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Prevention and Control of Subcritical Crack Growth in High-Strength Metals

R. J. Judy, Jr., and R. J. Goode

Metallurgy Division

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The integrity of structures that must operate in hostile environments depends on both the resistance to the propagation of cracks and the resistance to fracture of the structural material. Design procedures established to assure structural integrity are intended to enable designers systematically to take account of applicable parameters and their relation to various structures. The three-part Ratio Analysis Diagram (RAD) system was developed to provide an analysis technique for ascertaining the significance of fracture, stress-corrosion cracking, and sustained-load cracking in terms of the relationships of critical stress level to flaw size.

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INTRODUCTION

The increasing use of high-strength metals for critical components in highly stressed structures requires the designer to account for potential crack growth and fracture. The fracture problem is more simple than that of crack growth, in that several methods of designing to prevent catastrophic failure exist and are being used. The most direct means of fracture prevention is the use of a material which will withstand excessively high loading at sharp crack locations by yielding without rapid crack propagation; this method is often criticized as overly conservative, but in many cases it is the only practical approach for large complex structures. Crack growth is more insidious than fracture, because subcritical crack growth in a structure designed to be fracture-safe necessitates extensive maintenance and repair, which can be as severe a problem as fracture. For structures which must operate in seawater or in other corrosive environments, prevention of crack growth, as well as general corrosion, is a primary design factor.

There are many micromechanisms by which cracks grow; however, various aspects of macroscopic crack growth are most conveniently classified according to loading and environmental aspects: stress-corrosion cracking (SCC) — sustained load plus environmental factors; sustained-load cracking (SLC) — no aggressive or unfavorable environment; fatigue — cyclic load; and corrosion fatigue — cyclic load plus environment. This paper describes methods to analyze the significance of SCC and SLC properties of high-strength metals, as defined by fracture mechanics, for structural applications which require prevention of subcritical crack growth.

PROCEDURES FOR MEASURING CRACK-GROWTH RESISTANCE

The utilization of linear-elastic fracture mechanics for defining the resistance of structural metals to crack growth in aqueous environments is well documented and is advanced to the point where standardization of test procedures is imminent. As illustrated in Fig. 1, there are three phases of failure in structural components or in laboratory test specimens:

1. Formation of a small pit by corrosion processes
2. Formation and rapid growth of a crack
3. Final failure by fracture processes.

The second phase of rapid crack growth is either SCC, when an environmental effect is present, or SLC, when such an effect is absent. In most structures the presence of small

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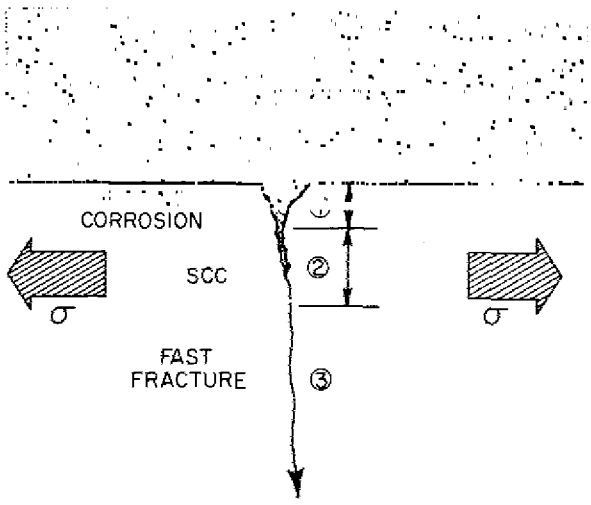

Fig. 1 — Sequence of events in structural failure due to environmental effects. A given metal may not be subject either to pitting or SCC or may be sensitive to both.

cracks and other defects which initiate rapid crack growth eliminates the necessity for considering the first phase. It is most important to understand that all metals are not necessarily subject to either phase 1, phase 2, or both.

For several years, data have been reported for a variety of structural metals defining their resistance to the initiation of SCC in terms of the threshold level of stress-intensity, K_{Iscc} (1-7). The use of linear-elastic fracture mechanics methods that were developed for describing brittle fracture to measure the initiation of crack growth in metals has given structural designers a potential for implementing "safe life" or other design concepts based on crack-growth laws. Before the available data can be incorporated into such design concepts, however, there are three independent questions which must be considered:

1. Is crack growth definitely involved in the reported result, or do the data represent the result of a mechanical test conducted in a wet environment?
2. Are the reported data valid with respect to minimum dimensions of the specimen so that the values are independent of geometry effects?
3. What do the reported data imply for the structure being designed?

The objective of an SCC test is to measure the threshold stress-intensity value K_{Iscc}, above which crack growth will definitely occur (1). This is done by testing fatigue-cracked specimens and applying the calibrations of K_I developed for fracture toughness testing; because of the physical similarities between test specimens, the requirement for crack growth is often forgotten or ignored. Figure 2 shows schematically the configuration of one type of test specimen and illustrates the difference between the "insensitive" case at the top and the "sensitive" case at the bottom. Tests involving no crack growth constitute long-term fracture tests conducted in a wet environment; the results of such tests are not significant for design to prevent subcritical crack growth.

The validity of the threshold concept using stress-intensity parameters for defining the resistance to SCC initiation has been demonstrated (2). There are two methods for applying

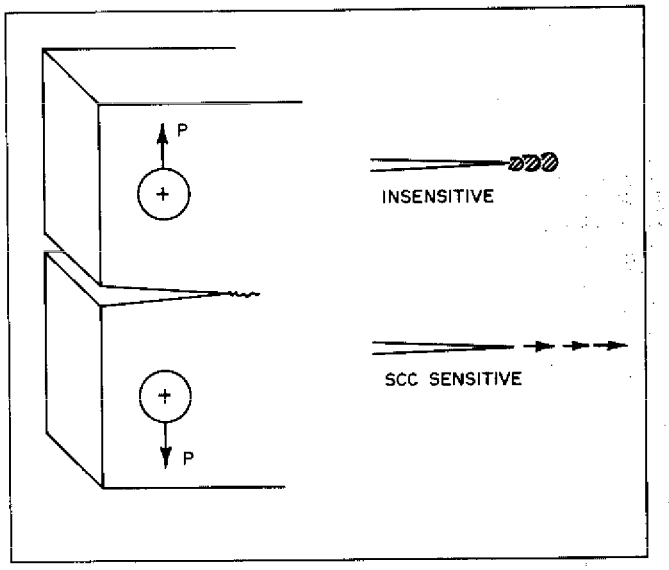

Fig. 2 — Schematic illustration of laboratory tests for stress-corrosion cracking. The intent of such tests is to measure the sensitivity of materials to crack propagation. By SCC mechanisms.

fracture mechanics. The initiation method (Fig. 3) employs a cantilevered, dead-weight loading system so that crack growth results in increasing applied K_I; for this reason a system of bracketing data derived from specimens with and without crack growth is necessary to define the threshold K_{Iscc} value (1). The arrest technique utilizes a bolt-loaded (constant deflection), modified wedge-opening-loaded specimen that has a decreasing K field with increasing crack length (2-4). In this method, the specimen is loaded to an applied K_I well above the expected K_{Iscc}, and the crack is allowed to propagate until it arrests at K_{Iscc}.

In both tests, there are criteria for assuring that the results are independent of geometrical effects. These take the form of minimum dimensions of the test specimen; i.e., crack length a and thickness $B \geqslant 2.5\ (K_I/\sigma_{ys})^2$. These dimensions are recommended until more definitive results on geometrical effects are available. Requirements for specimen dimensions and crack growth ensure that the K_{Iscc} value is characteristic of the material for a specific environment and that the analysis technology developed for fracture mechanics can be applied.

It is important to note that validity criteria for specimen size are not related to crack growth. It is certain that crack growth due to environmental effects can be a structural problem in cases where a completely valid K_{Iscc} could not be defined. The fact that valid K_{Iscc} values could not be measured does not alleviate the crack-growth problem; however, from general experience, it can be observed that severe crack-growth problems are most often associated with dimensionally valid K_{Iscc} values, as will be seen in later sections.

ANALYSIS PROCEDURES

There are no direct implications for structural design that are uniquely related to K_{Iscc}, as with other parameters, K_{Iscc} must be evaluated in the context of other design variables. The first line of defense for protection of a given structure from SCC is the selection of a material that is completely immune or insensitive to environmental effects. Such materials

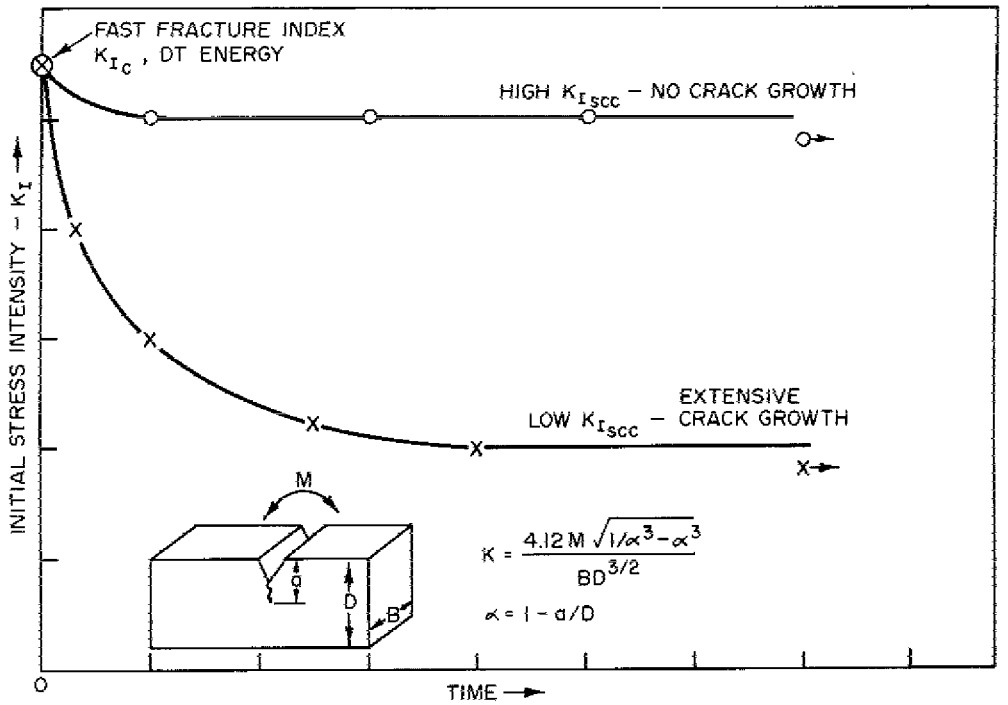

Fig. 3 — Graph of K_{Iscc} determined by cantilever test method. Purpose of test is to determine threshold level for crack propagation.

do exist; however, one is not always at liberty to use them and is therefore sometimes required to face the possible effects of crack growth on the operating life and general integrity of the structure. Furthermore, because of incomplete reporting in the literature, it is difficult to separate valid and invalid test data, and those data that involve crack growth from those that do not. Until this situation is rectified by standardization of test and reporting procedures, one must systematically attempt to evaluate the reported data in terms of the important factors and the design in question.

The procedure for making such analyses is to use existing relationships of critical stress/flaw conditions calculated from fracture mechanics equations and a general analysis capability afforded by the Ratio Analysis Diagram (RAD) (8) with modifications to include SCC (9). Since the parameter K_{Iscc} describes the applied K_I level for the beginning of crack growth, equations such as the surface-flaw equation and the through-crack equation apply only for the SCC initiation; nothing is implied regarding crack growth as a function of time. The available analysis tools are the stress-intensity for SCC initiation and the final crack size for failure as given by the fracture resistance parameter.

The surface crack equation (Fig. 4) can be utilized to demonstrate the type of analyses that can be made for either fracture or SCC. Plotting the crack-depth parameter a/Q versus the ratio of K_{Ic}/σ_{ys} or K_{Iscc}/σ_{ys} for various levels of applied stress reveals some crucial factors. Figure 4 is divided into regions of high ratio, low ratio, and intermediate ratio according to the following rationale: A general inspectability limit for flaws and defects

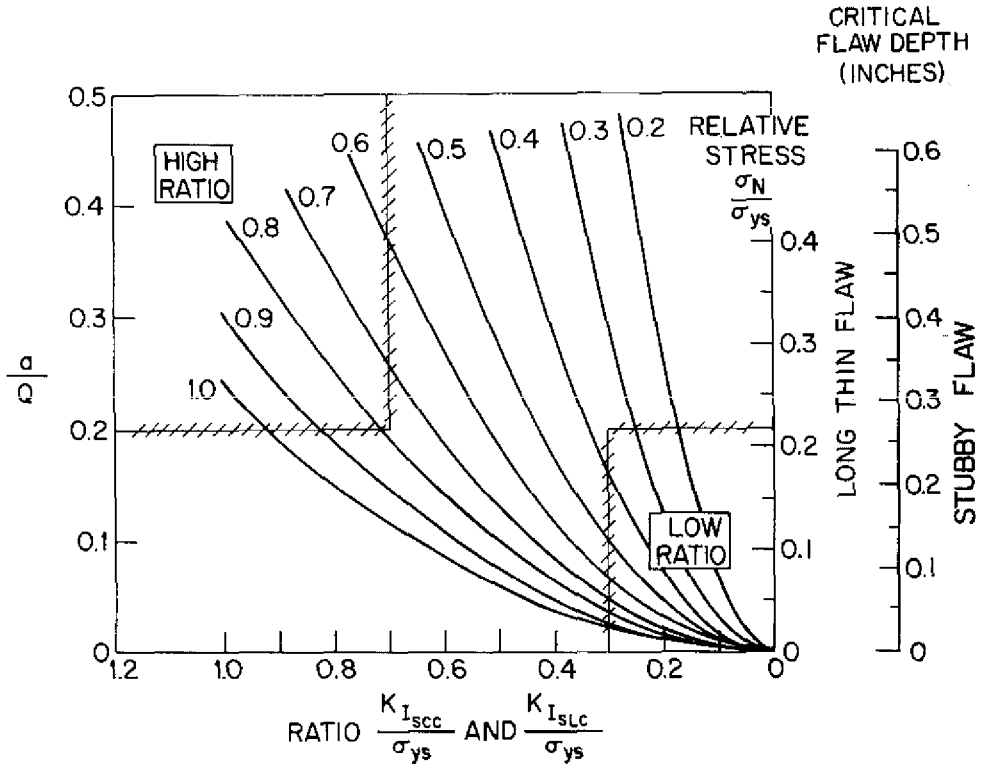

Fig. 4 — Fracture-mechanics plot of surface-flaw equation. The regions of "high ratio" and "low ratio" are related to limitations on detectability of flaws.

by the usual methods is considered to be at an a/Q value of approximately 0.2; this translates to actual flaw sizes in the range from 0.18 inch deep X 1.80 long up to 0.28 inch deep X 1.12 long. The range of K_{Iscc}/σ_{ys} ratios that is typical of the data reported can be divided into three parts by the ratio values of 0.7 and 0.3. Thus, the high-ratio region bounded by a/Q $\geqslant$0.2 and $K_{Iscc}/\sigma_{ys} \geqslant 0.7$ is representative of conditions where high stresses and large cracks are necessary to cause SCC initiation. Conversely, the low-ratio region is representative of conditions where SCC crack growth can initiate from very small defects at moderate to low levels of stress. The low-ratio region is therefore one to be avoided because of the present lack of capability to detect cracks of the critical size. The intermediate, or transitional, region is one where the combinations of high stresses and small flaws, low stressess and large flaws, or intermediate stress levels and flaw sizes are critical; these conditions are more tolerable than those in the low ratio and constitute the range where highly refined application of fracture mechanics technology is required for adequate design.

The significance of the separations is more apparent from the plot of Fig. 5. In this figure, K_{Iscc} data zones for a variety of steels are plotted against a grid of lines of constant K_{Iscc}/σ_{ys}. The lines represent a fracture-mechanics-based plot of K_{Iscc} and σ_{ys} and can be keyed to the flaw-size diagram of Fig. 4, or to other existing analyses. The location of the data points with respect to the grid lines indicates whether each material is in the low-, intermediate-, or high-ratio region.

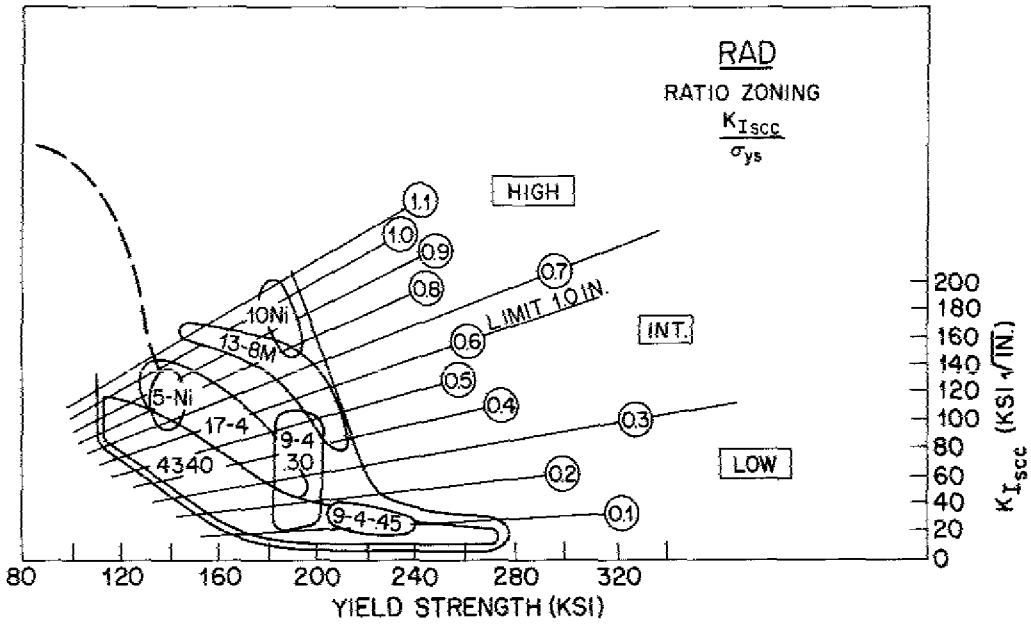

Fig. 5 — Characteristic data zones for various steels showing their relation to K_{Iscc}/σ_{ys} ratio lines. These lines reference combinations of flaw size and stress level for the onset of SCC as shown in Fig. 4. The dashed line illustrates the SCC sensitivity transition with increasing yield strength. The levels of "high," "intermediate," and low ratio are referenced to Fig. 4.

The dashed line in Fig. 5 shows another factor: the transition in sensitivity to SCC with increases in yield strength. Data for materials that are completely insensitive to subcritical crack propagation are not represented on this SCC plot; however, the notation of "insensitive" indicates that in the absence of environmental effects, the technology for guarantee of structural integrity is concerned only with fracture and fatigue crack growth. It has been observed for steels that a general trend does exist wherein the yield-strength range beginning at approximately 120 ksi marks the range where crack-growth problems begin to become apparent. This is somewhat lower than the yield strength for a similar transition in fracture resistance, but the effect is the same. It appears that the metallurgical principles that are utilized to increase strength contribute to crack-growth problems at the same time.

Plots of the type of Fig. 5 can be overlaid on the RAD (as shown in Fig. 6) so that fracture and SCC properties can be compared. Such comparison is necessary to interpret the severity of subcritical crack growth on structural integrity. If the final failure is by fracture, the life of the structure is determined by the size of defect or crack that can be tolerated for a given loading system; this in turn is defined by the fracture resistance property. Structures designed with materials having high fracture resistance have the capability of containing large flaws, so that the problems of SCC are related to inspectability and maintenance; however, those structures which are designed with materials of low fracture resistance might suffer sudden crack extension after a short period of crack growth.

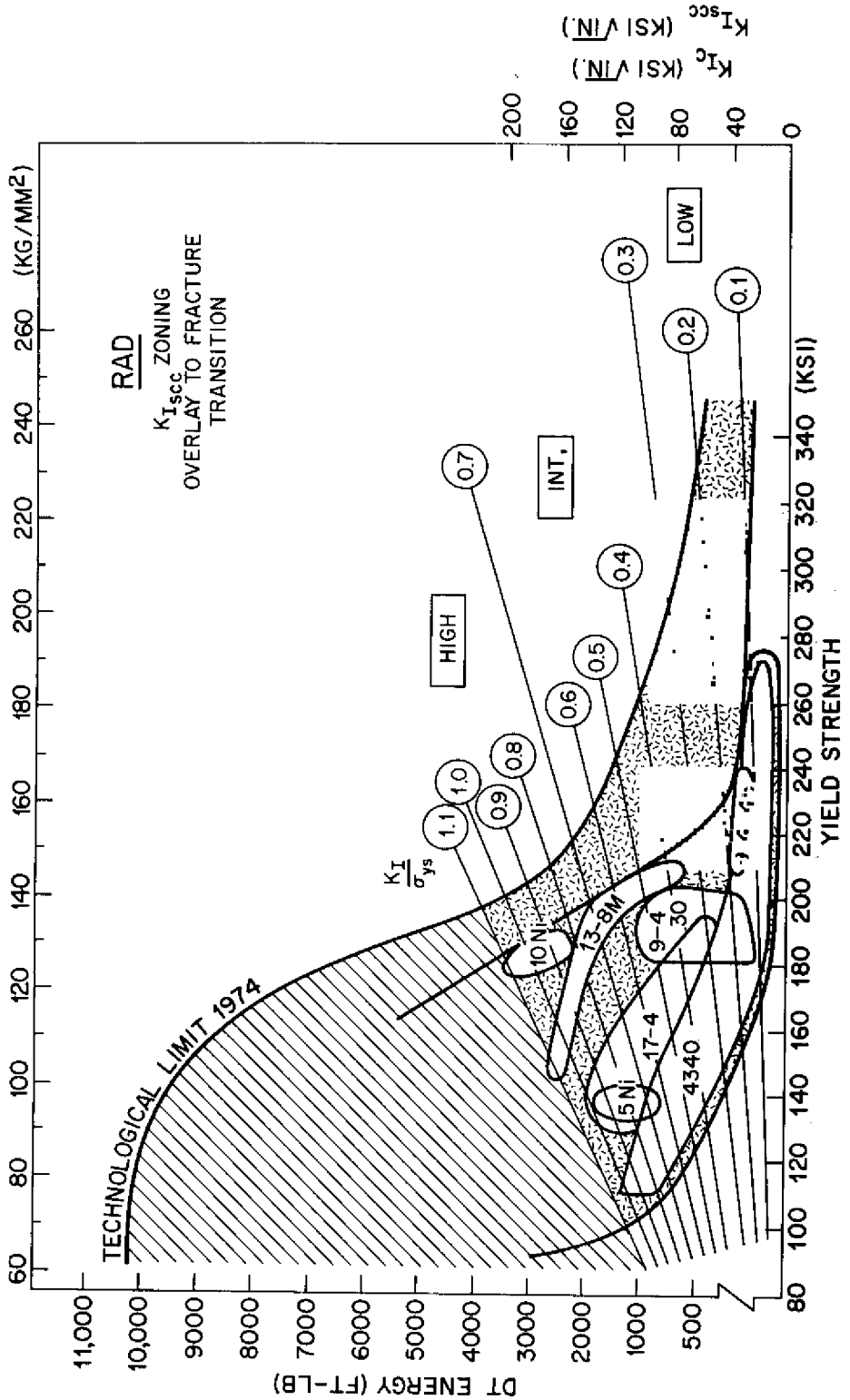

Fig. 6 — Ratio Analysis Diagram for SCC of various types of steel.

For the above reasons, the comparisons of fracture and SCC properties on the RAD are a most important factor in material selection. The RAD system has two independent indices of fracture resistance — K_{Ic} and dynamic tear (DT) energy — which apply to brittle or elastic fracture, and to ductile fracture, respectively. It is emphasized that K_{Ic} does not give a true measure of the fracture resistance of ductile materials and cannot be utilized for this purpose. The plane-strain limit is defined by the ASTM Committee on Fracture (10) in terms of the thickness B, as $B \geqslant 2.5\ (K_{Ic}/\sigma_{ys})^2$. On the RAD, plane-strain limits for given thicknesses of material are plotted as K_{Ic}/σ_{ys} ratio lines.

The data plots of SCC properties occupy the lower part of the RAD (Fig. 6); i.e., the higher fracture resistance levels indicated by the technological limit (TL) line are not attained for the case of SCC. This is because the only SCC zones shown are those for the cases where crack growth was present for linear-elastic loading; thus by definition these fall in the range of ratio lines. Materials that are insensitive to SCC would be represented on the RAD only by the fracture properties (DT or K_{Ic}).

The RAD provides a means of examining several factors simultaneously; the case of a high-strength, precipitation-hardening stainless steel (Fig. 7) is a good example of effects of strength and environment on the degree of SCC sensitivity. Fracture properties are shown to be in the plastic-fracture range for lower strength levels and in the plane-strain range for the higher strength levels. Such effects of decreasing fracture resistance with increasing strength have been observed for other metal systems. Similar effects are shown in the salt-water SCC properties of this steel by the data zones coded "SCC" and "cathodic-couple." These zones represent K_{Iscc} values for the open-circuit condition and for the condition of electro-chemical coupling to metals commonly used in cathodic protection systems — Al and Zn — as well as Mg. The shapes of the data zones outside the plane-strain region for "SCC" and "cathodic couple" are dictated by the thickness of the test piece. If very thick sections should be tested, these zones would likely assume a position parallel to the fracture zone. In point of fact, the data zones are plotted with the understanding that crack growth was present on the specimens that are dimensionally invalid for the values below approximately 140-ksi yield strength for SCC and 120-ksi for "cathodic couple" condition.

To use this high-strength stainless steel for applications in a seawater environment, one must perform a very careful analysis of potential crack growth. The most important single aspect is that a maximum must be placed on the yield-strength value that will absolutely preclude brittle fracture. The SCC properties dictate that a maximum allowable yield strength less than that for fracture would be necessary to absolutely prevent SCC under linear-elastic conditions. It was noted that crack growth in test specimens was present for all strength levels regardless of the stress state — linear-elastic or plastic loading. It is also apparent that cathodic protection systems which depend on sacrificial zinc or aluminum bars to prevent general corrosion aggravate the SCC problem by lowering the K_{Iscc} value.

An SCC RAD for titanium alloys including some of the major alloy families is shown in Fig. 8. Data to form this RAD were taken from the Damage Tolerant Design Handbook (5) and include only the data which meet the thickness criteria. Whether or not crack growth was present could not be determined from this listing. Some data from previous NRL studies are also included. Two of the alloy systems — 721 (Ti-7Al-2Cb-1Ta) and 811 (Ti-8Al-1Mo-1V) are well known for sensitivity to crack growth in salt water. The other two alloys—6-4

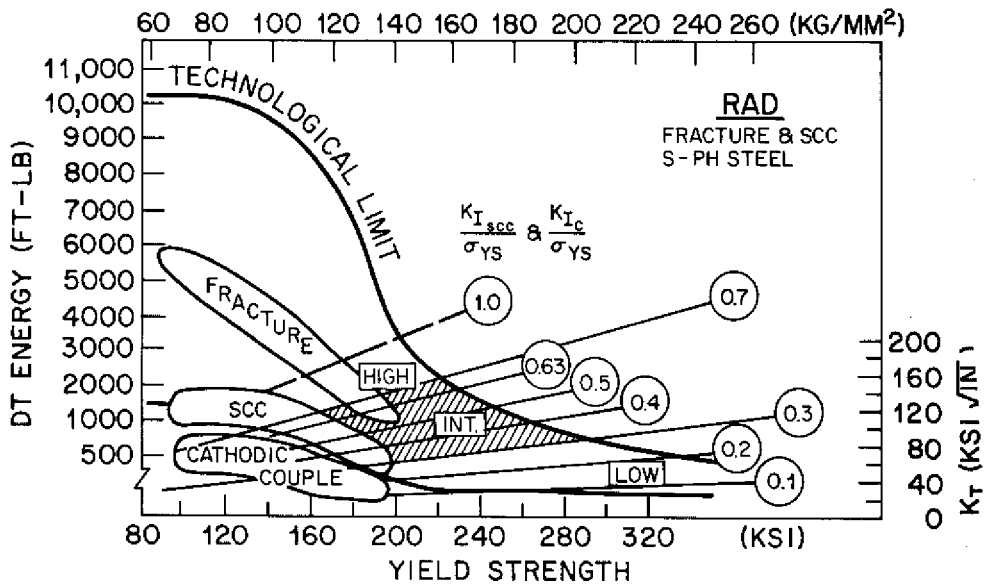

Fig. 7 — Ratio Analysis Diagram showing the fracture and SCC properties for S-PH, a high-strength stainless steel.

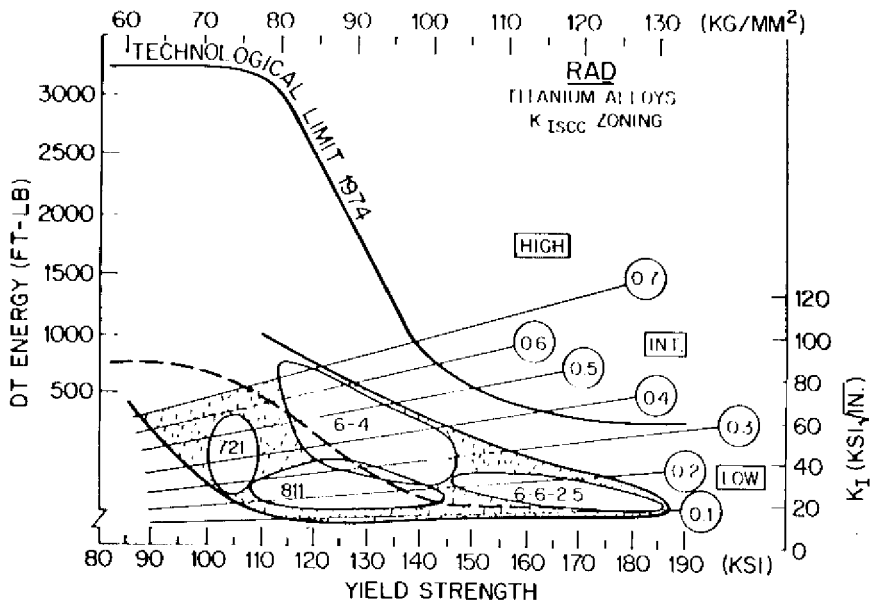

Fig. 8 — SCC RAD for several titanium alloy families.

(Ti-6Al-4V) and 6-6-2.5 (Ti-6Al-6V-2.5Sn) — are not sensitive to salt water in all heat-treated conditions; accordingly, the data zones may well be representative of either the fracture-resistance properties or the SLC properties of these alloys.

Sustained load cracking is a phenomenon that may affect titanium alloys to a higher degree than other structural materials. The failure mechanism is one of crack growth in an air environment at moderate to high stress levels. Figure 9 summarizes results for a sample of 6-4 (11) tested in the cantilever-bend configuration (top) and as a part-through crack (PTC) tension panel (bottom). The decrease in load-carrying capability for a PTC specimen with a constant flaw size is indicated in the circles denoted "applied stress/yield stress." It is noted that the absolute stress levels would change for different crack sizes, but the decrease would remain approximately the same.

Results obtained to date indicate that the SLC phenomenon is analagous to SCC and can be handled by the same RAD methods as apply to SCC. The data points in the 6-4 zone of Fig. 10 indicate the SLC properties for selected samples of 6-4. The particular samples of 6-4 included in this selection encompass a wide range of processing variables and interstitial oxygen content (which is the dominant factor in determining fracture resistance). Note that the data points cover the range of SCC properties measured for the Ti-6Al-4V system; this may be taken as evidence that the same phenomenon might be responsible for the crack growth in both cases. Therefore crack growth in this alloy may not be caused by the saltwater environment, although the K_{Iscc} values are completely valid with respect to dimensions and crack-growth evidence.

SUMMARY

The long-term reliability of structures is dependent on the tolerance for flaws and cracks that is inherent to the structural material. Problems of inspectability and maintainability can be as detrimental to the life of structures that must operate in a corrosive environment as the more apparent problem of catastrophic fracture. In this paper, methods based on technology derived for prevention and analysis of fractures are adapted to facilitate material selection and design for situations involving crack growth under sustained load. The significance of critical levels of stress intensity can be determined by use of a RAD format designed for this purpose. The three-part RAD permits determination of the degree of severity of crack growth problems in terms of the K_{Iscc}/σ_{ys} ratio or the K_{ISLC}/σ_{ys} ratio. The latter case (sustained-load cracking), rather than the dynamic fracture resistance properties, may well be the dominant design factor for applications involving highly stressed titanium alloys.

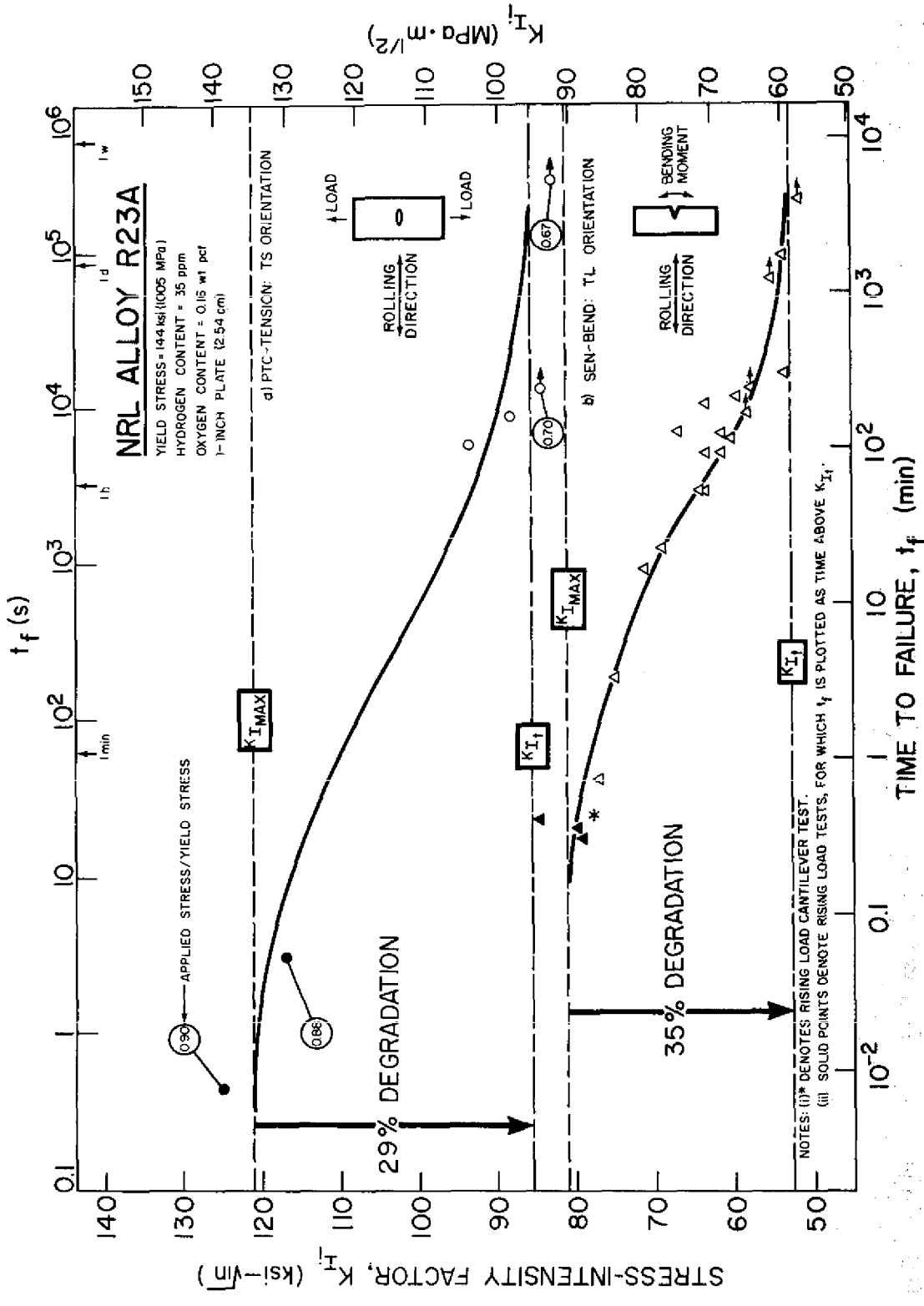

Fig. 9 — Sustained-load cracking of a commercial grade Ti-6Al-4V material in ambient air environment. Part-through crack specimens (top) and bend specimens (bottom) were used to measure the SLC properties for two crack-plane orientations.

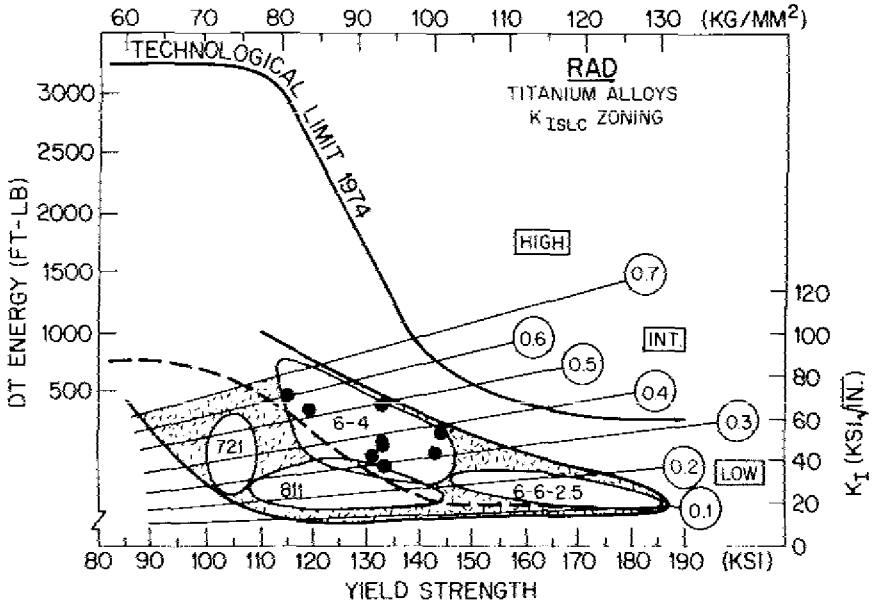

Fig. 10 — RAD comparison of SLC properties of Ti-6Al-4V alloys with the data zone for salt water SCC.

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