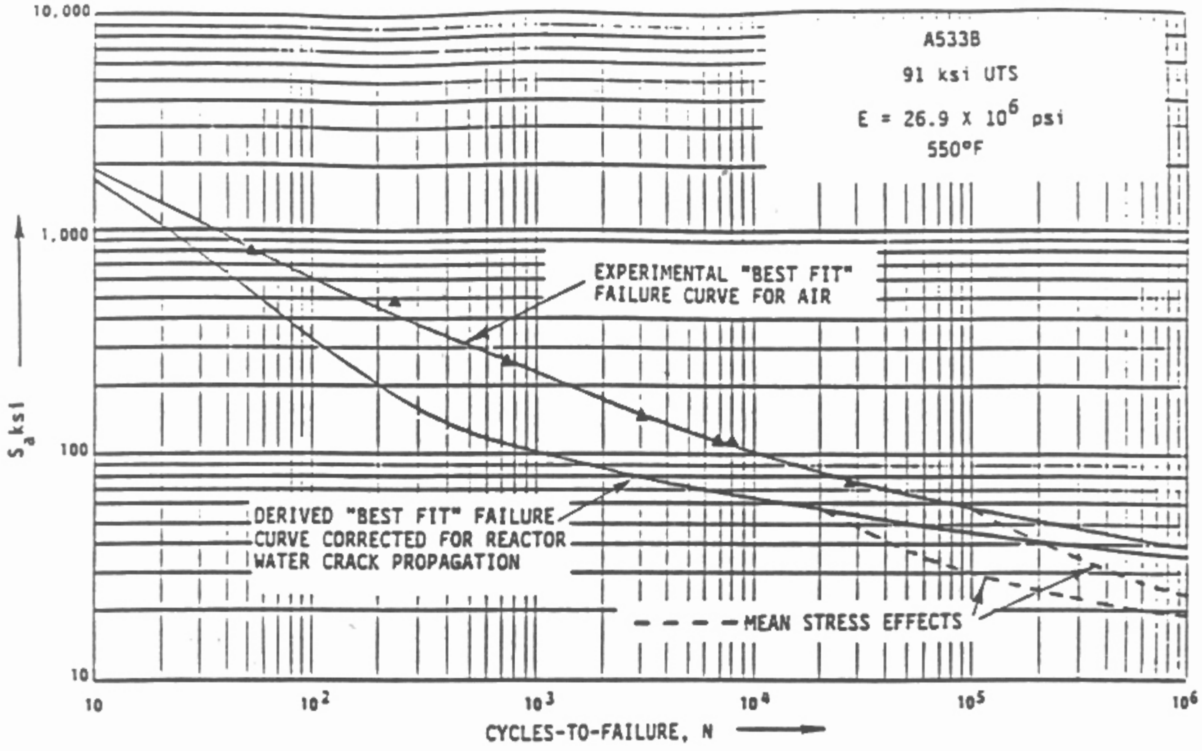

Figure 6 - *S-N* fatigue curve in hostile environment versus current ASME III data (ref.[11])

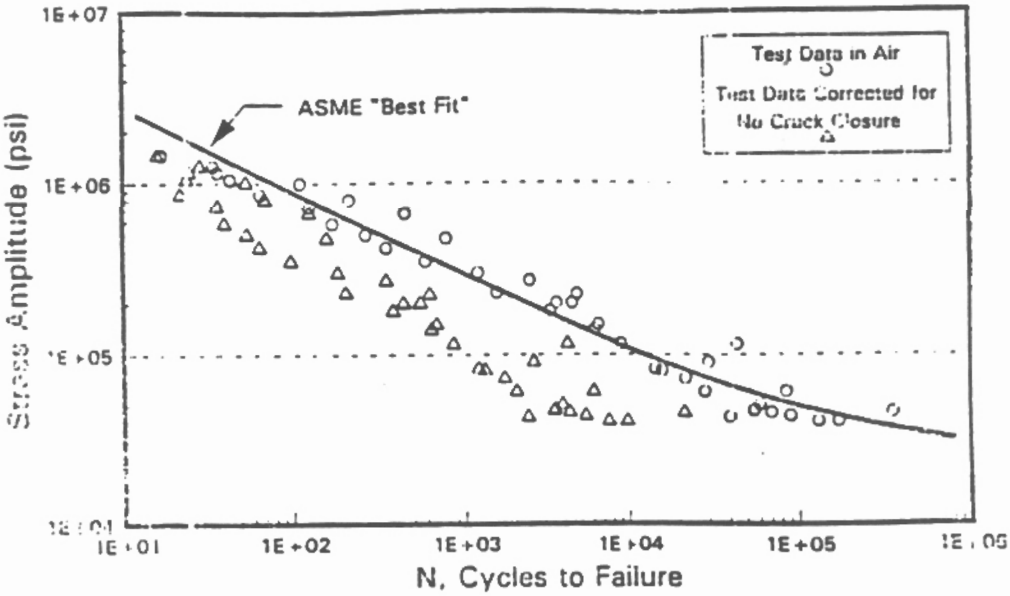

Figure 7 - *S-N* fatigue curve with no crack closure and ASME III current data (ref.[14])

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