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Corrosion of metals and alloys — Guidelines for assessing the significance of stress corrosion cracks detected in service

Corrosion des métaux et alliages — Lignes directrices pour évaluer l'importance des fissures de corrosion sous contrainte détectées en service

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Contents

Foreword

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ISO 21601 was prepared by Technical Committee ISO/TC 156, *Corrosion of metals and alloys*.

Corrosion of metals and alloys — Guidelines for assessing the significance of stress corrosion cracks detected in service

1 Scope

This International Standard provides guidelines on the appropriate steps to take when a stress corrosion crack has been detected in service and an assessment has to be made of the implications for structural integrity.

Such an evaluation should be made in the context of the perceived consequences of failure using appropriate risk-based management methodologies. Since this is application-specific, it is beyond the scope of this International Standard.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7539-6, *Corrosion of metals and alloys — Stress corrosion testing — Part 6: Preparation and use of precracked specimens for tests under constant load or constant displacement*

ISO 7539-9, *Corrosion of metals and alloys — Stress corrosion testing — Part 9: Preparation and use of pre-cracked specimens for tests under rising load or rising displacement*

3 Principle

When a crack is detected during a scheduled inspection programme, repair will in most cases be initiated in a relatively short time-scale, by removing the component or by cutting out the damaged section and re-welding. However, in some circumstances there may be limited opportunity for repair and a pressure to keep the system in operation until the next extended outage, to minimize lost production. In other applications, it may be considered that a crack can be tolerated, provided that there is an adequate framework for predicting the evolution of the crack, defining inspection intervals, and assessing the likelihood of failure. Such an evaluation may be incorporated with an assessment of the consequences of failure into a risk-based inspection methodology. The challenges faced in living with the crack for a short or long period are establishing when the crack started, relating this to service conditions including transients (i.e. assessing whether the crack would be growing 'continuously' or only in response to specific fluctuations in service conditions), evaluating the mechanical driving force, characterizing the state of material through which the crack initiated and will propagate, assessing the laboratory database and translating this to the perceived service operation conditions using fracture mechanics or other concepts.

Leak before break (LBB) may also need to be evaluated where there is the risk of explosive or catastrophic failure, but, in practice, stress corrosion is usually detected and repaired for operational reliability reasons.

The purpose of this International Standard is to provide guidance in developing a damage-assessment process with some guidance on measures to control growth rates.

4 Characterization of the nature and origin of the crack

A first step is to develop a complete physical assessment of the crack1) in terms of identifying its shape and dimensions (uncertainty in defect size assessment should be noted) as this will feed into any finite element/fracture mechanics analysis. This should include an assessment of the crack location in relation to local stress concentrators, welds, crevices (e.g. at fasteners, flanges), and also the details of the crack path. If more than one crack is present, the crack density and the spacing between the cracks should be noted in view of possible future coalescence. Also, the state of the surface should be assessed for general or pitting corrosion damage.

Characterizing the crack as a stress corrosion crack may be possible from visible observation, e.g. significant crack branching (although extensive branching, albeit possibly beneficial, may preclude simple stress analysis and warrant removal of the crack). In most cases it is deduced from prior experience and awareness of the likelihood of other failure modes but recognizing that loading in service does not usually correspond to the simple static load tests conducted in the laboratory. Thus, there may be cyclic loading to some degree or dynamic straining associated with transient temperature changes. In many cases, distinction between a stress corrosion failure mechanism and a hydrogen embrittlement mechanism may not be possible. Where crack extension and remanent life assessment are the primary concerns, this may not be a critical issue provided that the laboratory data used for assessment relate to the particular service conditions. However, mitigation procedures can be contingent upon knowledge of the cracking mechanism.

Attention should be given to the operational history to assess the extent, if any, of system upsets that may have contributed to the onset of cracking.

5 Definition of service conditions and system history

5.1 Stresses

5.1.1 Operational stresses

Operational stresses are usually well known from the design process and, in practice, rarely critical except in the sense of being additive to residual fabrication stresses. However, a word of caution is needed. These are sometimes higher than they were designed to be due to discrepancies between the design drawings and the as-manufactured components as a consequence of inadequate control during manufacture. This can result in higher stresses than intended by designers where changes in section occur. For instance, the low pressure (LP) turbine shaft failures at Ferrybridge (1975)[1] occurred because the radius of the centre-collar stress relief grooves was smaller than the design value as a result of poor machining.

Other problems can arise if machining score marks are not ground out, causing increased stresses locally and sites for localized corrosion.

5.1.2 Residual stresses

Residual stress characterization *in situ* in service may be undertaken by a variety of methods. X-ray diffraction (XRD) is most commonly used. However, since the depth of material sampled is less than 10 µm, rough surfaces can give misleading results. *In situ* neutron diffraction methods may be possible with some relatively portable components but it is expensive. Depth variation of residual stress can be obtained by incremental hole-drilling but this is destructive, albeit at a local level, and requires repair. There is more scope for evaluation of removable parts and here XRD and electrochemical polishing can also be used for depth profiling of residual stress. Non-destructive depth profiling of residual stress requires access to a synchrotron radiation source and by implication is limited to removable parts. In the

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1) Detection of the crack in the first instance may have been by a range of methods including ultrasonic testing, acoustic emission, visual inspection, dye penetration, electromagnetic and potential drop methods. More detailed information on crack shape and size may be derived from X-ray tomography, though confined to removable parts and potentially size limited.

absence of measurement, the residual stress may be assumed to be at the effective yield strength (taking into account multi-axial stress state) for the parent material or weld metal, as appropriate, according to the location. However, the yield stress needs to be carefully evaluated in the light of the work-hardening capacity of the material and likely extent of local deformation. For critical applications, mock-ups may be necessary for the evaluation of residual stresses and cold work by X-ray diffraction. Post-weld heat treatment should relieve residual stress but it may not always be performed fully or adequately. Hydrotesting of pipes or vessels may also relieve the residual stress, by an amount proportional to the applied pressure stress (e.g. Hewerdine et al.[2]). Since stress corrosion crack growth rates are often stress intensity factor (K) independent or weakly dependent on K in the Stage II region (see Clause 7) there may be some latitude in characterizing the residual stress for analysis above K_{ISCC} (KISCC: Mode I threshold stress intensity factor for stress corrosion cracking) but recognizing that there will be uncertainty in calculating the critical flaw size for unstable fracture.

5.1.3 Multi-axial stresses

Multi-axial stresses are usually dealt with by determining the maximum principal tensile stress direction and assuming that stress corrosion cracks grow perpendicular to that direction. In fact, this is certainly an oversimplification and remains an area requiring further study. Isolated studies have shown that the biaxial or triaxial stress state should not be ignored.

5.1.4 Transients (e.g. thermal transients)

The usual concern with thermal transients is that they superimpose a cyclic load on the static stresses, which may enhance the risk of cracking as described later. In addition, larger thermal transients typically associated with start-up or shut-down of a plant will introduce significant dynamic loading for significant periods which again can enhance the risk of cracking (see later).

5.1.5 Corrosion product wedging

Since the oxidized forms of common structural metals occupy a significantly larger volume than the metal from which they came, possible additional loading due to wedging cannot be ignored in crevices or growing cracks. In practice, only a few circumstances are known where this is practically important and usually arises where there is a significant occurrence of crevice corrosion.

5.2 Service environment

5.2.1 General

Intended service environments are normally well characterized (temperature, water chemistry, partial pressure of gases, total pressure) but lack of operator objectivity as to possible environmental transients is a serious handicap in many service failure investigations.

5.2.2 Excursions from normal operating conditions

The probability of a leaking condenser, ion-exchange failure, residue from chemical cleaning, cooling water failure (giving temperature rise), oxygen ingress etc. all require objective assessment and wishful thinking on the part of plant operators in this respect is a serious handicap to finding practical solutions. The operational history should be examined carefully to assess the extent to which excursions occurred.

The concern with a transient increase in temperature or change in service environment is that it may move the system into a domain for activation of stress corrosion cracking (SCC), which would otherwise not be a concern. Thus, in assessing the significance of a crack, the exposure history should be examined and the extent of available data for predicting the likelihood of growth and the growth rate at the normal temperature or chemistry following an excursion evaluated. Often, the data are limited.

5.2.3 Solution concentration processes — development of local environments (crevice formation, hideout/evaporation, deposits)

Attention should be given to the existence of crevices that may induce local changes in solution chemistry and lead to corrosion. These may be the precursors of cracks and need to be considered when assessing laboratory data or undertaking testing in simulated service environments. Concentration processes due to hideout/evaporation under heat transfer conditions can be much more powerful than those due to ion migration. The theoretical limit of concentration can be estimated from the solubility of impurity solutes at the operating temperature and the local superheat available. A solute will concentrate until it raises the boiling point, until boiling no longer occurs given the local superheat and system pressure, or until it reaches its solubility limit if that intervenes beforehand. In the last case, a thin, very concentrated, liquid layer will form, commonly covered in a blanket of steam (which may not necessarily be better from a stress corrosion viewpoint).

5.2.4 Corrosion monitoring

Corrosion monitoring can be an important tool in assessing the aggressiveness of the service environment and is particularly useful when operational conditions fluctuate due to transients in water chemistry or contamination. If these transients can be identified as the occasions when stress corrosion cracks might develop and propagate, then a more informed basis for prediction may be generated, based on the number of damaging cycles, rather than simply the elapsed time of exposure. This may also allow benchmarking of the onset of initial damage, from the first transient or when a coating or other protective system has failed.

6 Material characteristics

NOTE The first step is to ensure that the material of relevance actually corresponds to that specified at the design stage. There are a number of factors that may subsequently affect the performance of the material.

6.1 Cold work

Cold work in a material can be introduced during fabrication or in response to surface machining/grinding. In much laboratory testing, specimens are usually wet-ground to a well-controlled surface finish, typically with an *Ra* value less than 1 µm, the primary purpose being to ensure repeatability of data and avoid any influence of surface cold work. In service, materials are often ground fairly crudely (or indeed may be supplied with retained cold work from processing). Poorly controlled (abusive) machining can cause surface overheating. Correspondingly, there may be significant surface stresses, deformation layers, increased hardness, and the possibility of microstructural transformation (e.g. bainite to untempered martensite) if the alloy is metastable or metastability is induced by the thermal history. High dislocation densities and associated short-circuit diffusion pathways can enhance some types of stress corrosion. For this reason, cracking in service may not be reliably predicted from laboratory tests without attention to these details.

The uncertainty in prediction is the extent to which cracks initiated in this layer (with gradient in residual stress and deformation) will continue to propagate once they have grown beyond the cold-worked region. There are situations in service where non-propagating cracks have been observed but there are also indications that if the depth of cold work is sufficient the cracks will continue to propagate. A key aspect will be the residual stress gradient. If this falls off steeply from the surface a crack may initiate but then cease to propagate because the combination of stress and crack size is not sufficient to attain the critical value of the stress intensity factor for sustained propagation (see 7.1). If the stress gradient is more gradual then sustained propagation may ensue. The problem is that characterization of the degree and depth of cold work *in situ* may not be straightforward but may be inferred from experience with the material preparation route.

6.2 Welding

Assuming that radiographic assessment has ensured that there were no physical flaws of significance, the issue for welded sections as far as *propagation* of cracks is concerned is primarily in relation to residual stress, hardness, and local microstructural and/or microchemical changes, although joint geometry could have an influence on the mechanical driving force and local environment chemistry.

The concern for welds in relation to the microstructural and microchemical aspects and their impact on stress corrosion cracking is the possible departure from the weld procedure qualification, with perhaps too high a heat input and inadequate filler leading to sensitization at grain boundaries or at precipitate particles, elongated and clustered inclusions and local hard spots. Measuring these characteristics *in situ* is a challenge. In principle, electrochemical potentiodynamic reactivation (EPR) can detect sensitization depending on accessibility. Metallography is feasible for removable parts and similarly eddy current and Barkhausen noise can detect hard spots but both require surface polishing and are most applicable to removable parts.

6.3 Ageing

6.3.1 Thermal ageing

Materials operated at high temperature for extended periods can undergo thermal ageing induced microstructural and microchemical changes that often increase stress corrosion susceptibility. Common examples include cast stainless steels undergoing spinodal decomposition of the ferrite with very significant hardening and ageing of precipitation-hardened stainless steels such as 17-4PH. Once hardness values exceed 350 HV, experience shows that the risk of environmentally induced cracking in aqueous environments increases and above 400 HV cracking failures are practically guaranteed. Another problem is thermally induced sensitization of austenitic stainless steels (particularly if the C-content exceeds 0,03 % and they are not stabilized by Nb or Ti) due to the precipitation of chromium carbides at the grain boundaries on prolonged service at (or slow cooling through) temperatures in the range 425 °C (or less for low-temperature sensitization) to 875 °C.

Also, microstructural changes, e.g. in high pressure/intermediate pressure turbine components, can lead to a deterioration in toughness and hence in the critical flaw size for unstable fracture.

6.3.2 Irradiation damage

Irradiation damage, insofar as it may lead to significant hardening, may have a similar effect to the thermal ageing described above. Another effect observed in austenitic stainless steels subject to high neutron irradiation doses exceeding about one displacement per atom is a significant change in grain boundary composition due to the migration of point defects to sinks such as grain boundaries (as well as dislocations and free surfaces). The most notable consequence in common austenitic stainless steels is a reduction in the chromium concentration in a very narrow band about 10 nm wide at grain boundaries leading to intergranular stress corrosion cracking (ISCC) in oxidizing high-temperature water. It is sometimes called irradiation-induced sensitization but there are no grain boundary carbides as with thermally induced sensitization.

6.4 Microstructural orientation

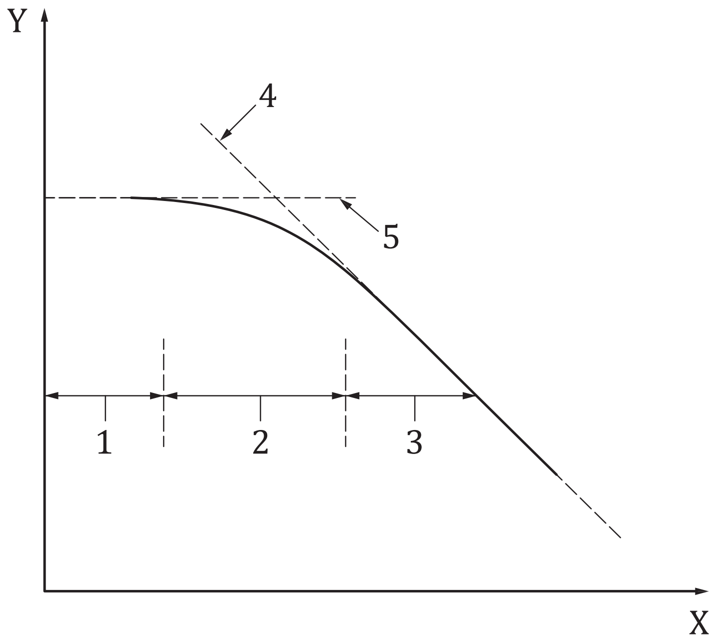
The orientation of the microstructure relative to the principal stresses can influence the evolution of stress corrosion cracking. This is a particular issue where there is an elongated grain structure and significant differences in properties between the longitudinal and transverse directions as observed, for example, in aluminium alloys.

7 Prediction of K_{ISCC} and crack growth rates

NOTE The complexity of service conditions and the corresponding uncertainty in crack growth kinetics necessitates a very conservative approach to crack-tolerant philosophies. If the consequences are perceived to be non-critical, in many cases the most relevant crack growth data may be derived from further monitoring of the detected crack. This has the virtue also of benchmarking laboratory predictions. The most commonly used approach is to characterize the K_{ISCC} value for the material and to make judgements as to whether the crack is beyond the limit for this threshold.

7.1 K_{ISCC}

Clearly, if the detected crack is perceived to be a stress corrosion crack then a threshold has been exceeded. However, that may be a threshold for initiation from a plain surface, corrosion pit or shallow defect for which linear elastic fracture mechanics (LEFM) is not applicable (Figure 1). In these cases, K_{ISCC} might be better perceived as a threshold for subsequent sustained crack growth (or for crack arrest).



Key

Y Stress (log)

X Flaw depth (log)

1 Initiation of stress corrosion cracking

2 Shallow cracks

3 Deep cracks

4 $K = K_{ISCC}$

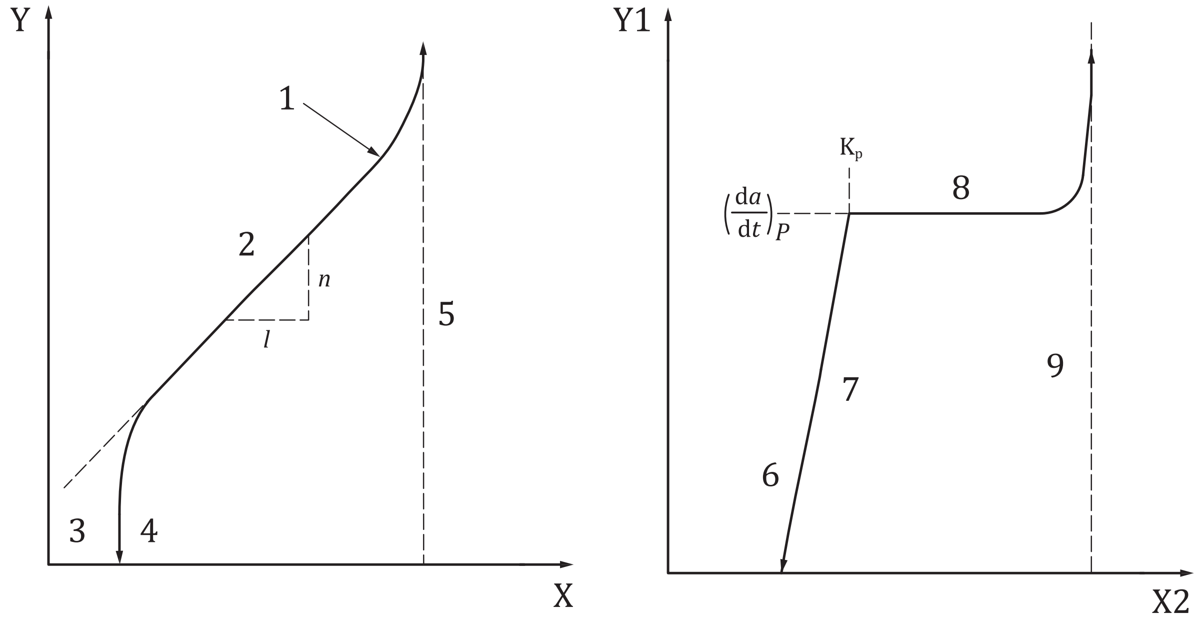
5 Stress = σ_{SCC}

Figure 1 — Schematic diagram of the two-parameter approach to stress corrosion cracking

The concept of K_{ISCC} is not trivial and the value is sensitive to the environmental conditions, temperature and loading characteristics. Accordingly, data obtained for one condition should not be transposed to another.

However, K_{ISCC} should not be regarded as an intrinsic characteristic of the material as it will depend sensitively on the environment and loading conditions, which should reflect those for the service application. Also, there may be long-term changes in the material due to exposure that are not reflected in short-term laboratory tests. The definition implies no sustained crack growth, or crack arrest, below this value, which intrinsically brings in issues of resolution of the crack size measuring method and the patience of the experimenter.

For long cracks, the behaviour is typically as represented in Figure 2, where typical behaviour for a fatigue crack is shown for comparison.



a) Fatigue crack growth

b) Stress corrosion crack growth

Key

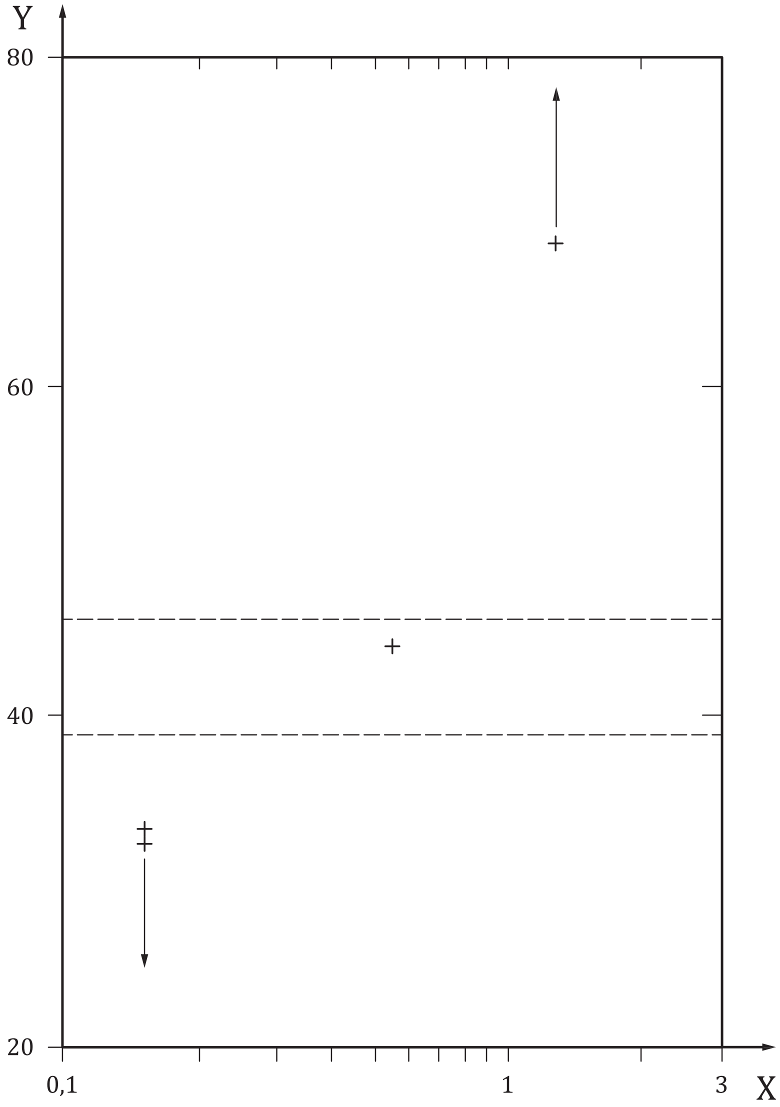
Y	Log (da/dN)	Y1	Log (da/dt)
X	Log (ΔK)	X2	Log (K)
1	Terminal region (C)	6	$K = K_{ISCC}$
2	Intermediate region (B)	7	Stage I
3	$\Delta K = \Delta K_{th}$	8	Stage II (Plateau, p)
4	Initial region (A)	9	$K = K_{Ic}$
5	$K_{max} = K_{Ic}$		

Figure 2 — Schematic illustration of typical crack growth behaviour in a) fatigue and b) stress corrosion cracking[3]

It is common to conduct K_{ISCC} tests under static load conditions and accordingly results unrepresentative of service are often obtained. Structures are seldom subjected to purely static loading and it is well known that the value of K_{ISCC} can be considerably reduced if a dynamic loading component is involved; for example a thermal transient, following an outage, or superimposed cyclic loading, even of small magnitude.

Should it be decided that K_{ISCC} values obtained under static loading are appropriate, these can be determined using the procedures described in ISO 7539-6. This International Standard describes both crack initiation and crack arrest methods using fatigue pre-cracked, fracture mechanics type specimens tested under constant load or constant displacement. For some systems, the value may vary depending on the method of measurement, e.g. increasing K or decreasing K experiments. As a fatigue pre-crack is somewhat artificial and may affect the transition to a stress corrosion crack, a decreasing K, crack arrest, type of experiment may be more pertinent.

The procedure for testing under rising load or rising displacement conditions is described in ISO 7539-9. The loading or crack mouth opening displacement rate is the critical parameter and it is best to test over a range to obtain conservatively the minimum, lower shelf, value of K_{ISCC} This may be lower than that obtained by conventional static loading or fixed displacement test under otherwise identical test conditions (Figure 3).

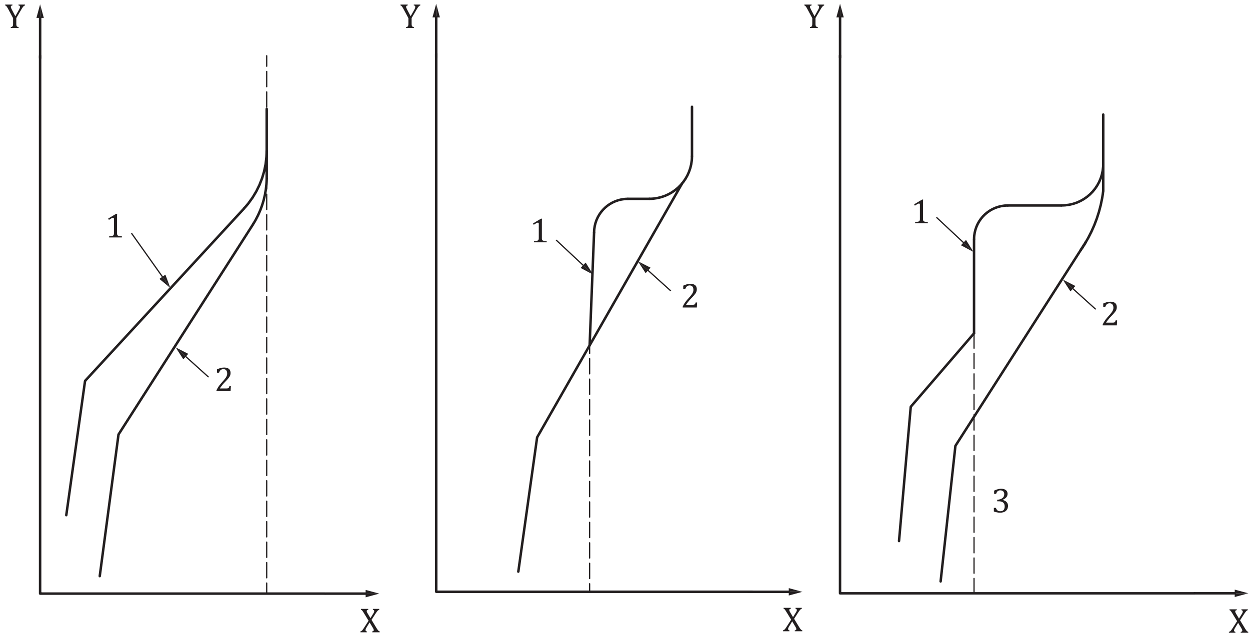


Key

Y	K_{ISCC} (KISCC/MPa·$m^{1/2}$)
X	Displacement rate across crack mouth (μm/h)
+	Rising displacement tests
- - -	constant load tests

Figure 3 — K_{ISCC} vs load-line displacement rate for AISI 4340 steel in ASTM seawater at 20 °C[4]

When there is a significant cyclic loading component, the concept of K_{ISCC} becomes less directly applicable. This is exemplified in Figure 4. Although there is a threshold K_{ISCC} indicated in this figure, this should not be confused with the static load threshold, as it will be particular to the cyclic loading parameters.



Key

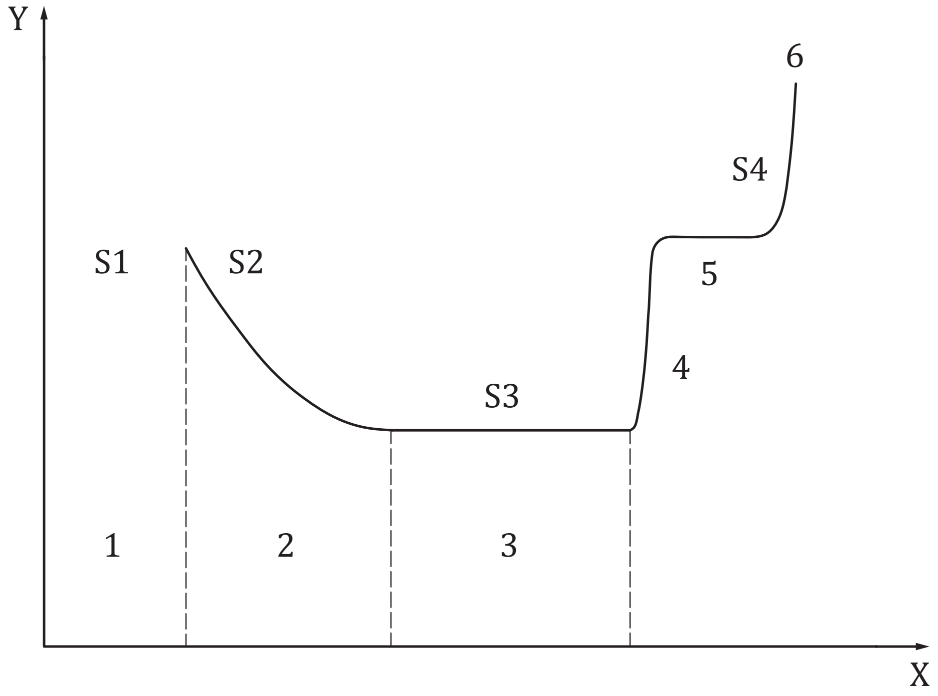
Y	Log (da/dN)
X	Log ΔK
1	Aggressive
2	Inert
3	$K_{\max} = K_{\mathrm{ISCC}}$

Figure 4 — Corrosion fatigue and stress corrosion cracking interactions[3]

A particular form of stress corrosion cracking is known in carbon and low-alloy steel boiler shells and similar pressure vessels subject to occasional large thermal transients which, translated from the original German terminology, is known as strain induced corrosion cracking. Thus, crack growth only occurs during dynamic straining and the crack tips usually blunt during quiescent loading periods; it is nevertheless a form of stress corrosion cracking and not fatigue. A good example was shown in the first edition of Uhlig's Corrosion Handbook[5] from a steam locomotive boiler about 50 years ago.

7.2 Prediction of growth rates below K_{ISCC}

In a number of examples, relatively shallow cracks may be detected and may grow at a rate much lower than that associated with long cracks. Figure 5, relating to a natural gas pipeline, is used often as a schematic illustration of such crack propagating behaviour.



Key

Y	Crack velocity
X	Time
S	Stage (e.g. stage 1, Stage 2, etc.)
1	Conditions for SCC do not exist
2	Cracks initiate, CV reduces due to decreasing strain rate, Few cracks coalesce
3	Initiation continues, Coalescence increases
4	Large cracks coalesce
5	Faraday upper bound
6	Fast fracture

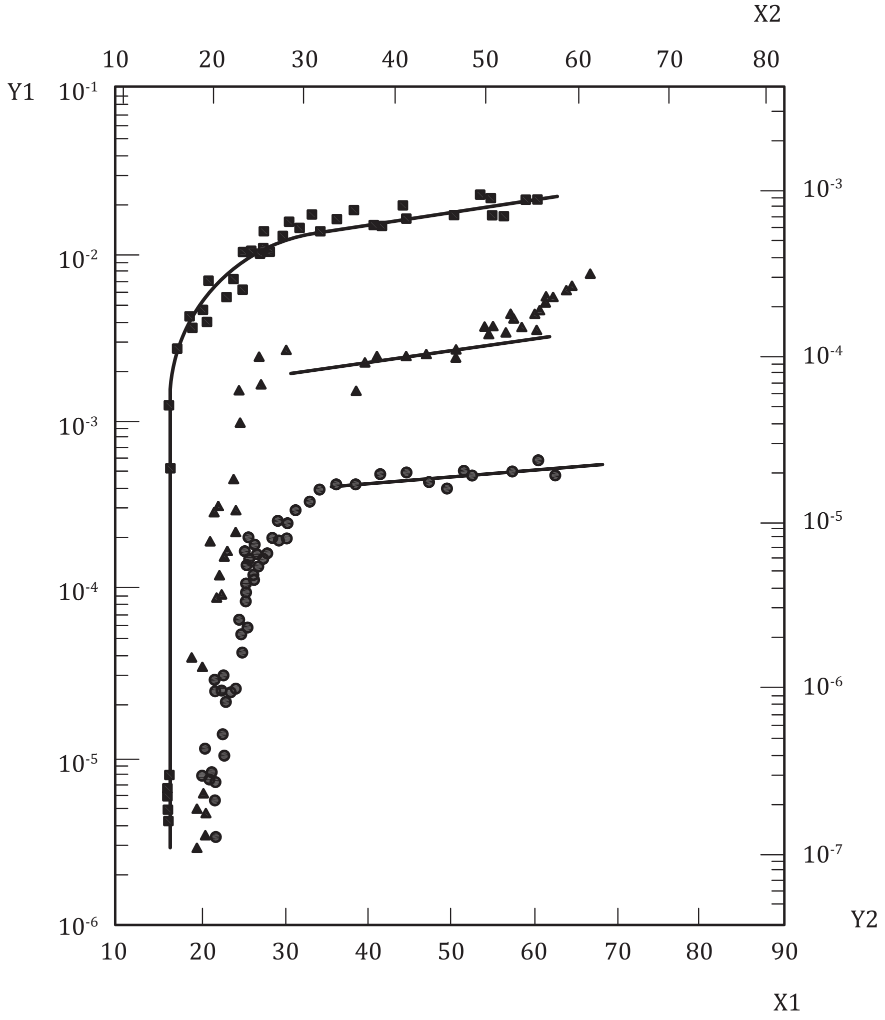
Figure 5 — Schematic illustration of the evolution of crack velocity as a function of time based on stress corrosion cracking of a pipeline steel in bicarbonate solution[6]

However, this should not be generalized as there are few published data for the growth rate of short cracks and its evolution with crack size. The growth rate of short cracks will depend on the microstructure (which may be affected by surface preparation), stress gradients, and on changes in local crack chemistry or electrochemistry with crack depth.

7.3 Crack growth above K_{ISCC}

For a number of systems, the crack growth above K_{ISCC} may be fast. In that circumstance, a crack-tolerant philosophy would only be viable if the propagation were considered to be intermittent, e.g. associated with an occasional short-term excursion in system chemistry. However, there are systems for which the growth rate in Stage 2 is not fast (e.g. steam turbine disc steels) and laboratory crack growth rates may be used to define inspection intervals.

In that context, examples of crack growth data for several systems are shown in Figures 6 to 9 (note the differences in the crack growth rate scales in these figures).



Key

Y1 Stress corrosion crack growth rate, d*a*/d*t*, mm/s

X1 Stress intensity *K* (MPa·m$^{1/2}$)

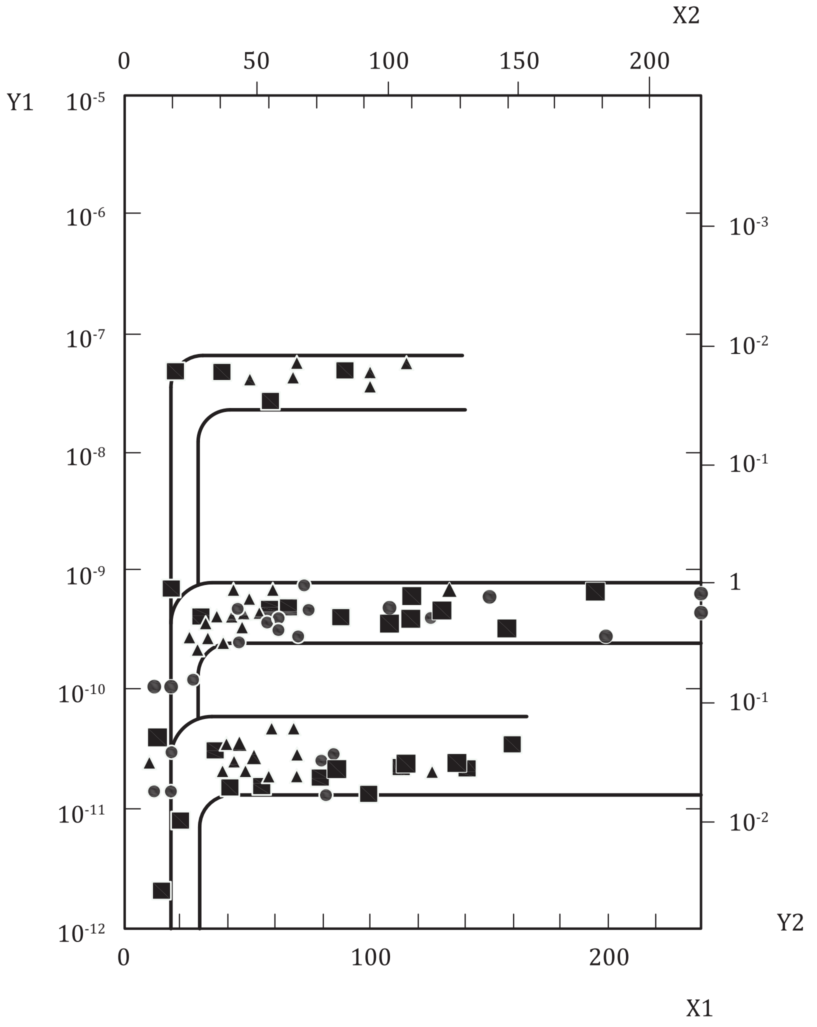
Y2 d*a*/d*t* (inches/s)

X2 *K* (ksi·in$^{1/2}$)

	Steel	**Austenitizing treatment**	**Temper** (1 h)	K_{Ic} (MPa·m$^{1/2}$)	K_{ISCC} (MPa·m$^{1/2}$)
■	4340	870 °C oil	300 °C	62,7	16,6
▲	300-M	870 °C oil	470 °C	68,9	18,0
●	300-M	870 °C, iso 250 °C	300 °C	88,5	18,5

AISI 4340 and 300-M, Distilled water at 23°C, constant yield strength 1 497 MPa

Figure 6 — Stress corrosion crack growth kinetics of high strength low-alloy steels in distilled water[7]



Key

Y1 Stress corrosion crack growth rate $\Delta a/\Delta t$ m/s

X1 Stress intensity K_I MPa·m$^{1/2}$

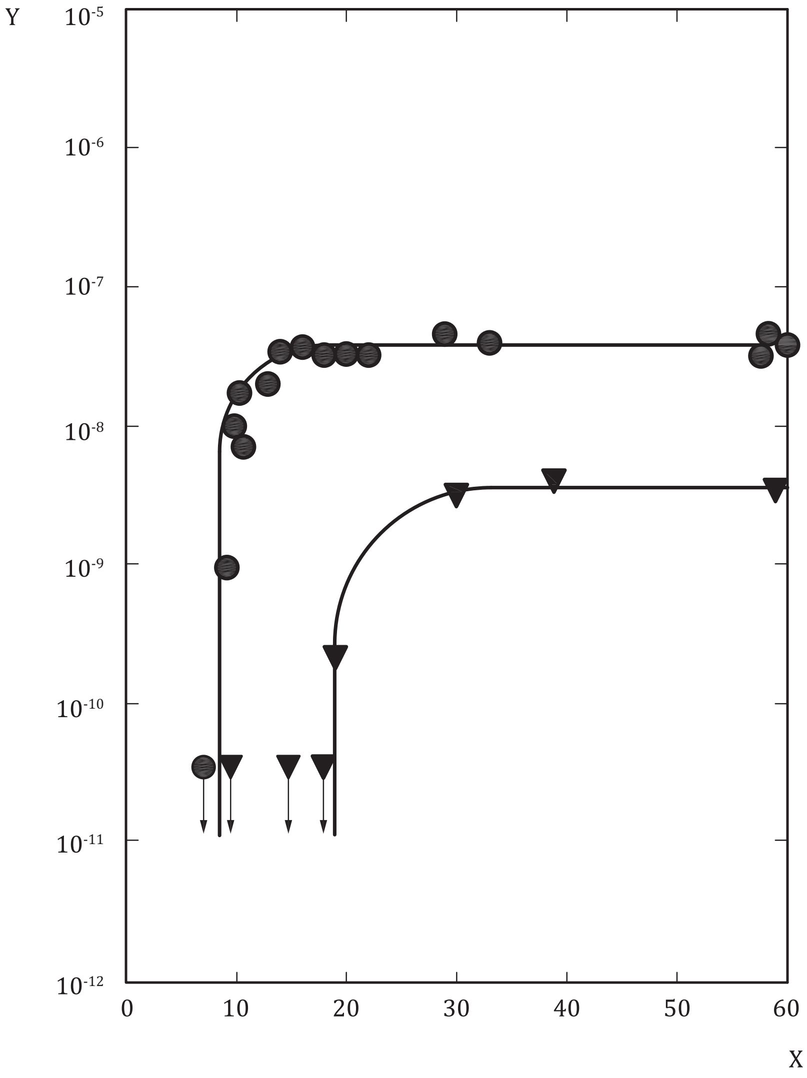
Y2 Stress corrosion crack growth rate $\Delta a/\Delta t$ inch/year

X2 Stress intensity K_I ksi·in$^{1/2}$

Steam turbine rotor steels, SCC, in H_2O

■	2Cr −1Ni steel
▲	“clean steels”, specially alloyed steels
●	3-3,5 % Ni steel

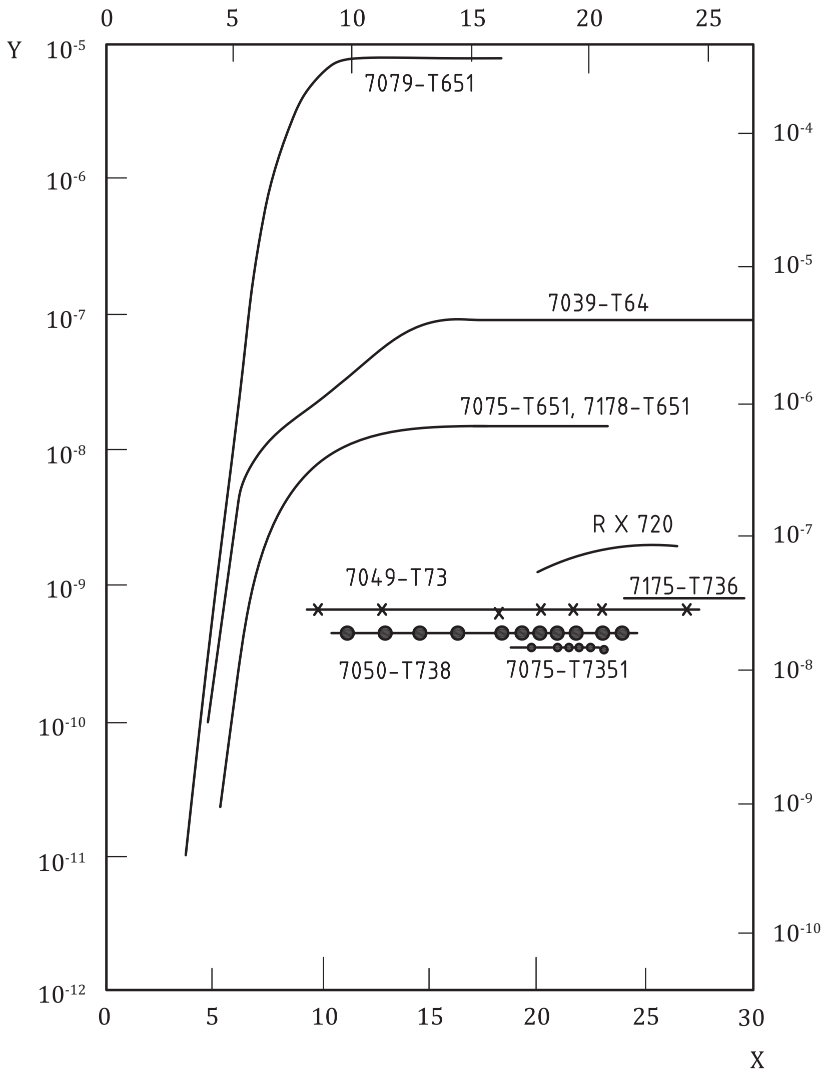
Figure 7 — Effect of temperature on the growth rates of stress corrosion cracks in steam turbine rotor steels[8]



Key

Y	Stress corrosion crack growth rate $\Delta a/\Delta t$ m/s
X	Stress intensity K MPa·$m^{1/2}$
●	austenitic stainless steel in 42 % $MgCl_2$ solution 130 °C
▼	austenitic stainless steel in 22 % NaCl solution 105 °C

Figure 8 — Stress corrosion crack growth data for 304L stainless steel in $MgCl_2$ solutions[9]



Key

Y Stress corrosion crack velocity m/s

X Stress intensity MPa·$m^{1/2}$

Figure 9 — Stress corrosion cracking in 3,5 % NaCl for several aluminium alloys[10] (Data for die forgings and averaged data for plates, short transverse direction, alternate immersion, 3,5 % NaCl solution temperature: 23 °C (73 °F), DCB specimens)

An upper bound approach has the advantage of safety and security but may give rise to a judgement that a particular degradation mechanism cannot be allowed to continue even for a limited time whereas a less severe assumption corresponding more to average behaviour may indicate large margins of security. This is a complex question where probabilistic methods and risk analysis are essential complementary tools.

The crack growth rate above K_{ISCC} is often represented by:

$$\mathrm{d}a/\mathrm{d}t = C(K_{\mathrm{I}})^n \qquad K_{\mathrm{ISCC}} \leq K \leq K_{\mathrm{c}}$$

where: C and n are constants and K_{c} is the dynamic fracture toughness.

Expressions have been derived for specific applications and these should be used as appropriate.

7.4 Non-propagating cracks

The observation of a crack in service should always be assumed conservatively to imply that the crack is propagating. However, there are circumstances when cracks initiate, propagate for a period and then stop. This behaviour may occur when there is a loss in mechanical driving force because of stress relaxation or redistribution, or a reduced strain rate. A crack propagating into a more resistant material (e.g. from a cold-worked surface) may also blunt at the crack tip and stop growing.. There are circumstances where the growth of the crack may gradually slow because of transport-limited kinetics for the crack tip reactions and the crack will stop. Cracks may arrest if the initial advance is induced by a transient excursion in chemistry, temperature or stress and may only re-start following a further excursion.

Ongoing monitoring is required to ensure that the crack has stopped but it is important to establish also the reason for the crack arrest and then to predict the circumstances in which it might be reactivated.

7.5 Probabilistic issues

For mass-produced items, which have proportionally a greater number of failures, failure frequency analysis can be used to establish the probability of a particular failure mode. The major difficulty for engineering structures in terms of establishing such probability relationships is that failures are relatively rare and information from service behaviour may be limited. Indeed, the failure may be a one-off, induced by upset conditions.

However, there are exceptions. The common design and incidence of failures by cracking for sensitized stainless steels in boiling water reactors, and of Alloy 600 in pressurized water reactors, enables statistical treatment.

In such cases, the analysis of service failures is often based on fitting to statistical distributions, e.g. exponential, log-normal, extreme value, and Weibull distributions. Of these, the Weibull distribution is becoming increasingly popular owing to its flexibility, and is readily adaptable to situations in which relatively few failures have occurred in a large population potentially at risk.

The Weibull cumulative probability of failure is given by:

$$F(t) = 1 - \exp\{-[(t - t_0)/\eta]^{\beta}\}$$

where: $F(t)$ is the fraction of components failed after time t; t_0 is the origin of the distribution (when $t = t_0$ the fraction of failures goes to zero); η is the characteristic life or scale parameter (understood as the time when $F(t) = 0.632$); and β is the shape parameter of the linear transform.

The shape parameter determines whether the risk of failure decreases or increases with time, and the extent of variability in times to failure. For example, it can reflect the change in crack velocity with time.

The cumulative distribution is often presented as the natural loglog plotted as a function of time:

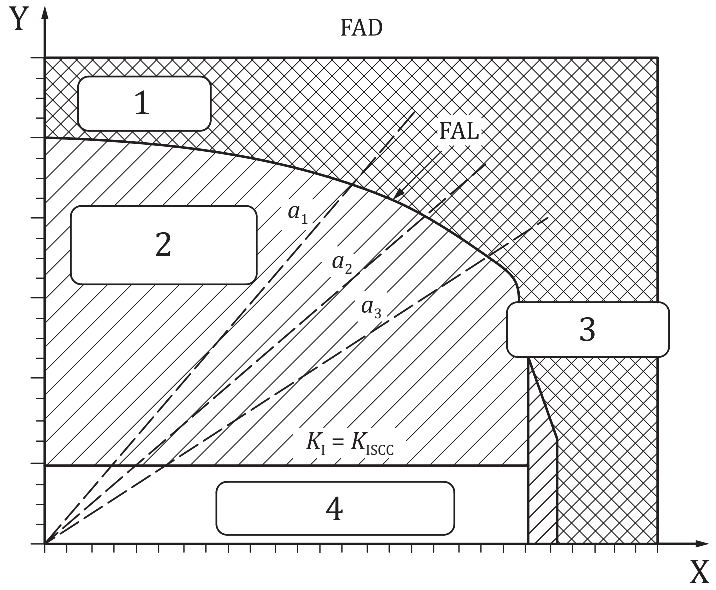
$$\ln\ln\{1/[1 - F(t)]\} = \beta\ln(t - t_0) - \beta\ln(\eta)$$

from which the parameters η and β can be obtained.

8 Structural integrity assessment

Analysis of equipment containing growing cracks requires specialized skills, expertise, and experience because of the inherent complexity of the crack advance mechanism. The analysis involves the use of a fracture assessment and the numerical integration of a crack growth law.

Step 1: Perform a fracture assessment for the initial crack size, based on the measured detected value or upon a maximum value reflecting the uncertainty in detection. If the component is demonstrated to be acceptable, i.e. well within the Failure Assessment Diagram (FAD) boundary of Figure 10 and, where applicable, the crack depth is small compared with through-wall thickness, then remedial steps to prevent further crack growth should be considered. Remedial steps may include reducing the stress so that $K < K_{\mathrm{ISCC}}$ and crack arrest ensues, modifying the environment or the tempera-



ture.

Key

Y	K_r
X	L_r
1	Fracture
2	Sub-critical crack growth (a_1, a_2, a_3: crack depths)
3	Yielding
4	No crack growth

Figure 10 — Failure assessment diagram where $K_r = K_I/K_{IC}$ and L_r is the ratio of the net section stress to the flow stress. FAL is the Failure Assessment Line

Step 2 – If effective remedial steps are not possible and/or slow subcritical crack growth can be tolerated, then fully characterize the nature of the crack and the service conditions driving it. Establish whether a crack growth law exists for the material and service environment. If a crack growth law exists, then a crack growth analysis can be performed. Otherwise, where applicable, a leak before break (LBB) analysis should be performed to determine if an acceptable upper bound crack size can be established

Step 3 – Compute the stress at the flaw, including any dynamic components, based on anticipated future operating conditions. In these calculations, all relevant operating conditions including normal operation, start-up, upset, and shut-down should be considered.

Step 4 – Determine the evolution of the crack size based on the previous flaw size, *K* value and crack growth laws. If a surface crack is being evaluated, the crack depth is incremented based on the stress intensity factor at the deepest portion of the crack and the length is incremented based on the stress intensity factor at the surface (which may be different).

Step 5 – Determine the time for the current crack size (a_0, c_0) to reach the limiting flaw size in relation to the FAD or LBB criteria. The component is acceptable for continued operation provided: the time to reach the limiting flaw size, including an appropriate in-service margin, is more than the required operating period; the crack growth is monitored on-stream or during shutdowns, as applicable, by a validated technique; the observed crack growth rate is below that used in the remaining life prediction as determined by an on-stream monitoring or inspections during shutdowns; upset conditions in loading or environmental severity are avoidable or are accounted for in the analysis. If the depth of the limiting flaw size is re-categorised as a through-wall thickness crack, the conditions for acceptable LBB criteria should be satisfied. At the next inspection, establish the actual crack growth rate and re-evaluate the new flaw conditions per procedures of this section. Alternatively, repair or replace the component or apply effective mitigation measures. An outline of the assessment process is illustrated in the flow chart of Figure 11.

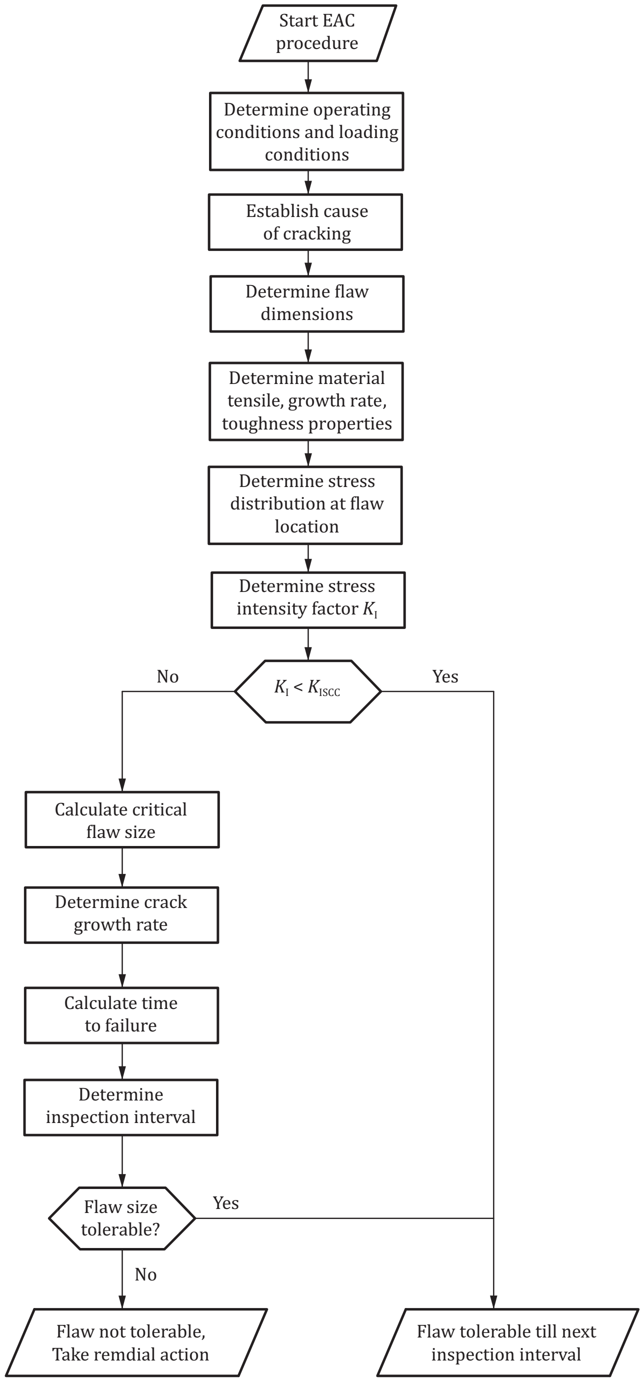


Figure 11 — Structural integrity assessment flow chart. EAC is environment assisted crack

9 Modification of service conditions to mitigate crack growth

9.1 Temperature change

In general stress corrosion crack growth rates decrease with decreasing temperature. However, in circumstances when the growth mechanism is related to hydrogen embrittlement, the behaviour is more complex and generalisations are not possible.

9.2 Reduction of operational stresses

An obvious step, where it is relevant and feasible, is to reduce operational stresses; for example by reducing the pressure. Also, managing the rate of temperature change during start-up and shut down to minimize the thermal stresses will be beneficial.

9.3 Alteration/more rigorous control of the environment

A key objective is to control the electrode potential so that the potential is in a region of minimum susceptibility to environment assisted cracking. This may be achieved by controlling the concentration of oxidizing species or, where feasible, by applied current. Since stress corrosion cracking occurs often because of deviation from optimum operating conditions, e.g. oxygen/water content of ammonia spheres, the most effective route is often to tighten up on water chemistry control to minimize the extent and frequency of out-of-specification water chemistry. Less commonly, long-term generic compatibility problems between a material and its environment, unsuspected at the design stage, come to light as systems age. This is an increasing problem with the growing trend towards life extension in order to avoid new costly investments.

In addition to control of the oxidizing species, other means of chemical inhibition may be used, but it is important to select the inhibitor wisely to ensure that it will be effective with a pre-existing defect.

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