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Stress-Corrosion Cracking Characterization Procedures and Interpretations to Failure-Safe use of Titanium Alloys

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ABSTRACT

Ratio Analysis Diagram (RAD) interpretive procedures have been evolved recently to provide generalized engineering solutions for fracture toughness assessments of structural titanium alloys. Failure-safe design also requires consideration of possible subcritical crack propagation (slow fracture) due to stress-corrosion cracking (SCC). Procedures for the incorporation of SCC characterizations into the RAD system have now been developed. These procedures serve the dual purpose of providing simplified interpretations of critical flaw size-stress instability conditions by the consideration of the resistance of the material to both fast fracture and SCC. The failure conditions are expressed in terms of K_I/σ_{ys} ratios, which provide an index of the general level of critical flaw sizes. The combination RAD also features limit lines that indicate (1) the highest level of K_{Iscc}/σ_{ys} ratios for which accurate plane strain interpretation to flaw size-stress conditions for SCC can be made for 1-in.-thick plate and (2) the highest level of SCC resistance measured in extensive surveys of plate material of this thickness.

PROBLEM STATUS

This report completes one phase of the problem; work on other aspects of the problem is continuing.

AUTHORIZATION

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STRESS-CORROSION CRACKING CHARACTERIZATION PROCEDURES AND INTERPRETATIONS TO FAILURE-SAFE USE OF TITANIUM ALLOYS

INTRODUCTION

Titanium alloys are of interest for use in structures requiring materials of a high strength-to-density ratio. As with other metal systems, alloys which otherwise feature desirable fracture toughness characteristics have been found to be susceptible to stress-corrosion cracking (SCC) in aqueous and other liquid environments. The degree of susceptibility is strongly influenced by metallurgical variables, such as chemical composition, processing, heat treatment, and microstructure. Such susceptibility results in subcritical flaw growth (slow fracture) for flaw size-stress conditions which would be considered safe with respect to the development of fast fracture.

Fracture mechanics theory has provided procedures for defining the critical crack-tip stress-intensity K value for the initiation of both subcritical and fast fracture. Laboratory specimens featuring cracks of a defined type provide for establishing the characteristic instability K value for a material of interest. The characteristic value may then be used for the calculation of flaw size-stress conditions which relate to natural flaws in structures. Accurate definitions of such instabilities are presently limited to the case of plane strain K_{Ic} conditions. This is the condition of maximum crack-tip constraint and therefore of the smallest possible plastic zone size which can be imposed on the metal. For the case of plane stress K_c conditions, the plastic zone is larger; the specific size depends on the level of geometry-dependent constraint that is applied. For the plane stress K_c conditions approximate lower bound definitions of critical flaw instabilities can be made from approximations of K_c-K_{Ic} relationships. For such calculations the specific section size must be considered in relation to the critical value required for plane strain conditions. While the approximation procedures (1) may serve a wide variety of engineering purposes for the case of fast fracture, there is presently no basis for extension of this approach to the case of subcritical flaw growth. This report is concerned with providing a preliminary analysis of the interpretability of fracture mechanics K_{Iscc} data to failure-safe design for titanium alloys susceptible to SCC in salt water. In particular, the position of SCC-sensitive materials in the Ratio Analysis Diagram relating to fast fracture is explained so that direct comparisons of the two types of fracture instability processes can be made.

EXPERIMENTAL PROCEDURE

The SCC test method used in this study was the precracked-cantilever bend test introduced by Brown (2). The specimen consisted of bars of rectangular cross section, containing a fatigue crack at the root of a machined notch, Fig. 1. Some specimens were side grooved along the surface to a depth of 5% of the specimen width B to induce a desired, straight stress-corrosion crack front. The specimen dimension D indicated in Fig. 1 corresponds to the thickness of the plate material being investigated. The specimens were loaded in cantilever fashion in the presence of a 3-1/2% NaCl solution. Details of the testing procedures used are given in Ref. 3. Typical SCC characterization curves obtained in cantilever bend tests for 1-in. plate are shown in Fig. 2 for an alloy

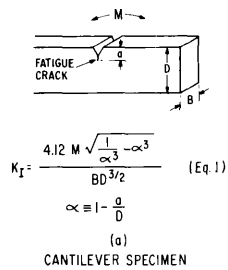
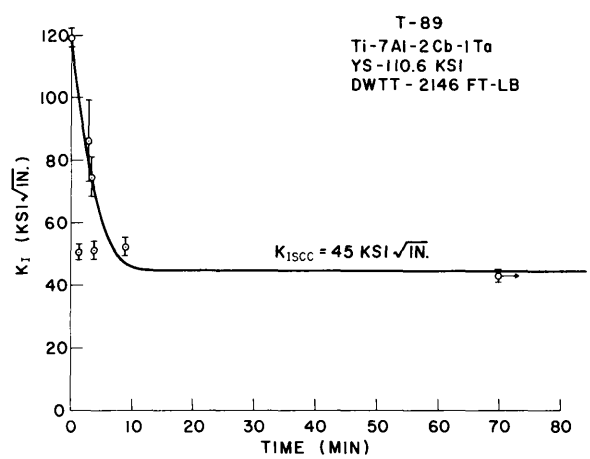
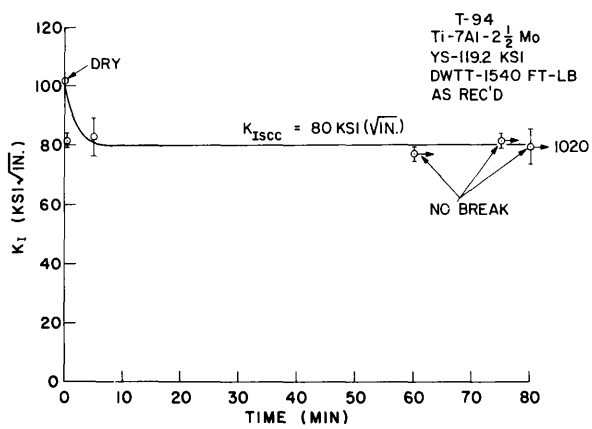


Fig. 1 - Cantilever bend SCC specimen; the equation applies to the calculation of the stress-intensity factor K_I



(a) Alloy of low resistance to saltwater SCC



(b) Alloy of high resistance to saltwater SCC

Fig. 2 - Typical SCC characterization curves

which is susceptible to saltwater SCC (2a) and an alloy which is highly resistant to the environment (2b).

FRACTURE MECHANICS ASPECTS OF SCC

The K_{Iscc} values obtained for the cantilever bend specimens accurately predict conditions for SCC for surface-cracked plates provided the conditions for plane strain are met. For example, Judy and Dahlberg have shown exact predictions by the cantilever bend test for the tensile load failure of large plates containing surface fatigue cracks. The tests were conducted for a titanium alloy of relatively high sensitivity to SCC (4).

Fracture mechanics tests require that maximum mechanical constraint exist at the crack tip to ensure that conditions for valid plane strain measurement are attained. The specimen thickness (B of the cantilever bend specimen) must be of a specified minimum dimension for the attainment of the plane strain condition. All the data to date indicate that conditions for plane strain and minimum K_{Iscc} threshold values are definitely met for the cantilever bend SCC test, if the thickness of the specimen conforms (5) to

$$B \geq 2.5(K_{Iscc}/\sigma_{ys})^2,$$

where

B = specimen thickness,

K_{Iscc} = plane strain stress-intensity threshold value for SCC (ksi $\sqrt{\text{in.}}$),

and

σ_{ys} = yield stress (ksi).

If the B value is less than specified by the above equation, the fracture conditions may entail either mixed-mode, plane stress (elastic-plastic), or full plane stress (gross strain) constraint features. For the plane strain condition, shear lip formation is minimized, and the SCC crack will extend completely across the B dimension of the specimen with a straight front. For mixed-mode fracture conditions, the stress-corrosion crack tunnels between shear lips which are formed at the surfaces of the specimen due to the loss of constraint at these positions. For full plane stress conditions, where mechanical constraint is essentially lost across the entire B dimension, stress-corrosion cracking is not observed. Detailed discussions of mechanical constraint aspects are presented in a simplified form in Ref. 6. It is important to note that use of side grooves does not decrease the defined B thickness requirement for plane strain conditions (7).

A simplified quantitative procedure for generalized characterization of fracture toughness in terms of critical flaw size-stress level relationships for fast fracture was evolved recently for high-strength titanium alloys (1). This concept has been defined as the Ratio Analysis Diagram (RAD). The RAD procedure was based on correlations developed between the Dynamic Tear (DT) and K_{Ic} fracture toughness tests. Engineering interpretations of the critical flaw size-stress levels for fast fracture are derived by the location of K_{Ic}/σ_{ys} ratio lines of 0.5, 1.0, 1.5, and 2 in the subject diagram, Fig. 3. The significance of the ratio lines is as follows:

1. Above a ratio of 2 — Nominal stresses considerably in excess of yield and crack lengths and depths many times the plate thickness are required for fracture of 1- to 3-in. plates in a fully ductile mode.

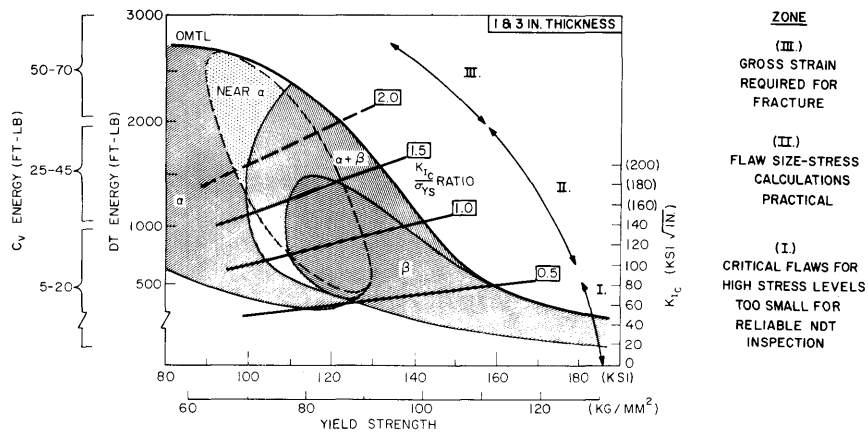


Fig. 3 - K_{Ic}/σ_{ys} RAD for generic titanium alloy families

2. Ratios between 1.5 and 2 — Nominal stresses above yield and through-thickness flaws, with lengths and depths in excess of the plate thickness, are required for the initiation of fracture of 3-in.-thick plate. Mixed-mode, plane stress conditions will prevail for the 3-in. plate thickness.

3. Ratios between 1.0 and 1.5 — Stresses considerably in excess of the plate thickness are required for fracture propagation of 1-in. plate in a plane stress, fully ductile mode.

4. Ratios between 0.5 and 1 — Critical flaw depths in the order of tenths of inches are sufficient to cause plane strain fracture at relatively high levels of elastic stress for both 1- and 3-in. thicknesses.

5. Below a ratio of 0.5 — Relatively low elastic stresses and minute flaws (critical flaw depths in the order of hundredths of inches) are sufficient to initiate and propagate plane strain fractures for 1-in. and larger thicknesses.

A further simplification, which is applicable for 1- to 3-in. sections, may be made for preliminary engineering assessment purposes:

$K_{Ic}/\sigma_{ys} > 1.5$ — No need to calculate flaw sizes — these are very large and are associated with plastic loading.

$K_{Ic}/\sigma_{ys} < 1.5$ but > 0.5 — Definition of approximate critical flaw size and stress may be derived from charts presented in Ref. 1.

$K_{Ic}/\sigma_{ys} < 0.5$ — Critical flaw sizes are very small and may be below reliable detectability limits.

The position of the zones representing the expected properties of various generic families of titanium alloys are noted in Fig. 3. The relative location of these zones with respect to the K_{Ic}/σ_{ys} ratio lines defines the fracture characteristics of the material. Because of the wide ranges of fracture toughness involved for each family, it is obvious that specific data for a metal of interest should be obtained for meaningful analysis. The Optimum Material Trend Line (OMTL) depicts the highest fracture toughness quality (best material) obtained for the level of yield strength, as defined by the DT test. This line may be considered as the "leading edge" of the present technology.

It should be emphasized that subcritical (slow) crack propagation due to environmental factors does not represent a degradation of the fast fracture toughness of a material as defined by the RAD. For a specific flaw subjected to a stress intensity less than the K_{Ic} value but above the K_{Iscc} value, crack growth due to SCC will occur until the flaw size-stress conditions corresponding to K_{Ic} stress intensity are reached. Fast fracture separation of the remaining metal will then follow. The final failure by fast fracture may also develop for K_c stress intensities involving nominal stresses below yield. High SCC sensitivity for a metal of high fracture toughness results in a drastic reduction of its fracture safety in the presence of large flaws to a condition such that small flaws and low elastic stresses can cause failure due entirely to relatively slow subcritical crack growth. The definition of "slow" signifies fracture times that may involve minutes or even hours as compared to fractions of a second for fast fracture.

DISCUSSION OF RESULTS

The K_{Iscc} data obtained from NRL studies on titanium alloy plate and weld metals are displayed as a function of yield strength in the OMTL diagram shown in Fig. 4. The diagram is the same as that of Fig. 3 with the elimination of the ratio lines and zonal designations. The data points are coded according to the generic families of alloys. An apparent K_{Iscc} limit line, which falls well below the fast fracture OMTL curve, indicates the highest levels of K_{Iscc} measured to date for 1-in.-thick titanium alloy plate. These represent materials which were used also to determine the fast-fracture OMTL curve.

The B dimension of the cantilever bend specimens used in these studies was nominally 0.75 in. — the maximum that could be used in the available SCC test equipment. The B thickness requirement for maximum mechanical constraint effectively limits the

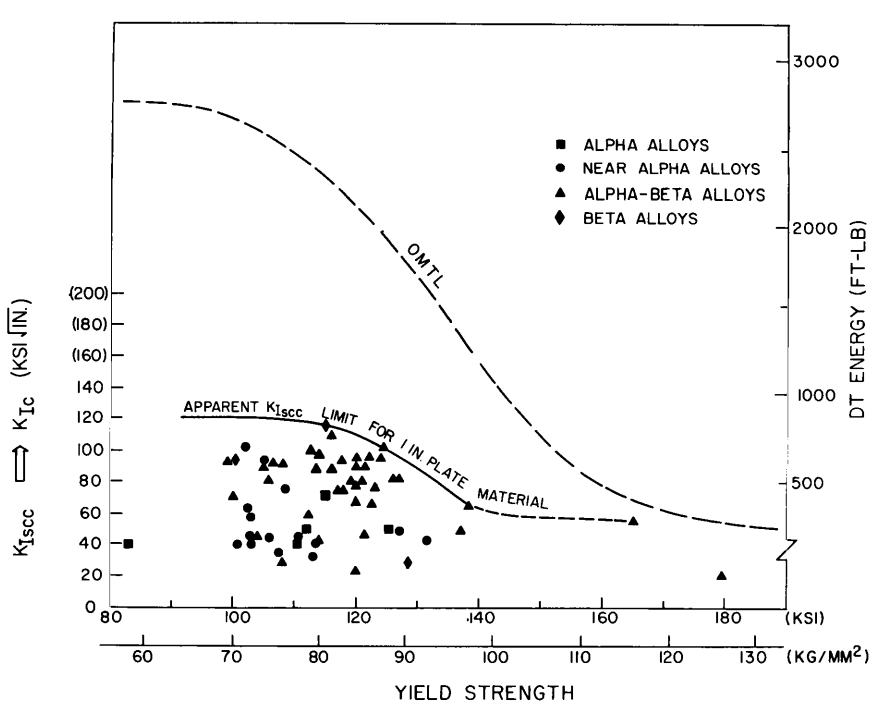


Fig. 4 - Summary of the K_{Iscc} data for generic titanium alloy families. The B thickness dimension of the specimen is 0.75 in.

reliable determination of minimum K_{Iscc} threshold values, based on these specimens, to materials of K_{Iscc}/σ_{ys} ratios below 0.55. For these low ratios, the stress-corrosion cracks extend completely across the B dimension of the specimen with a straight front, as shown in Fig. 5a. Ratios of K_{Iscc}/σ_{ys} above 0.55 correspond to conditions for which maximum mechanical constraint conditions were not attained with the subject specimens. As a result, the stress-corrosion cracks were observed to "tunnel" between shear lips, Fig. 5b, which are formed at the specimen surface. Because of this non-plane strain condition of propagation, the quoted threshold stress-intensity values of ratios above 0.55 may not represent the characteristic minimum K_{Iscc} value for the material. To determine if such K_{Iscc} values are accurate, further tests would be required with specimens of increased B thickness following usual fracture mechanics procedures for such validation. In this report, only plate of 1-in. thickness is considered with respect to SCC characteristics; therefore, the conclusions to be made with respect to sensitivity are valid.

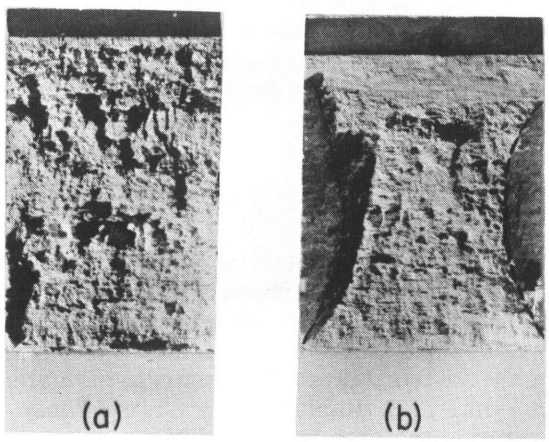


Fig. 5 - Typical appearance of SCC surface for a titanium alloy of (a) K_{Iscc}/σ_{ys} ratio of 0.40 and (b) K_{Iscc}/σ_{ys} ratio of 0.75. Note the development of "tunneling" through central plane strain regions for full section, plane stress K_c conditions as indicated by the development of shear lips.

STRESS-CORROSION CRACKING RAD

The foregoing discussion provides the basis for evolving a stress-corrosion cracking RAD for 1-in.-thick titanium alloy plate, as shown in Fig. 6. It essentially features the apparent K_{Iscc} limit line and the fast-fracture OMTL curve superimposed by the ratio lines of the RAD. Below the apparent K_{Iscc} limit line, the ratio lines should be interpreted to signify constant K_{Iscc}/σ_{ys} ratios. Above the limit line, the correspondence is to K_{Ic}/σ_{ys} ratios relating to fast fracture. For a metal of high K_{Ic}/σ_{ys} (e.g., a ratio of 2.0) and low K_{Iscc}/σ_{ys} e.g., a ratio of 0.5) a dramatic loss of resistance to fracture propagation is indicated. It would also signify that the extension of the SCC fracture would occur without transition to fast fracture because of the high value of fast-fracture toughness. In the case of K_{Ic}/σ_{ys} ratios of less than 1.0, fast fracture may be expected to result following a small increase in the initial flaw size by SCC processes. Such combined analyses provide valuable engineering information and may be made in a simple, straightforward fashion.

Direct entrance into the combined diagram can be made from the K_{Iscc} or K_{Ic} scale. For material of high fast-fracture toughness, DT data are required because K_{Ic} values cannot be obtained. The C_v scale (Fig. 3) is not of value because of its very poor indexing capability. The yield strength of the material fixes the location of the data point entry with respect to the ratio lines and provides for the definition of flaw size-stress conditions, as explained above.

The upper limit of strictly valid K_{Iscc} measurements and accurate interpretation to flaw size-stress conditions for SCC is indicated by the lower, dashed limit line. This line relates the limit of SCC developed under maximum constraint conditions (plane strain) and corresponds to the ratio conditions of $K_{Iscc}/\sigma_{ys} = 0.55$ for the reasons cited. The region between the plane strain limit line and the apparent K_{Iscc} limit line defines the regime of SCC "tunneling" through the central material, which is controlled by plane

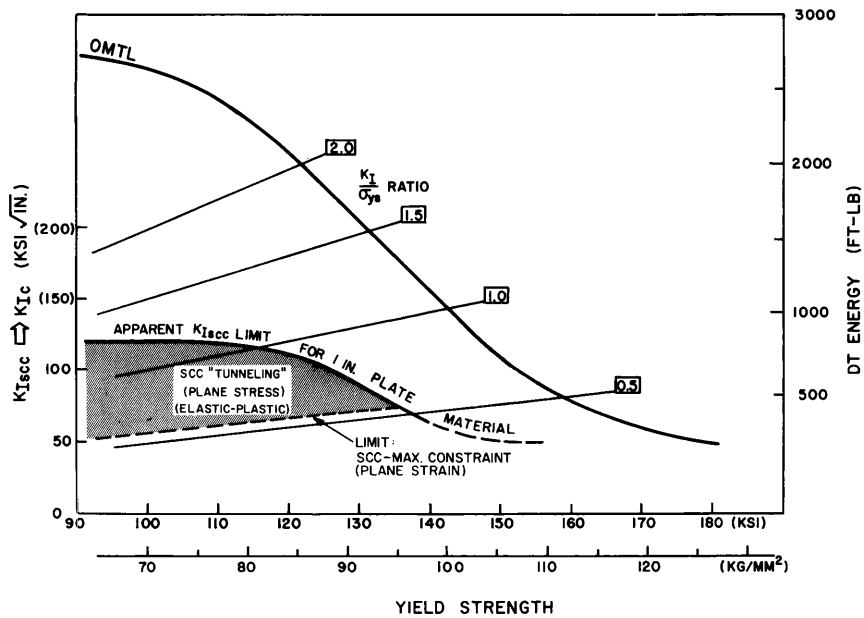


Fig. 6 - Dual RAD including SCC aspects for 1-in.-thick titanium alloy plates

strain conditions. Since the total constraint, including the surface, involves mixed-mode, plane stress K_c, meaningful interpretation to flaw size-stress conditions for SCC cannot be made at this time. To provide exact interpretations for materials falling into this regime, further testing is required using specimens with the B dimension increased sufficiently to ensure plane strain SCC conditions across the entire section. Other dimensions of the specimen may also require adjustment — this aspect is beyond the scope of this report. An increase of B to 1.0 in. would shift the SCC maximum constraint (plane strain) limit line to a K_{Iscc}/σ_{ys} ratio of 0.63. To reach a valid ratio of 1.0, specimens of approximately 2.5 in. in B thickness are required.

It should be noted that tunneling does, in fact, indicate that SCC sensitivity exists; the only question is the accuracy of the K_{Iscc} value. It is possible that increasing the specimen thickness may shift the "tunneling" region to higher K_{Iscc}/σ_{ys} ratios. Obviously, additional studies to examine this question are in order.

SUMMARY

The spectrum of titanium alloys investigated reveals a wide range of saltwater, stress-corrosion cracking (SCC) properties. Tests based on linear elastic fracture mechanics principles provide the best definition of SCC resistance of these alloys in terms of a K_I parameter defined as K_{Iscc} for the SCC case. The tests used in this investigation were based on fatigue precracked specimens. Other types of tests, including those involving arrest conditions for determining K_{Iscc} (8), may be used. However, the B requirement is critical for any test. Calculations of flaw size-stress conditions for SCC in structures may be made from the K_{Iscc} value.

Recently evolved Ratio Analysis Diagram (RAD) procedures for characterization of fast fracture and for interpretation to failure-safe design for titanium alloys can be extended to cover the case of SCC. Thus, the procedures serve the dual purpose of providing

simplified engineering definitions of flaw size-stress conditions for failure by the consideration of both fast-fracture toughness and SCC fracture resistance of the material. The failure conditions are expressed in terms of K_I/σ_{ys} ratio lines which index the general level of critical flaw sizes and stress levels. The dual RAD for fast and subcritical fracture features other aspects of interest, including

1. An apparent K_{Iscc} limit line that defines the highest level of SCC resistance measured in the cantilever bend SCC test with specimens of 0.75-in. B thickness dimension.

2. A SCC-maximum constraint (plane strain) limit line that indicates the highest level of K_{Iscc}/σ_{ys} ratios for which accurate interpretation of K_{Iscc} data can be made at this time for the size of the subject specimen.

The SCC-maximum constraint and apparent K_{Iscc} limit lines define the boundaries of a regime involving SCC by "tunneling" processes through the plane strain portion of the specimen. However, the through-section conditions are of the plane stress K_c type. For this regime, accurate interpretations to flaw size-stress conditions cannot be made at this time.

The limit lines may be increased with an increase in specimen size and material thickness. For material of 1-in. plate thickness, the subject limits apply for engineering consideration of flawed structures. The same limitations apply to engineering analyses as to specimen configuration.

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13. ABSTRACT

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