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Table of contents

0. Summary

The assessment of possible sub-critical crack growth through environmentally assisted cracking (EAC) is a commonly encountered problem in safety evaluations of light water reactor components. The numerous factors influencing EAC fall into three main groups (material, medium and loading), but their interactions are highly complex. Field assessments usually rely on the evaluation of experimental results, with or without parallel attempts to model the cracking process, but they are hampered by the extreme scatter often exhibited by laboratory data under nominally identical testing situations. Furthermore, doubts often exist as to the extent to which the field conditions have been adequately simulated in autoclave tests.

The approach presented in the present report to resolve this problem involves a systematic assessment of the **quality** of the experiments performed by reference to acceptance criteria for specific aspects of testing, followed by downgrading, on a weighted scale, of those data which are associated with inadequate experimental techniques. Subsequently, cut-off points can be set so as to rationalize the overall data assessment.

Generalised criteria are developed and justified for the individual test parameters within the three groups of factors influencing EAC. However, it has to be recognized that the weighting will vary for different classes of material and operating environments. The viability of the approach is demonstrated by means of a full-scale analysis of data on the stress corrosion cracking behaviour of low-alloy steels under simulated BWR conditions.

Although the approach described in this report is capable of further refinement, it has already enabled the actual assessment of possible SCC of low-alloy steel components in BWR plant to be performed with greater confidence, whilst eliminating undue conservatism. Examination of existing EAC data in an analogous way would permit its extension to austenitic stainless steels and nickel-base alloys, as well as to PWR environments.

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1. Introduction

Environmentally assisted cracking (EAC) is a possible degradation mechanism for various components in nuclear power plants. As with mechanical or thermal fatigue, it results in sub-critical crack growth and this may have to be tolerated, as long as adequate safety margins are retained with regard to sudden, catastrophic failure. With fatigue, however, the guidelines for assessing both the initiation of cracks and crack growth behaviour are well known and laid down in the relevant nuclear codes (e.g. ASME Sections III and XI). Evaluating EAC is more difficult, since the factors of influence are numerous and their interactions highly complex:

- **material** (type, exact composition, microstructural state, surface condition, etc.)
- **medium** (composition, impurities, temperature, flow, redox potential, etc.)
- **loading** (level, static/cyclic, frequency/strain rate, residual stress etc.)

The relative importance of each of these factors can be very different from case to case, so that field assessments of EAC behaviour are usually based upon one or both of the following approaches:

- **experimental simulation of the field situation.**
- **modelling of the cracking process**

1.1 Experimental simulation of the field situation

Because the chemistry of LWR operating media is carefully controlled so as not to be generally aggressive to the materials of reactor construction, **accelerated corrosion tests** are of little value in assessing propensity to EAC. Insofar as these are used with regard to field problems (e.g. the standard tests for intergranular corrosion according to ASTM or the electrochemical potentiokinectic reactivation (EPR) test developed especially in connection with IGSCC problems in stainless steels) it is important to realise that they only provide data on the basic material condition (and microstructure). Direct extrapolation to behaviour under operating conditions is not possible.

Autoclave tests, in which the operating medium is simulated as far as possible, have been used to generate the vast majority of available data on EAC. However, it is essential to realise the limitations of experimental technique here (see Section 3.2). E.g., even in the minority of BWR tests where water purity approached that of an operating reactor, the flow conditions were almost invariably different. It is generally argued [1, 4, 5] that the lack of flow in laboratory autoclaves produces EAC data which is on the conservative side with regard to reactor operation and there is some experimental evidence to support this [6, 7, 8]. A particular problem in autoclave simulation of the field situation relates to the existence of creviced components: attempts to model realistic geometries here have often been unreliable with the data produced being non-conservative or, in a minority of situations (e.g. use of crevices packed with graphite wool), unduly negative.

Some of the most valuable data on EAC have been obtained using **bypass loops** attached to operating reactors. However, even here care must be taken to ensure that realistic chemistries are obtained in the test vessel. E.g. consumption of oxygen and heterogeneous decomposition of hydrogen peroxide on the walls of small diameter sampling lines may render reproduction of BWR reactor water chemistry difficult and particular problems are associated with test media extracted from two-phase systems.

Direct insertion of EAC test specimens into test or operating reactors (even into the core area) has occasionally been performed and is, e.g., the only way of ensuring realistic simulation of hydrodynamic conditions. However, apart from the obvious problems associated with such work, methods of stressing the test specimens are usually limited to displacement control (see Section 3.3) and techniques to monitor in-situ crack initiation/growth have not yet been adequately applied. Nevertheless, this approach - together with the use of bypass loops, where appropriate - would appear to offer the best chance of ensuring or prelonging plant service life by providing objective evidence that EAC problems have been avoided, or at least brought under control.

1.2 Modelling of EAC

The appearance of intergranular stress corrosion cracking (IGSCC) at the welds of stainless steel piping in BWR's stimulated a vast amount of research on EAC, including attempts by several groups to model cracking behaviour in a mathematical way. The best known model is that of Ford and Andresen, which has been described at length on various occasions in the literature, but is summarized particularly clearly in [1]. This model assumes as its "working hypothesis" that EAC is fundamentally an anodic process, whose rate is determined by the slip-dissolution / film-rupture model. The approach has been used with impressive success to predict the behaviour of stainless steels in a wide variety of environments and loading situations. However, the predictions are less convincing with nickel-base alloys and its extension to carbon and low-alloy materials is controversial. In part, this stems from the fact that the Ford/Andresen model deals primarily with crack propagation, whereas initiation may sometimes be of equal (or greater) importance. This is particularly true with less noble materials which are capable of undergoing relatively rapid general corrosion, rather than cracking, if the thick, protective layers of oxide are mechanically disturbed. Even higher-alloy materials are not truly passive under LWR operating conditions, however, so that the validity of assuming that a pre-existing defect is always available to act as a short crack may sometimes be questioned.

A particular strength of the Ford/Andresen model lies in the use of crack-tip strain rate ( ) to rationalise data obtained under a variety of loading conditions, i.e. to describe the spectrum of EAC mechanisms (see Section 2). The relation between and engineering terms such as stress or stress intensity is not always uniquely clear, however, and this has proved to be a particular problem with SCC.

The electrochemical basis of the above model has been criticised because of the way in which it concentrates on the crack tip environment alone and Macdonald et al. have put forward a so-called "coupled environment fracture model " [2] which claims to take better account of reactions at the surfaces external to the crack. These could be decisive in determining crack growth rate in certain situations (e.g. if the water contains electrochemically active impurities), but the Macdonald model has not yet been justified to the same degree as that of Ford and Andresen.

Finally it is worth pointing out that the basic assumption of an "anodic" mechanism inherent in the above models is not universally accepted. Hänninen [3], in particular, has often argued for the involvement of hydrogen in the cracking process and in certain situations (e.g. with heavily cold-worked material) at least mixed-mode behaviour might be expected.

2. Spectrum of EAC mechanisms considered

For many years, it was thought possible to assign incidents of EAC uniquely to one of two categories: under "constant" tensile loading to stress corrosion cracking (SCC) and under the simultaneous action of corrosion and alternating mechanical loads to corrosion fatigue. At the end of the Sixties, the additional concept of stress-induced corrosion cracking was introduced in Germany to explain the formation of cracks at nozzles and welds of boiler vessels in conventional power stations. During the Eighties, it has become necessary to revise this picture as a result both of a series of failures involving low-alloy steel components in LWR systems (particularly of thin-walled piping in BWR's) and of increased understanding of the fundamental mechanisms of SCC and corrosion fatigue. The term strain-induced corrosion cracking (SICC) has been introduced [9] to cover the "grey" area of overlap between these two EAC processes, the failures described originally as stress-induced corrosion cracking now being seen as a special case of SICC.

Thus it is necessary to consider a spectrum of EAC mechanisms, bearing in mind that the boundaries between them are often hard to define and that practical problems in plant usually involve loading which spreads (at different times) right across the range considered.

Standardisation of terminology in the area of EAC has always presented particular problems, so that the definitions of SCC ("a process involving conjoint corrosion and straining of the metal due to residual or applied stresses") and corrosion fatigue ("a process involving conjoint corrosion and alternating straining of the metal") contained in [10] are of little assistance here. In the following, more use is made of a relevant German standard [11] and subsequent commentary on this [12].

2.1 "Classical" stress corrosion cracking

Classical SCC is used to cover those cases of EAC where the strain resulting from mechanical loading is truly constant (or even decreases) with crack growth. Crack initiation takes place when the stress acting at a smooth surface exceeds some critical value, which is lower than the yield point of the material. I.e., crack formation is not a result of localised plastic deformation, but can even take place during stress relaxation (and thus at negative values of strain rate). Similarly, crack propagation does not rely upon positive values of strain rate being achieved at the crack tip and thus does not involve considerations of low-temperature creep effects, either in actual components, or in notched or precracked specimens.

Typically, classical SCC involves the establishment of a critical combination of material and environmental parameters, often resulting in numerous cracks, whose path can be either intergranular or transgranular.

2.2 "Strain-induced" corrosion cracking

SICC always involves the effects of positive strain rates, either achieved through large-scale yielding of the material or, more commonly, in the form of localised yielding at the roots of notches and the tips of pre-existing cracks. Cyclic loading is either absent, or is restricted to a limited number of infrequent events (e.g. as a result of plant start-up). The extent of damage tends to increase as the rate of dynamic straining decreases (sometimes, however, exhibiting a critical value) and cracking usually tends to be transgranular.

Mechanistically, SICC is closely related to what has often been termed "strain-rate-sensitive" (or "non-classical") SCC, with both anodic dissolution and hydrogen embrittlement mechanisms possibly being involved. From an engineering standpoint, however, it can usefully be regarded as the limiting case of corrosion fatigue as the frequency of cyclic loading tends to zero.

2.3 Corrosion fatigue

In considering corrosion fatigue, it is useful to distinguish between crack initiation (as represented classically by so-called "Wöhler" or S/N curves) and crack propagation, usually represented in terms of the dependence of crack growth per cycle (da/dN) on magnitude of the alternating stress intensity (K). However, it is important to note that the usual form of testing to failure of smooth specimens in order to obtain S/N curves can involve a considerable proportion of crack propagation. I.e., the definition of "initiation" is critical here.

A further useful distinction with regard to corrosion fatigue at smooth surfaces is between low-cycle loading at high stress levels, which produces gross cyclic deformation of the material, and high-cycle loading at lower stress levels, where plastic deformation is highly localised. Corrosion effects are usually most evident with the former, which is often referred to as the region of time-dependent fatigue strength. However, corrosion can also lead to the disappearance of material endurance limits at high numbers of cycles. With regard to corrosion fatigue crack growth, the analysis of environmental enhancement on a time-domain basis [4], rather than in terms of crack growth per cycle, provides a valuable tool for assessment purposes [13]. However, due attention must be paid to the existence of realistic thresholds for corrosion effects at very low frequencies and/or high R ratios.

3. Acceptance criteria for experiments to asse EAC susceptibility under LWR conditions

Laboratory experiments to determine EAC behaviour under conditions relevant to LWR systems are notoriously difficult to perform and there is a huge amount of scatter in existing data (particularly with regard to crack propagation) under nominally identical test conditions. It appears worthwhile to attempt to rationalize this scatter in terms of the **quality** of the experiments performed and a systematic approach, involving weighting factors (on a scale of 1 to 5) to downgrade data associated with inadequate experimental techniques, is proposed. Table 1 represents a generalised attempt to take various, specific features of the experimental conditions into account, but it has to be recognized that the assignment of "points downgraded" for a particular aspect should really be unique to the corrosion system under consideration. E.g., it is unlikely that exactly the same assessment of the influence of loading techniques (the "B" parameters in Table 1) is appropriate with stainless steels and nickel-base alloys as with carbon and low-alloy steels, for which the present approach was originally developed [14]. For this reason, a range of points downgraded is presently suggested for each parameter in Table 1 and further work is needed to refine the approach for a particular situation.

Whether or not an individual deficit leads to downgrading can also depend upon the general nature of the results obtained, i.e.

- **always** (symbol # in Table 1) in the case of a general inadequacy;
- **only if crack growth is measured** (da/dt > 0, symbol * in Table 1) if the deficiency does not invalidate the quality of an experiment with negative result;
- **only if no EAC is found** (da/dt = 0, symbol o in Table 1) if the deficiency is **only** misleading with regard to an experiment with negative result.

3.1 Materials characterization

The following details are required to characterize adequately the materials tested:

- **actual composition.**

A full analysis is desirable, with the emphasis to be placed upon specific elements particular to the class of material being investigated. Thus for carbon and low-alloy steels, the S content is always critical, whereas for stainless steels, C, Cr, Ni and stabilizing elements such as Nb or Ti are also vital. With Ni-base alloys, elements such as P may also be important.

It is suggested that data from experiments where only the type of material is quoted, or where the content of a key element is missing, be downgraded by 1 to 3 points.

- **fabrication, heat treatment and microstructure attained.**

The emphasis to be placed upon this again depends upon the class of material being studied. Thus for carbon and low-alloy steels the shape, size and distribution of MnS inclusions may be the critical factor, whereas for stainless steels and Ni-base alloys, the state at grain boundaries is usually the key parameter. The effort required to characterize this may be considerable, ranging from electrochemical tests (such as the "electrokinetic potential reactivation" (EPR) method) to transmission electron microscopy (TEM). In all instances, it is crucial to define whether EAC is being measured in the base metal, a weld metal (dendrite orientation?) or a heat-affected zone (coarse or fine-grain HAZ?). Tests where crack propagation can include more than one of these zones are generally very difficult to interpret and compare.

It is suggested that data from experiments with inadequate characterization in this area must be downgraded by 3 to 5 points.

- **strength level of material and way in which it was obtained.**

With carbon and low-alloy steels, the strength level of the material is often crucial to the question of whether a hydrogen cracking mechanism (usually involving extremely high rates) can become operative or not. For stainless steels, the question of strengthening through cold work is often more important.

It is suggested that data which is deficient with regard to this point be downgraded by 2 to 4 points.

- **specimen surface condition.**

Since corrosion processes always take place at the phase boundary between the metal and the medium, it is clear that this factor can always be of crucial importance in determining crack initiation.

With fracture mechanics specimens containing a fatigue precrack, it tends to be forgotten that the local surface condition at the crack tip (including the immediate sub-surface stress state) can also affect the initial stages of crack propagation. Thus it is unreasonable, e.g., to expect immediate growth of intergranular cracks from a pre-existing transgranular defect.

Furthermore, specific deficiencies, such as electromachining of a notch in iron-base alloys using copper electrodes (leading to copper contamination of the surface), can have pronounced effects on the validity of experimental data.

Downgrading of 1 to 3 points is suggested for inadequate characterization of this parameter.

3.2 Simulation of operating medium

Inadequate simulation of the intended LWR operating medium is probably the biggest deficiency in existing EAC data in the literature. The following factors are considered to be critical:

- **water purity.**

In all laboratory work simulating BWR conditions, e.g., it is extremely difficult to reach and maintain the degree of water purity achieved in most operating reactors (i.e. typical conductivities of 0.1 to 0.2 S/cm). Furthermore, conductivity alone is not necessarily a guide to the extent of possible EAC enhancement, since the latter is known to be anion specific. Particular attention should be paid to the possible presence of oxidising sulphur species (e.g. arising from thermal decomposition after ingress of ion-exchanger resins) and to contaminants such as lead, which have been shown to affect EAC dramatically at very low concentrations. However, it is now recognised that even seemingly inert species such as silica can influence crack growth rates in some alloys.

Measurements performed only at the autoclave inlet often provide a very poor guide to the situation existing at the specimen surface, since this tends to be strongly affected by corrosion of both the specimens and the autoclave internals in small-volume vessels. In circulating, as opposed to refreshed systems, there is a real danger of enhanced (and often undetected) chromium levels being achieved under oxidising conditions. Measurements of electrochemical potential (in themselves highly desirable, compare remarks below) can lead to contamination from leakage of reference electrodes. Finally, use of precracked specimens can unwittingly result in locally bad water chemistry arising from contaminants left within the machined notch.

Water purity representative of PWR conditions is generally easier to obtain in the laboratory, since the use of deliberate chemical additions on both primary and secondary sides simplifies experimental procedures. However, simulation of all volatile treatment (AVT) can present problems and due attention must be paid to indications of incorrect pH values being obtained.

In view of the above comments, all data where detailed water purity at the autoclave outlet is not documented, or is clearly worse than the desired level, should be downgraded by 3 to 5 points.

- **level of oxidants.**

EAC processes are highly potential dependent, so that the level and effect of oxidants in the test medium is usually critical to the data obtained. It is important to remember that not only dissolved oxygen may be involved (the effective level of which may be difficult to assess due to consumption at specimen surfaces and within sampling lines), but that species such as H_2O_2 and Cr^{6+} may be more active. Ideally, direct measurement of electrode potential at the outside surface of the test specimen is required (but without contaminating the environment through leakage from reference electrodes) and even then differences due to the lack of flow in laboratory systems must be taken into account.

Work in which the specimen potential is not adequately established should be downgraded by 3 to 5 points. If only a general indication of oxidant level is given, the extent of downgrading will depend upon the range considered (e.g. downgrading by 3 points is usually appropriate for "air-saturated water", but the full 5 points should be applied to data from water which is nominally "free of oxygen", since the gradient of potential dependence upon oxygen content is particularly steep in the region of 5 to 50 ppb O_2).

- **flow conditions.**

In view of the importance generally considered to be attached to higher flow rates in alleviating EAC (through dilution or removal of aggressive species from within the crack enclave, compare [1]), remarkably little experimental work has been carried out on this parameter. Clear evidence of the magnitude of such effects is provided by [7]. However, even where an attempt was originally made in one case to simulate turbulent flow conditions [15], subsequent hydrodynamic analysis revealed that only relatively low Reynolds numbers were in fact attained in the region of the growing crack [16].

A further effect of flow rate on EAC is to be expected from its influence on mass transport of reducible species (e.g. O_2) to the specimen surface, since this will alter the electrochemical potential attained there and may, under certain circumstances, be rate determining with regard to cracking [2].

Ideally, clear evidence of actual Reynolds numbers should be given for experiments where flowing conditions are considered to have been achieved. Otherwise, it must be assumed that conditions were, in fact, stagnant. Particular attention has to be paid to experiments under so-called "flowing" conditions, where only adequate refreshment of autoclave solutions so as to maintain the desired chemistry in fact took place.

Downgrading by 1 to 3 points is probably appropriate where no clear allocation of data to the actual flow conditions can be carried out.

- **temperature.**

The existing database on EAC suffers from having been obtained predominantly at typical LWR operating temperatures of around 288 °C, whereas plant loading known to have produced damage often takes place over a range of intermediate temperatures. The effect of temperature is controversial and may be specific to combinations of material, medium and loading, so that general statements regarding the degree of conservatism in applying data obtained at higher temperature to lower ranges are not possible. E.g., both Atkinson [17] and Hänninen [18] have shown clear evidence for enhanced EAC in low-alloy steels at temperatures of around 200 °C.

In an experimental context, control of specimen temperature within autoclave systems is clearly important. Particular problems arise with so-called "daisy chains" of fracture-mechanics specimens within large autoclaves, where unexpected thermal stratification effects can lead to considerable differences in temperature between nominally identical specimens.

Deficient temperature control should lead to downgrading by 1 to 2 points, whereby the sensitivity is expected to vary between different classes of alloy.

3.3 Type of specimen and loading characteristics

The choice of both an appropriate specimen geometry and means of loading to obtain EAC data is extremely important and use of fracture-mechanics specimens alone does not necessarily guarantee comparability of results or relevance to loading in real components. An excellent guide is provided in [19].

The following points are considered to be relevant, whereby assessment ultimately concentates on the question of what strain rate is achieved (generally and locally) in the specimen.

3.3.1 Smooth specimens under displacement loading.

Specimens which fall into this category are typically U-bends, C-rings and 3 or 4 point, bent-beam specimens. Whereas U-bend specimens, always involving a large and ill-defined amount of plastic deformation, are seldom considered relevant to plant components (with the exception of so-called "RUB" specimens for steam generator tubing), the other types can be used to attain more or less defined amounts of (usually elastic deformation). Particular care is needed here in assessing results obtained from notched specimens.

Since the above specimens always undergo stress relaxation, both upon loading and during crack initiation/growth, a negative result obtained (i.e. lack of cracking) must be downgraded by <u>3 to 5 points</u> with regard to the behaviour of actual plant components, where loading purely through displacement is rare. On the other hand, the appearance of EAC in such specimens is clear evidence for a classical mechanism of SCC (compare Section 2.1), and this can be of great advantage in assessing potential susceptibility in plant, even though quantitative data on crack growth rates are usually difficult to obtain. A further advantage of these specimens is the ease with which effects of material surface condition or flow of the medium can be studied, and creation of defined crevice geometries is often relatively simple.

3.3.2 Smooth specimens under active loading.

These are usually tensile testing specimens with loading through a mechanical or servo-hydraulic device, although other geometries (e.g. internally pressurized tubes) have also been used. Their main advantage is in producing clear evidence on initiation of EAC, or lack of this, at defined stress levels. Since loading increases after cracks are formed, the results can usually be regarded as conservative. Particular care is needed in assessing the reliability of data obtained at around the HT yield point of the material, however, since the combination of material variability and inaccuracies in loading can lead to wide differences in the extent of plastic deformation and thus to considerable scatter under nominally identical loading conditions. An example of this is shown in Fig. 1 and 2. Furthermore, it is important to recognise the role of low-temperature creep in tests which are deliberately carried out with loading above the material yield point. Under certain conditions, e.g., this can lead to no cracking being obtained if the test environment is introduced/attained some time after loading, whereas loading (or a load increase) whilst the specimen is exposed to the realistic medium can lead to rapid crack initiation. Downgrading by <u>1 to 3 points</u> is probably appropriate here, if such effects are not recognized.

With the exception of dead-weight loading, a hidden component of dynamic loading is often present in such tests (e.g. "ripple" associated with the feedback circuits of servo-hydraulic testing machines, effect of slight changes in ambient temperature on control of mechanical testing machines) and this can be decisive in initiating EAC (compare Section 2.2). Data should be downgraded by 2 to 4 points if the absence of ripple loading cannot be demonstrated.

3.3.3 Slow strain rate testing (SSRT).

SSRT of tensile specimens in the appropriate environment, sometimes referred to as constant extension rate testing (CERT), was originally intended only as a comparative test for material susceptibility to SCC. However, it is now realised that the type of loading achieved here is basically relevant to SICC and corrosion fatigue (compare Sections 2.2 and 2.3), even though increasing the load until specimen rupture occurs is clearly foreign to plant operation. Since the key fact in SSRT testing is the strain rate achieved locally at a particular point on the specimen surface, multiple initiation of cracks is a complicating factor. Furthermore, lack of stiffness in the testing machines often used can falsify results.

Crack growth rates derived from SSRT should be treated with considerable scepticism, since they usually imply (more or less explicit) assumptions about strain to initiation and uniformity of crack growth thereafter. E.g., with low-alloy steels, EAC often occurs only in the necked region of the specimen immediately prior to mechanical overload fracture. Interrupted SSR tests, with subsequent steady-state loading, can be of some value here.

Lack of susceptibility to EAC in SSRT is sometimes regarded as proof of immunity to cracking. This is particularly dangerous for two reasons: firstly, it may just mean that a sufficiently low, applied strain rate for EAC has not been achieved and, secondly, it must be remembered that SSRT, by its very nature, is of limited duration. If long-term changes in either the material (ageing) or the environment (concentration of aggressive species, formation of surfaces deposits etc.) are necessary for EAC, these will be missed in SSRT.

The results from SSRT are not generally appropriate for direct use in assessments of plant behaviour, as discussed, e.g., in [20], and data of this type should be eliminated before attempting to prepare firm guidelines on EAC behaviour. However, these tests can be of value in determining the relative importance of different material and/or environmental parameters, prior to longer-term tests using conventional specimens.

3.3.4 Pre-cracked, fracture-mechanics specimens under displacement loading

Bolt or wedge loaded, fracture-mechanics specimens are often used in autoclave experiments and are particularly popular for testing within reactor systems, because of their inherent simplicity. They also have the advantage that loading is truly static and, in general, if cracking **does** occur, the results can be regarded as fully reliable, since growing cracks can generate positive crack-tip strain rates as a result of dislocation activity. Furthermore, the reduction in effective stress intensity with increasing crack growth can be used to estimate K_{ISCC} (the threshold stress intensity value for stress corrosion cracking): this is simply the remaining K_I-value when crack arrest occurs (after a sufficiently long period of testing). It is advisable to **measure** this value upon unloading the specimen, since the accuracy of calculation alone is limited, and otherwise downgrading of the data by <u>1 to 3 points</u> is suggested. Furthermore, it is important that the difference between the initial and final K_I-values is not excessive, since otherwise it becomes difficult to plot the results satisfactorily: ideally, a determined crack growth rate should be associated with a single value of stress intensity for purposes of data assessment.

The major problem with these methods, however, is that they are non-conservative with regard to the initiation of EAC (despite the existence of a fatigue pre-crack in the specimen), a fact which often remains unrecognised. It arises through the inevitable relaxation of stress at the crack tip which takes place after loading (no matter how careful), both through low-temperature creep processes and as a result of changes in the elastic modulus of the material upon heating up to test temperature. Thus crack-tip strain rates initially are always negative and results from such specimens must be downgraded by <u>3 to 5 points</u>, if **no** crack growth is registered.

The minimum size of the fracture-mechanics specimens needed to obtain valid data on EAC is a subject of intensive and controversial debate. Strict adherence to the ASTM guidelines for testing of such specimens in air is obviously desirable in a conservative sense in terms of applicability to thick-walled components. However, it usually requires the use of unreasonably large specimens with the ductile alloys used in nuclear systems. Furthermore, data is often required for relatively thin-walled components, where plane strain conditions of loading will not, in practice, be achieved in any case. As a compromise, it is suggested that data from specimens where the nominal K_I value exceeds the ASTM validity limit be downgraded by <u>1 to 3 points</u>. If the nominal K_I value is greater than 2x the validity limit, the validity of linear elastic fracture mechanics

(LEFM) is clearly breached and it is considered that the data should be downgraded by 3 to 5 points, since crack growth through mechanical overloading alone can no longer reliably be excluded.

Data obtained from all fracture-mechanics specimens should be downgraded by 2 to 4 points if the determination of final crack depth only takes place at the end of the experiment, since the exposure period may involve an incubation time and thus lead to estimates of crack growth rate (da/dt) which are lower than that actually occurring. Similarly, data should be downgraded by 3 to 5 points if the crack depth determination is only performed visually on the sides of the specimen. This is at best inaccurate and will sometimes be highly misleading, since EAC often occurs predominantly only at the centre of such specimens as a result of enhanced crevice effects and/or higher triaxiality of the stress state. With increased use of NDT techniques, such as the potential drop method, for continuous monitoring of crack growth, objections to the way crack depths are measured can largely be avoided. However, it is recommended that reports of declared extents of crack growth <0.03 mm be treated with scepticism (and downgraded by 1 to 3 points), since this is hardly detectable, even fractographically.

3.3.5 Pre-cracked, fracture-mechanics specimens under active loading.

Except in the case of deliberate load shedding, use of active loading ensures that the effective stress intensity rises with increased crack depth so that positive crack-tip strain rates can be achieved and objections to possibly non-conservative results usually disappear. As with displacement-loaded specimens, however, it is important to ensure that overloading does not occur at any stage during specimen preparation (including the final stages of fatigue precracking), since this would produce an unrepresentative (locally compressive) stress state at the initial crack tip. Of more concern with active loading, however, is the inclusion of intentional or unintentional (inadequate machine control) cyclic loading, either directly before the relevant phase of the experiment (downgrade data by 1 to 3 points, since this can lead to acceleration of crack growth) or - even worse - during the period of measurement under nominally static loading. In the latter case, the results should be downgraded by 3 to 5 points, since corrosion fatigue effects may unintentionally predominate. A similar objection arises in SCC studies with whole or partial unloading of the specimen in order to determine crack depths by the compliance method. It is often argued that cyclic loading in some form, or at least periodic unloading of specimens, is more representative of loading on real plant components than truly static stressing and in some EAC systems (e.g. Ni-base alloys) the effects would indeed appear to be non-critical. With low-alloy steels, however, they can lead to crack growth through

EAC when **none** would otherwise have occurred through SCC alone. In this case, the loading profile has to be examined in detail for its real relevance to operating systems.

The concerns expressed in Section 3.3.4 with regard to specimen size for applicability of LEFM and to methods of determining the extent of crack growth apply equally to actively loaded specimens. Ideally, crack growth measurements of sufficient sensitivity should always be performed in "real time", i.e. continuously throughout the test. In addition, it should be realised that lack of crack growth in a particular experiment cannot be regarded as evidence of immunity to EAC unless the testing time was sufficiently long. The minimum duration needed is difficult to generalise, since it depends both upon the material and the environmental conditions. With low-alloy, ferritic steels in HT water containing only moderate levels of oxygen, however, it is considered to be at least 5000 hours. If there is evidence that the chosen test duration may be less than the incubation time for EAC, data showing absence of cracking should be downgraded by 3 to 5 points.

3.3.6 Special types of specimens

Progress in understanding EAC has often been linked to the use of special types of test specimens. Thus the importance of crevice conditions in promoting IGSCC in non-sensitized stainless steel was demonstrated by Hänninen using double U-bend specimens [21]. A more recent development has been the use of fracture-mechanics specimens containing a defined notch geometry, rather than a fatigue pre-crack (so-called "keyhole" specimens). Ljungberg, in particular, has refined these techniques by creating controlled crevice geometries through the use of side plates and filler material [22].

Sometimes, simulation of EAC in the field has only been possible through the use of relatively large specimens of similar geometry to failed components. Examples here are the use of so-called "hole-in-plate" specimens to simulate nozzle cracking in BWR pressure vessels [23], bolted constructions with lubricants [24] and large-scale pipe tests for SCC and corrosion fatigue behaviour [25].

Some pitfalls which have now become apparent are the use of graphite wool to enhance susceptibility of Ni-base alloys under crevice conditions [26], since this can lead to extreme variability in results associated with contamination and unexpected electrochemical effects, and the inclusion of weld residual stresses in piping tests, where realistic simulation of field conditions has proved to be unexpectedly difficult [27].

It is difficult to make general comments on the use of non-standard specimens for EAC testing and each application should be considered on its merits.

4. Examples for the application of EAC acceptance criteria to the question of crack growth through SCC in low-alloy steels under BWR conditions

4.1 Background

In safety analyses of LWR pressure vessels, it is common to postulate that the high-alloy cladding (if present) contains a crack-like flaw extending to the phase boundary with the low-alloy material of construction, so that the latter is in contact with the operating medium under occluded cell conditions. Analysis of possible fatigue crack growth is then carried out according to ASME Section XI (possibly also taking account of later knowledge on corrosion fatigue which has not yet been incorporated into the code [28]). However, in recent years it has been postulated [29] that crack growth in the base material may also occur during normal BWR operation under nominally constant load through a SCC mechanism and this would obviously be of immense concern in safety assessments. Although present field experience [30] does not support this contention, it is obviously desirable to examine more closely the existing data base from experimental studies [14].

For this purpose, known experiments (up to September 1991) on SCC of low-alloy, pressure-vessel steels in oxygenated HT water using pre-cracked, fracture-mechanics specimens were collated in an electronic database. From a total of about 175 individual autoclave tests, some 220 separate data points for the rate of crack growth (da/dt) at a constant, nominal stress intensity (K_I) were obtained. Some interpretation of data was necessary in the case of those experiments where a range of measured values had been reported for da/dt and/or K_I. The result of this exercise is shown in Fig. 3 as the well-known "night-sky" diagram, which has also been reported in the literature by Ford and Andresen [31]. I.e., there is enormous scatter in the existing data and if this is simply bounded by an envelope curve, it would imply that SCC occurs with catastrophic rates even at low stress intensities, a conclusion which experience in both nuclear and conventional power generation clearly shows to be false.

As a next step, the data was classified according to type, using the key shown in Table 2, and data selection was restricted to those points more directly relevant to RPV steels under normal BWR water chemistry. However, as shown in Fig. 4 (together with a theoretical curve from the work of Ford and Andresen [32]) this did not in itself serve to eliminate the inherent scatter, particularly with regard to experiments showing **no** crack growth at relatively high stress intensities. It was then realised that some assessment had to be made of the **quality** of the experimental data concerned. The impetus for this was provided by a direct comparison (Fig. 5) between the data obtained from one laboratory, where control of both water chemistry and specimen loading/crack growth measurement was known to be poor, with other comparable data in the database. This approach resulted in development of the assessment procedure shown in Table 3, which was the predecessor to the generalised acceptance criteria for EAC developed earlier in this report and itemised in Table 1.

4.2 Justification for acceptance criteria

In many cases, the justification for some of the acceptance criteria contained in Table 3 can be seen from their individual application to the whole database. Thus, e.g., the value of distinguishing between active and passive loading is revealed in Figs. 6 and 7: when a specimen **does** show crack growth, there is little apparent effect of this parameter. However, the passively loaded specimens are over-represented in those experiments **without** crack growth, justifying the downgrading factor "B.2" applied in Table 3 for data showing apparent immunity to SCC.

Analogously, Figs. 8 and 9 show the effect of load changes (including those for the purpose of compliance measurements) on the measured data during experiments with actively loaded specimens. There appears to be no clear effect on crack growth **rates** (at least at higher oxygen levels and/or stress intensities), but it can be seen that load changes may definitely lead to crack growth in specimens which would **not** otherwise have shown this. This provides the justification for the factor "B.4" in Table 3.

The effect of exceeding "formal" LEFM validity limits (i.e. from ASTM guidelines for K_{IC} testing) is analysed in Figs. 10 to 12. Bearing in mind that more specimens are bound to be invalid at higher stress intensities (and that certain data from one laboratory at the top of Figs. 10 and 12 were obtained with particularly thin specimens, but also under badly controlled water chemistry), no clear influence can be seen of adherence to the formal validity criterium for specimen size on crack growth rates in the complete data set. However, Fig. 11 does suggest a possible effect in terms of higher growth rates with smaller specimens at the lower oxygen level of 0.2 - 0.4 ppm. Again, this provides the reasoning for the factors "B.5" and "B.6" in Table 3.

The possible effect of transient conditions with tests of short duration and/or of test interruptions is analysed in Figs. 13 and 14, but the results are inconclusive. Thus data points were not downgraded dramatically for this reason alone, but fundamental worries concerning creep effects in actively loaded specimens at short times (e.g. < 160h), or of removing passively loaded specimens from the autoclave for visual inspections, provide justification for the factor "R.3" in Table 3.

4.3 Application of acceptance criteria

Ideally, first-class data would be subjected to no downgrading ("Class A" = 0 points, compare footnote to Table 3). However, application of such stringent acceptance criteria reduces the existing EAC database to such a dramatic extent that it no longer becomes possible even to attempt an analysis of material behaviour. Accordingly, "Class B" data, worthy of evaluation but possibly subject to some uncertainty, were defined to exist if the sum of points after the downgrading exercise lay between 1 and 4. Data which attracted a sum of downgrading points equal to or greater than five ("Class C") were regarded as not normally suitable for evaluation, since performance of the experiment was clearly unsatisfactory. It should be noted here that certain single deficiencies, e.g. inadequate control of water chemistry or repeated load changes during the experiment (for da/dt 0), may, by themselves, lead to the rejection of data (compare Table 3).

The result of excluding Class C data is dramatic, as shown in Fig. 15. Even though this diagram still contains data over a wide range of temperatures (170 - 290 °C), the key importance of oxygen concentration in the medium immediately becomes apparent. As expected from theory, oxygen levels of around 8 ppm lead to much higher crack growth rates, which begin to approach the so-called "high sulphur" line [32]. At the levels of interest for BWR reactor water under normal operating chemistry (0.2 - 0.4 ppm), growth rates are 1 to 2 orders of magnitude lower and exhibit an apparently higher dependence upon nominal stress intensity.

Equally striking in the comparison between Figs. 3 + 4 and Fig. 15 is the absence of all data points at high stress intensities showing **no** crack growth whatsoever. This results mainly from the effects of the Table 3 acceptance criteria B.2 (lack of active loading) and R.5 (duration of experiment shorter than probable incubation time) upon data purporting to show immunity to SCC.

Although the data points for realistic BWR reactor water oxygen levels are certainly bounded by the so-called "low sulphur" line, it was felt that this curve is probably unreasonably conservative for actual assessment of plant behaviour for a number of reasons. Predominant among these were the relatively high conductivities even in the tests leading to Class B data and, in particular, the absence of flow in virtually all the experiments considered. For this reason, a revised bounding line was proposed in Germany [33] as a realistic curve for plant assessment. As shown in Fig. 16, the so-called "MPA theoretical line" is actually non-conservative with regard to a single data point. However, re-examination of all the details from this particular experiment had shown that it was unusual in some respects, even though not having qualified for downgrading to Class C and thus rejection.

In considering the relevance of the above approach for safety assessments of the reactor pressure vessel, it should not be forgotten that the original postulate of a defective vessel cladding with immediate access of the operating medium to the ferritic steel is, in itself, conservative and that no credit has been taken either for the beneficial effects of flow, or for the apparent existence in many tests of an incubation period before crack growth is observed.

The same approach to the analysis of existing data was also used to classify the conditions under which SCC might be expected in low-alloy steels throughout a BWR plant [34] and the results are shown in Table 4. As a result of the insights gained during the data analysis exercise, it was considered imperative here to distinguish between conditions leading to crack initiation at a smooth surface (which are relevant, e.g., to thin-walled piping) and those which would permit an existing, crack-like defect (as usually postulated to exist in thick-walled components) to grow through SCC.

5. Discussion and conclusions

The approach to the analysis of EAC data outlined above inevitably involves some subjectivity, so that independent confirmation of its usefulness is required. Ideally, this would come from the performance of new experiments in which sufficient attention is paid to all the issues discussed, so that no downgrading of data is required. In the case of SCC of low-alloy steels under BWR conditions, work is ongoing worldwide. A first opportunity to check the validity of the conclusions reached in Section 4, above, was provided by results recently published by Van Der Sluys and Pathania [35]. In these experiments, both the control of water chemistry and the techniques used to monitor crack growth were exemplary. Mechanical loading was also extremely accurate, although deliberate use was made of load variations to examine initiation and arrest of cracking.

The key conclusion in [35] is that crack growth is **intermittent**, even in HT water containing 8 ppm oxygen: no **sustained** cracking (detection limit 1.10^{-8} mm/s) was observed in pressure vessel steels tested in genuinely high-purity water. This finding lends weight to the scepticism attached to many previous experiments without effective crack-growth monitoring, as expressed in the "R" factors in Table 3. Moreover, the relatively high rates (up to a maximum of 6.10^{-6} mm/s) occasionally observed for brief periods in the highly oxygenated environment were normally the result of changing some external variable, such as the load (compare "B" factors in Table 3). **No** SCC crack growth was observed at all in water with the more typical BWR oxygen content of 0.2 ppm, or in a steam environment (even at oxygen levels above 20 ppm).

The criteria discussed in Section 4 were developed specifically for BWR environments. Because of the usually lower oxygen levels, SCC of low-alloy steels in PWR's would not generally be expected. However, a series of field incidents involving cracking of steam generator shell materials has been attributed, at least in part, to this mechanism [36]. Only a few plants have been affected and this is thought to be associated primarily with bad control of secondary water chemistry after shutdown (high levels of oxygen, anionic impurities and - in some cases - dissolved copper in the SG feedwater). Thus the justification for severely downgrading (or discarding) EAC experiments with bad control of water chemistry is apparent. Even under the above conditions, the **maximum** da/dt values from the service cracking were estimated to lie in the region of 7.10^{-7} mm/s at an effective stress intensity of around 57 MPa m. This is only just above the so-called "low-sulfur" line (see Fig. 15) and thus well below some of the reported lab data (compare Fig. 5).

Table 1 has been deliberately formulated so as to be more comprehensive than the approach used for low-alloy steels in BWR environments as detailed in Table 3. Further analysis of existing data is required before the generalised acceptance criteria contained in Table 1 can be narrowed down and applied with confidence to tests for EAC of stainless steels and nickel-base alloys. As indicated in Section 3, it is known that certain factors such as material microstructure (sensitization) and exposure geometry (crevices) are likely to be far more important here than for low-alloy steels. On the other hand, the effects of load changes (or even of limited cyclic loading) are likely to be less critical in systems where EAC is predominantly intergranular in nature. The final factors shown in Table 3 for low-alloy steels under BWR conditions were derived in an iterative manner by examining the effect of various selection criteria on the data contained in an extensive database of experimental results and it is suggested that a similar approach should be adopted for the austenitic materials. This could then lead to the creation of subsets of acceptance criteria specific to a particular material/environment combination.

Furthermore, it would be desirable to assess the way in which the points downgraded are combined to decide upon the admissibility of data. In Section 4 and Table 3, the simple approach of adding together the points resulting from fixed weighting of individual factors was adopted, but more sophisticated methods could be considered to take account of the undoubted presence of synergistic effects. Similarly, the cut-off levels between different classes of data, used to establish which results are retained for actual assessment of EAC behaviour in plant, were fixed in a relatively arbitrary way and refinement is possible here.

In an ideal world, assessment of EAC in nuclear plant would be based only upon the results from "perfect" experiments. However, despite the vast improvements in experimental technique made over the last 10 to 15 years, this is never likely to be the case, since - in practice - compromises have to be made. Thus the development of accurate, but complicated and costly, techniques for monitoring crack growth has often led experimenters to reduce the period of measurement under a particular set of conditions, sometimes with unexpected results. On the other hand, long testing times are useless without a reliable way of detecting crack initiation (and possibly arrest) and will, in any case, always lag behind the actual time of operation of real plant. For these reasons, it is worthwhile to re-examine the vast body of data on EAC already available in the literature in a systematic manner and the approach suggested in this report is intended to indicate a sensible way forward. Despite the obvious needs for statistical refinement and further work using experimental data from systems other than low-alloy steels in BWR environments, it is considered that the ability to rationalize the data studied to date has been clearly demonstrated. Furthermore, the approach has already enabled actual assessment of possible SCC behaviour of low-alloy steels in BWR plant to be performed with greater confidence, whilst eliminating undue conservatism [33, 34].

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LWR

Proposed acceptance criteria for EAC experiments: KEY TO ASSESSMENT OF DATA QUALITY

(# = ALWAYS leads to downgrading)
(* = does NOT lead to downgrading for result da/dt = 0)
(o = leads ONLY to downgrading for result da/dt = 0)

KEY	Range of points down-graded		PERFORMANCE OF EXPERIMENT
M.1	1 - 3	#	Information on material composition inadequate
M.2	3 - 5	#	Inadequate characterization of material fabrication/heat treatment/microstructure
M.3	2 - 4	#	Material strength level inappropriate or inadequately defined
M.4	1 - 3	#	Surface condition and/or sub-surface stress state not representative of real component
W.1	3 - 5	#	Detailed water purity at autoclave outlet not documented, or clearly worse than desired level
W.2	3 - 5	#	Specimen potential not adequately established (e.g. only general description of oxidant level)
W.3	1 - 3	#	Inadequate characterization of flow conditions
W.4	1 - 2	#	Temperature control deficient
B.1	1 - 3	#	Mechanical loading inadequately defined (e.g. through stress relaxtion or lack of measurement after crack growth)
B.2	3 - 5	o	Specimen loading passive rather than active (can lead to infinitely long incubation times)
B.3	1 - 3	*	Cyclic loading directly before the relevant phase of the experiment (can lead to acceleration of crack growth)
B.4	3 - 5	*	Repeated load changes during the period of measurement (since fatigue effects may predominate)
B.5	1 - 3	*	Strict application of LEFM not possible (nominal KI value > validity limit for spec. size), since relevance of result more difficult to assess
B.6	3 - 5	*	LEFM clearly breached (nominal KI value > 2x validity limit) , since crack growth through mechanical overloading cannot be excluded
R.1	2 - 4	*	Crack depth determination only at the end of the experiment (i.e. real da/dt possibly higher, since incubation time unknown)
R.2	3 - 5	#	Crack depth determination only performed visually on the sides of the specimen (i.e. inaccurate and possibly misleading)
R.3	2 - 4	*	Test of very short duration, or repeatedly interrupted, since cracking possibly measured only during transient conditions
R.4	1 - 3	*	Declared extent of crack growth <0.03 mm (since this is hardly detectable, even fractographically)
R.5	3 - 5	o	Duration of experiment possibly < incubation time for cracking

Table 1

BWR

SCC crack growth rate data for low-alloy ferritic steels in HT water: KEY TO DATA CLASSIFICATION

Key

W TYPE OF MATERIAL
1 Current RPV steels (i.e. A508 Cl.2, A508 Cl. 3, A533-B or international equivalents)
2 Other low-alloy pressure vessel and piping steels
3 Plain carbon steels

F STRENGTH LEVEL OF MATERIAL
1 Typical for RPV (i.e. 0.2 % proof stress (RT) from 345 to approx. 500 MPa)
2 Higher strength (but 0.2 % proof stress (RT) < 800 MPa)
3 Lower strength

G MICROSTRUCTURE OF MATERIAL
1 Base metal
2 Weld metal
3 Heat affected zone

V TEMPERATURE OF EXPERIMENT
1 Typical for RPV (i.e. from 270 to 290 oC)
2 Typical for feedwater or condensate systems (i.e. from approx. 170 to 270 oC)
3 Not typical for LWR components outside turbine area (i.e. < 170 oC)

O OXYGEN CONTENT OF MEDIUM
1 >>0.4 ppm (i.e. accelerated test, typical only for stagnant BWR condensate at locations without steam bleed-off)
2 Typical for RPV (i.e. from 0.2 to 0.4 ppm)
3 From 0.02 to 0.2 ppm (i.e., typical for feedwater systems)
4 <0.02 ppm (i.e. relevant only for PWR)

L CONDUCTIVITY OF MEDIUM
1 Typical for a good experiment (i.e. < approx. 2 uS/cm at high oxygen levels, otherwise < approx. 0.2 uS/cm)
2 Raised through impurities

S FLOW CONDITIONS
1 Stagnant (leads automatically to downgrading of data quality unter characteristic "P", i.e inadequate control of water chemistry)
2 Typical for a good experiment (e.g. "refreshed" autoclaves for close control of water chemistry, but no real flow at the specimen)
3 High flow rate (i.e. > approx. 1 m/s at the specimen for laminar flow, or turbulent conditions)

Table 2

BWR | **SCC crack growth rate data for low-alloy ferritic steels in HT water: KEY TO ASSESSMENT OF DATA QUALITY**

Points downgraded
(* = does NOT lead to downgrading for result da/dt = 0)
(o = leads ONLY to downgrading for result da/dt = 0)

Key	Points downgraded		PERFORMANCE OF EXPERIMENT
P	5		Inadequate control of intended water chemistry
B.1	2		Stress intensity factor badly defined (e.g. through lack of measurement at the end of the experiment)
B.2	5	o	Specimen loading passive rather than active (can lead to infinitely long incubation times)
B.3	2	*	Cyclic loading directly before the relevant phase of the experiment (can lead to acceleration of crack growth)
B.4	5	*	Cyclic loading during the period of measurement (since fatigue effects may predominate)
B.5	2	*	Application of LEFM uncertain (nominal KI value probably > validity limit for spec. size), since relevance of result more difficult to assess
B.6	5	*	LEFM clearly breached (nominal KI value > 2x validity limit) , since crack growth through mechanical overloading cannot be excluded
R.1	2	*	Crack depth determination only at the end of the experiment (i.e. real da/dt possibly higher, since incubation time unknown)
R.2	3		Crack depth determination only performed visually on the sides of the specimen (i.e. inaccurate and possibly misleading)
R.3	3	*	Compliance measurement with whole or partial unloading of specimen (i.e. with possible effects on da/dt)
R.4	3	*	Declared extent of crack growth <0.03 mm (since this is hardly detectable, even fractographically)
R.5	5	o	Duration of experiment < 5000 h (for <= 0.4 ppm O2) or < 1000 h (for >>0.4 ppm O2), since possibly < incubation time

DATA QUALITY

0 : Class A (first-class data)
1 - 4 : Class B (data worthy of evaluation, but possibly subject to some uncertainty)
>=5 : Class C (data not normally to be evaluated, since performance of experiment unsatisfactory)

Table 3

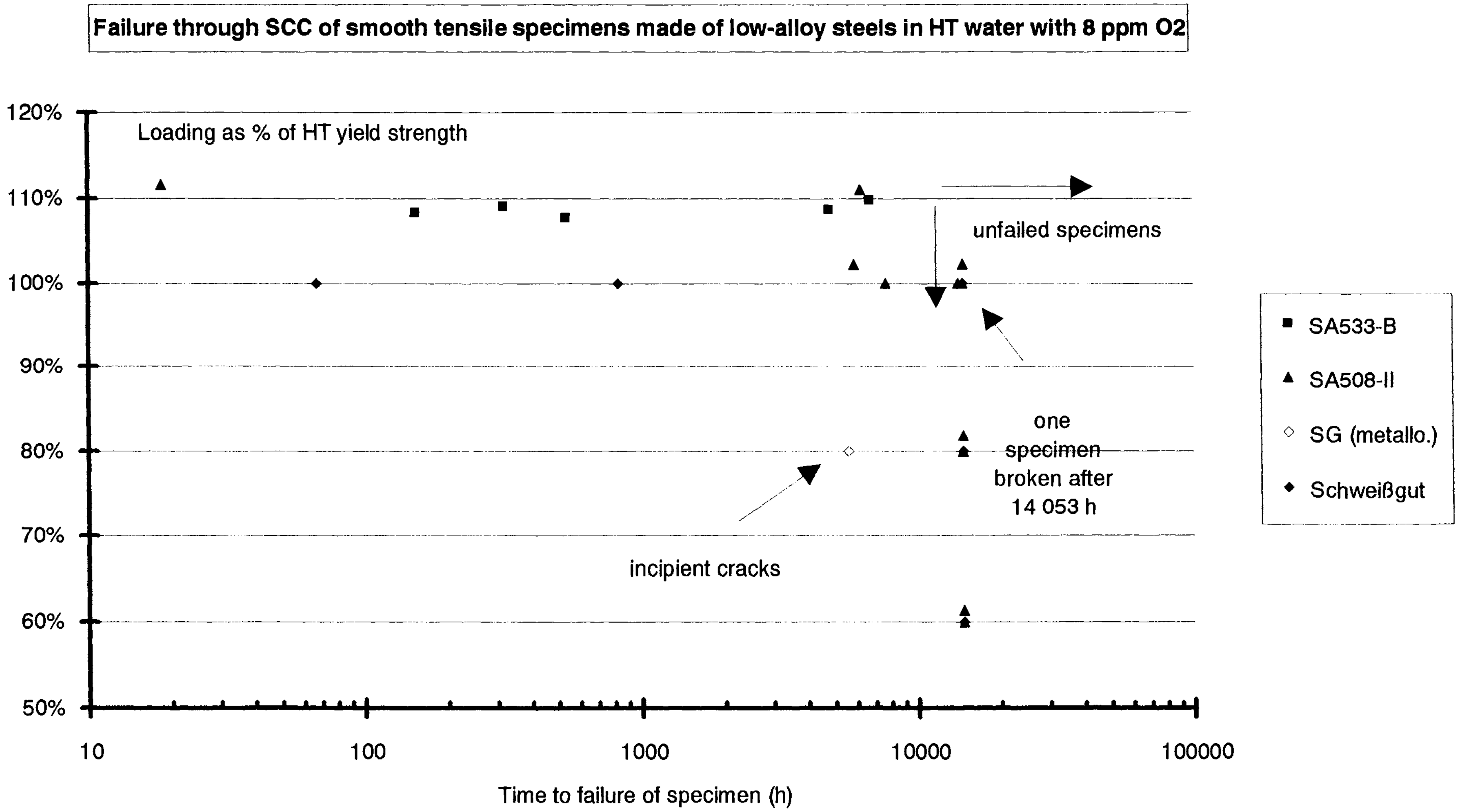
Table 4

Assessment scheme for SCC susceptibility of components made of low-alloy steels at normal strength levels (i.e. yield point < 800 N/mm²) im BWRs

Operating medium: high-temperature water or steam condensate with T > 170 °C						
O_2 content in ppm	Flow conditions	Conductivity* in µS/cm	Crack initiation through SCC?	Derivation	Crack growth through SCC?	Derivation
< 0.2	typical for reactor	typical for reactor (i.e. < 0.1)	no susceptibility	1	no susceptibility	1
< 0.2	quasi-stagnant	(approx. 0.2)	no susceptibility	1	no susceptibility	2
< 0.2	quasi-stagnant	raised (e.g. through lubricants)	x (for stress levels at the water-wetted surface in the region of the HT yield point)	2	o	3
0.2—0.4	typical for reactor	typical for reactor (i.e. approx 0.2)	no susceptibility	1	no susceptibility	1
0.2—0.4	quasi-stagnant	(approx. 0.2)	x (for stress levels at the water-wetted surface > the HT yield point)	2	o	2
0.2—0.4	quasi-stagnant	raised (e.g. through lubricants)	x (for stress levels at the water-wetted surface in the region of the HT yield point)	2	o	2
>> 0.4	typical for reactor	typical for reactor (i.e. < 0.2)	in general, no susceptibility (? at stress levels >> HT yield point)	1 3	susceptibility is suppressed through flow	2
>> 0.4	quasi-stagnant	< 1 (approx. 0.2)	x (for stress levels at the water-wetted surface > = the HT yield point)	2	o	2
>> 0.4	quasi-stagnant	raised (e.g. through lubricants)	x (for stress levels at the water-wetted surface in the region of the HT yield point)	2	o	2

x possibility cannot be excluded, perhaps after long incubation time
o possibility cannot be excluded, perhaps after incubation time even with pre-existing crack
* measured at 25 °C

Derivation:
1 from experiments in more aggressive environments
2 from appropriate autoclave experiments
3 no experimental results of direct relevance



Failure through SCC of smooth tensile specimens made of low-alloy steels in HT water with 8 ppm O2
Loading as % of HT yield strength
120%
110%
100%
90%
80%
70%
60%
50%
unfailed specimens
one specimen broken after 14 053 h
incipient cracks
10
100
1000
10000
100000
Time to failure of specimen (h)
SA533-B
SA508-II
SG (metallo.)
Schweißgut

Fig. 1

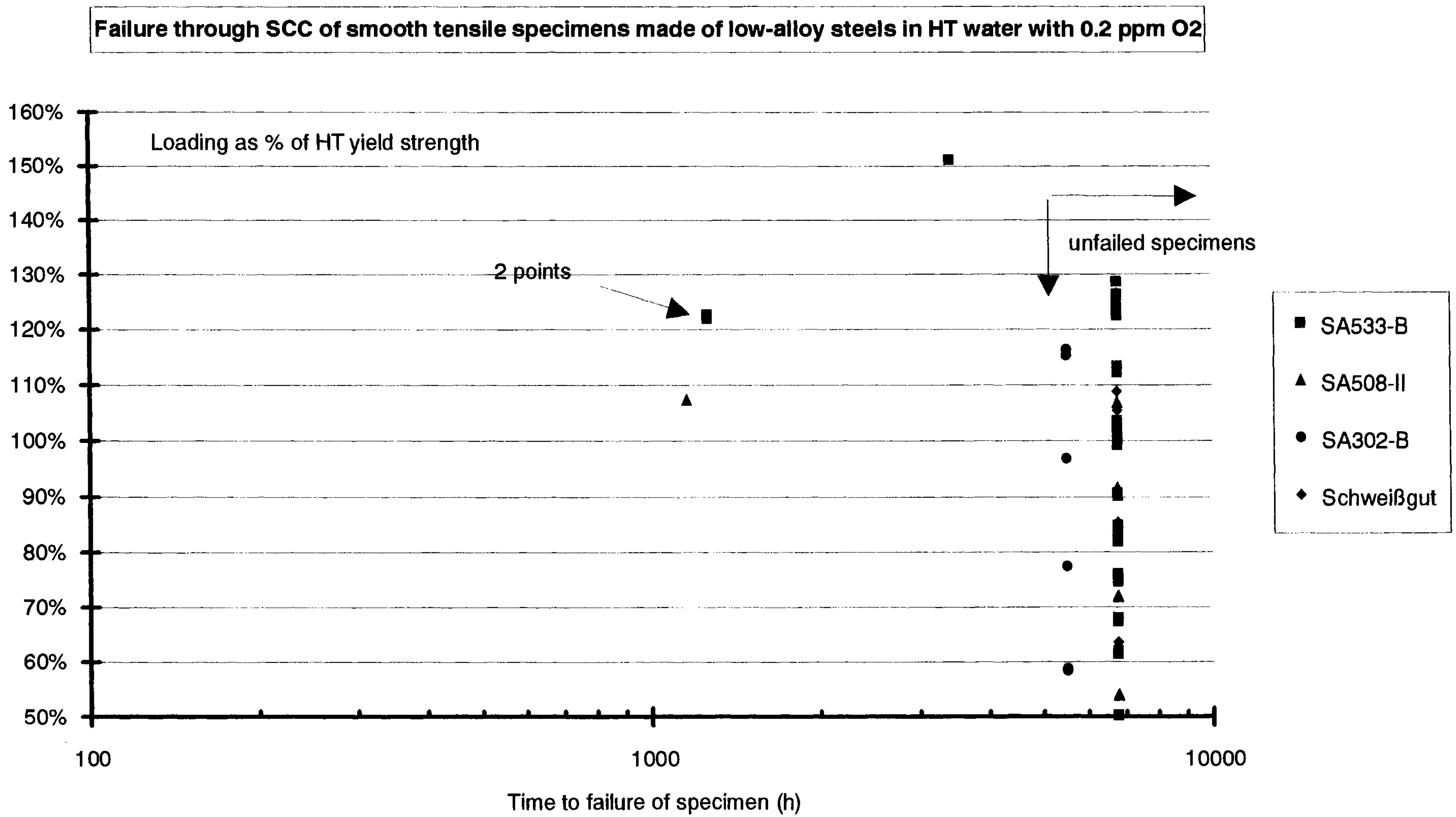

Failure through SCC of smooth tensile specimens made of low-alloy steels in HT water with 0.2 ppm O2
Loading as % of HT yield strength
160%
150%
140%
130%
120%
110%
100%
90%
80%
70%
60%
50%
2 points
unfailed specimens
100
1000
10000
Time to failure of specimen (h)
SA533-B
SA508-II
SA302-B
Schweißgut

Fig. 2

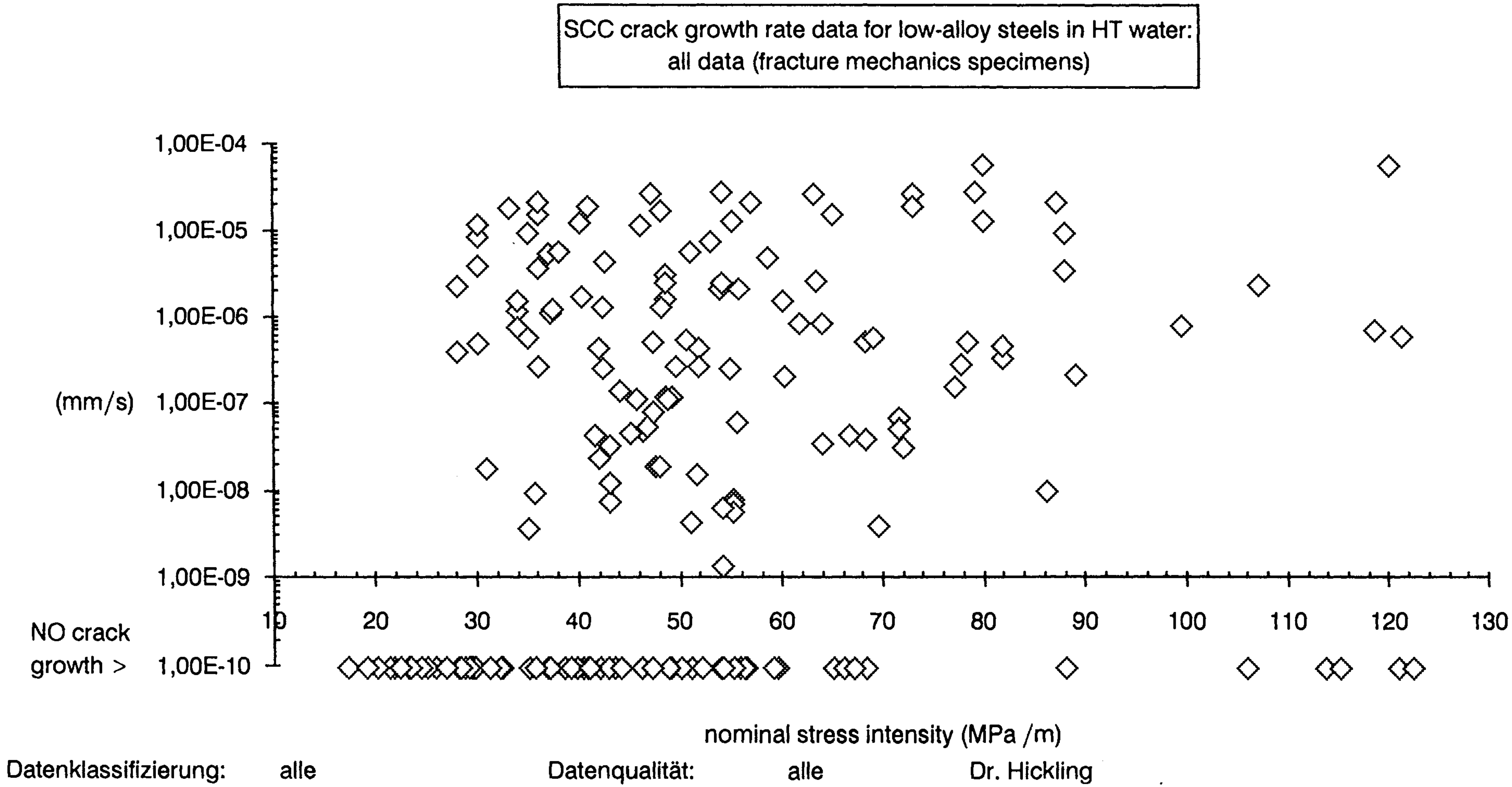
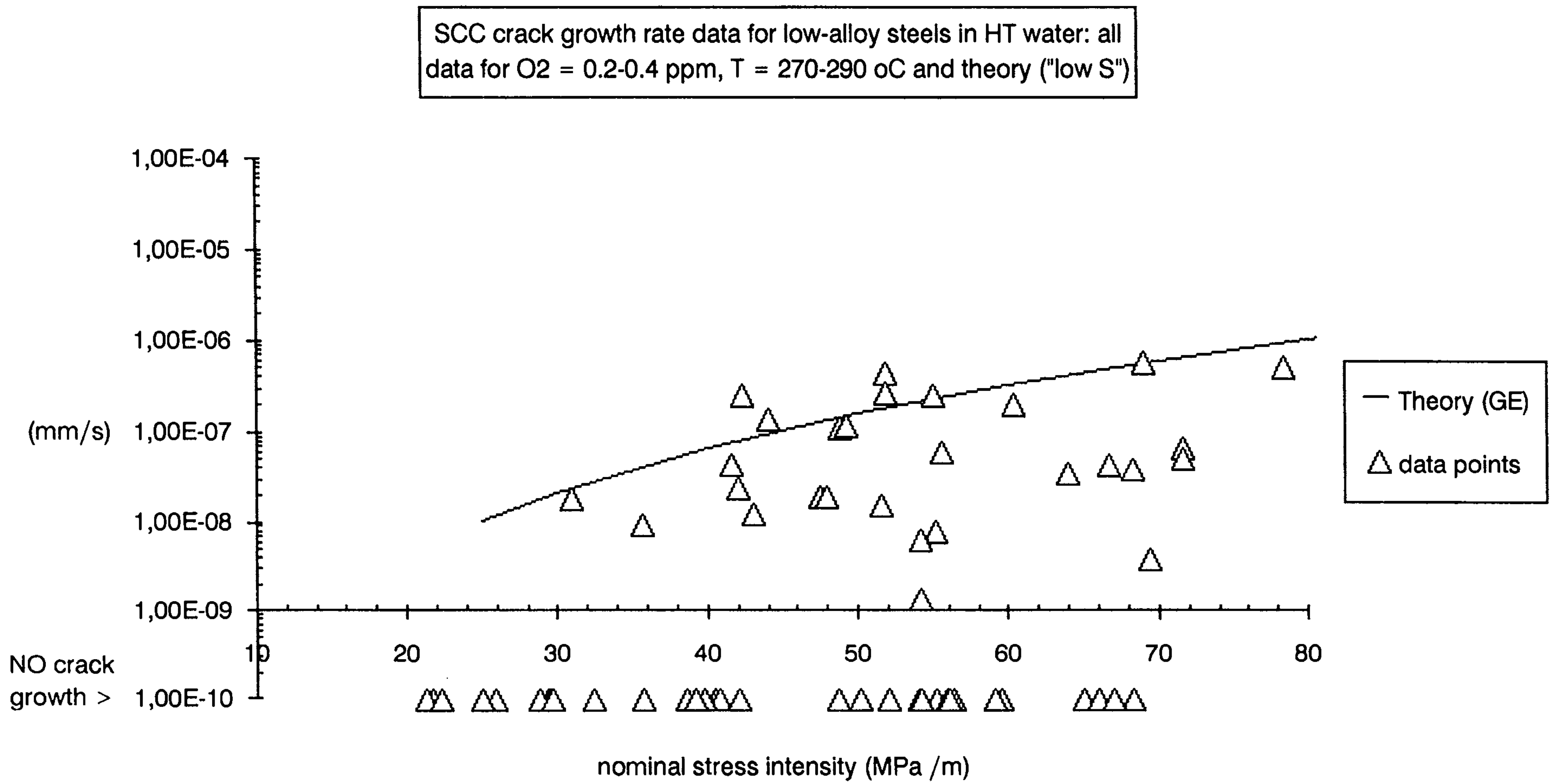
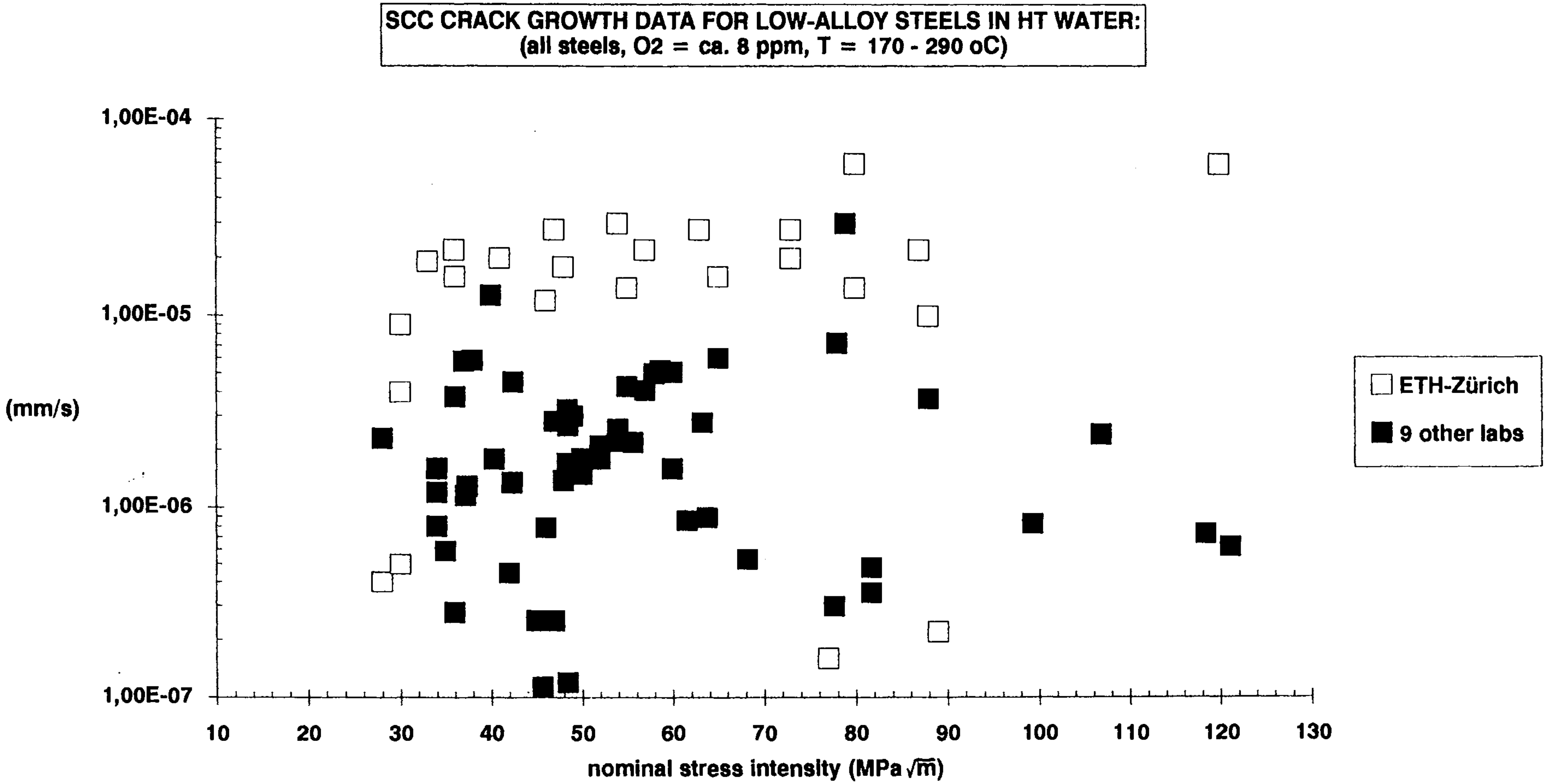

SCC crack growth rate data for low-alloy steels in HT water:
all data (fracture mechanics specimens)
1,00E-04
1,00E-05
1,00E-06
(mm/s)
1,00E-07
1,00E-08
1,00E-09
NO crack
growth >
1,00E-10
10
20
30
40
50
60
70
80
90
100
110
120
130
nominal stress intensity (MPa /m)
Datenklassifizierung:
alle
Datenqualität:
alle
Dr. Hickling

Fig. 3



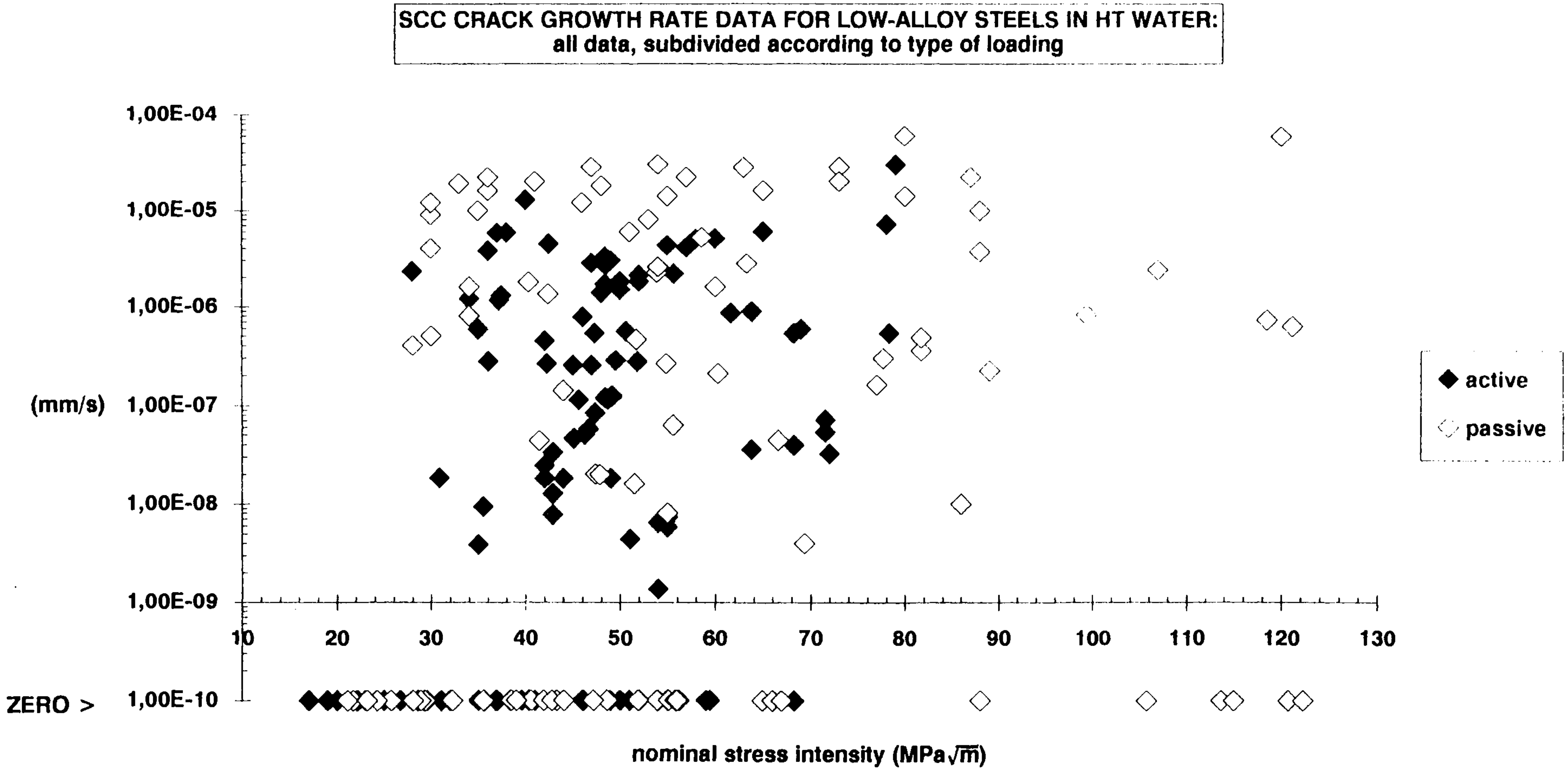
Datenklass.: W>0/F>0/G>0/V1/O2/L1/S2 Datenqualität: alle Dr. Hickling

Fig. 4



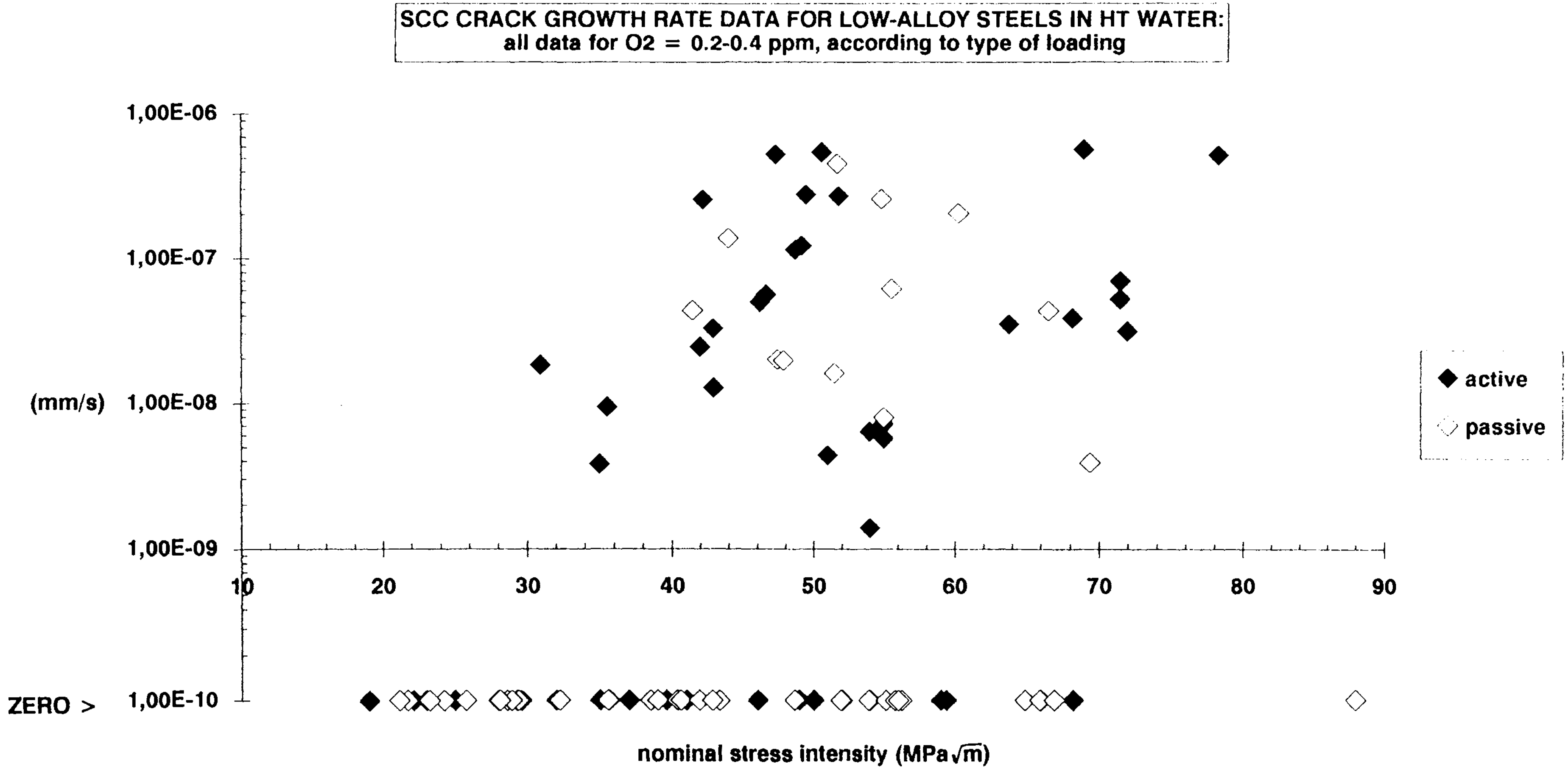
Datentyp: W > 0/F > 0/G > 0/V > 0/O1/L > 0/S > 0 Datenqualität: alle Dr. Hickling

Fig. 5



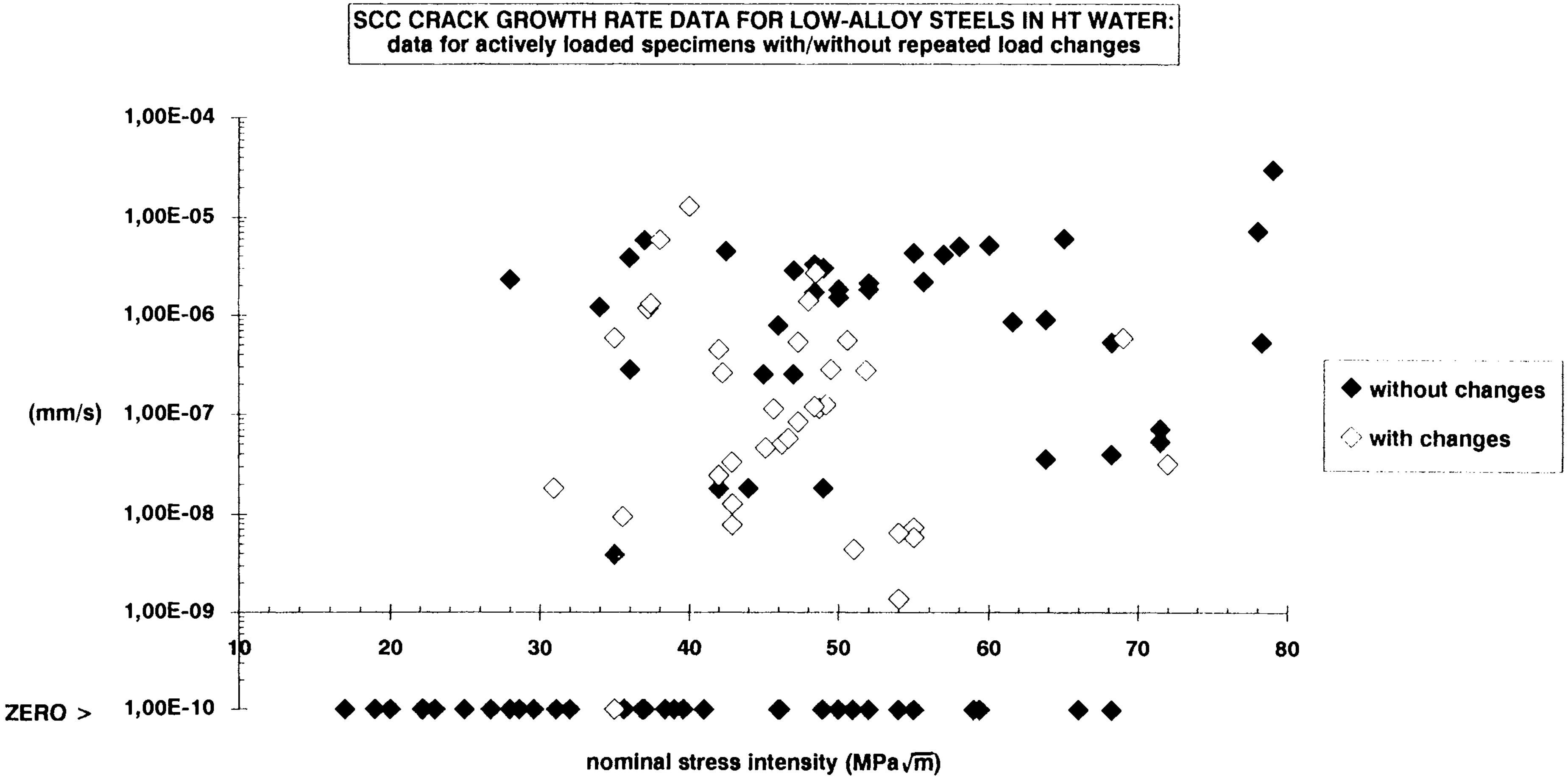
Datentyp: alle Datenqualität: alle Dr. Hickling

Fig. 6



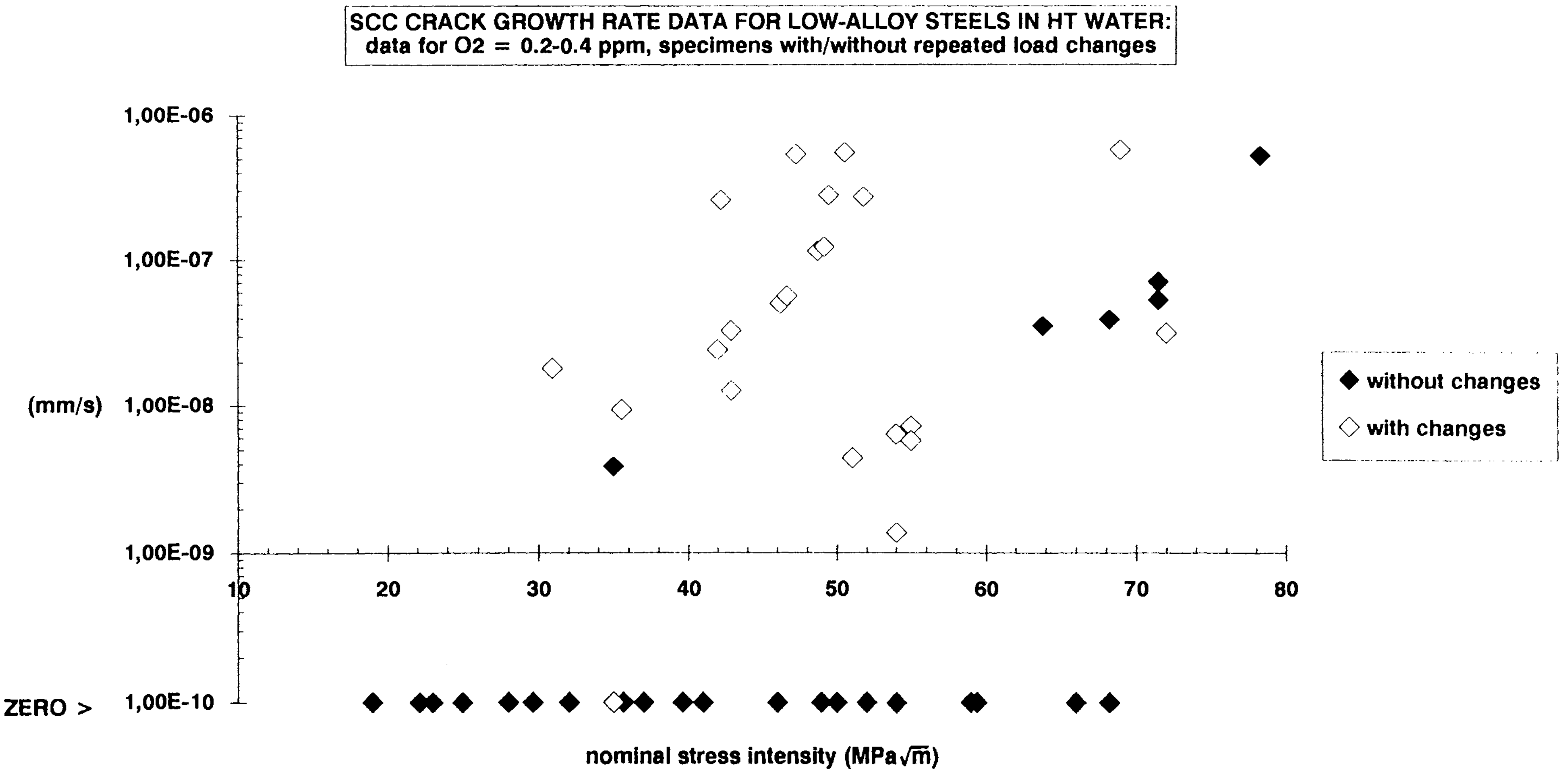
Datentyp: alle Datenqualität: alle Dr. Hickling

Fig. 7



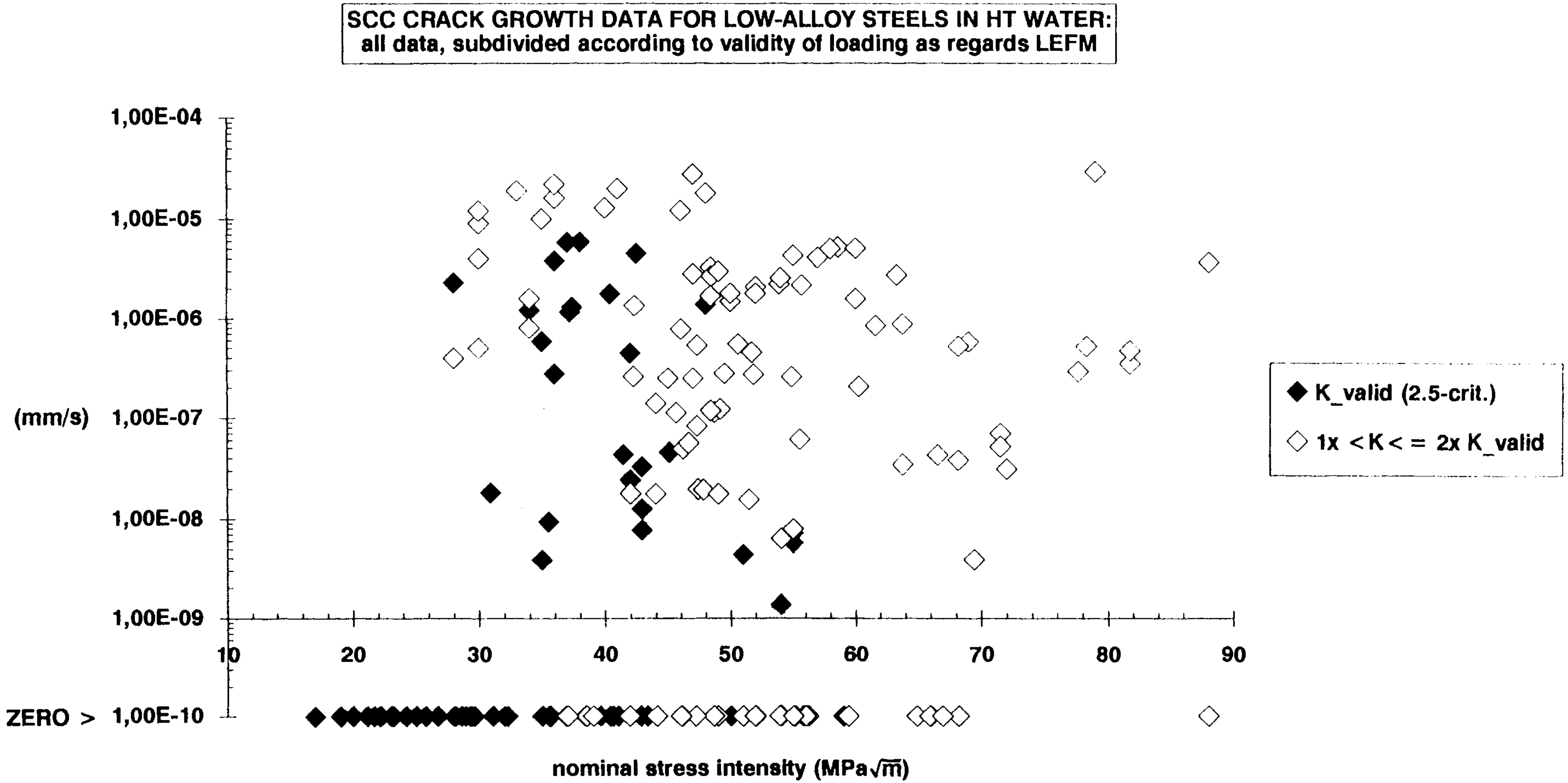
Datentyp: alle Datenqualität: alle Dr. Hickling

Fig. 8



Datentyp: alle Datenqualität: alle Dr. Hickling

Fig. 9



Datentyp: alle Datenqualität: alle Dr. Hickling

Fig. 10

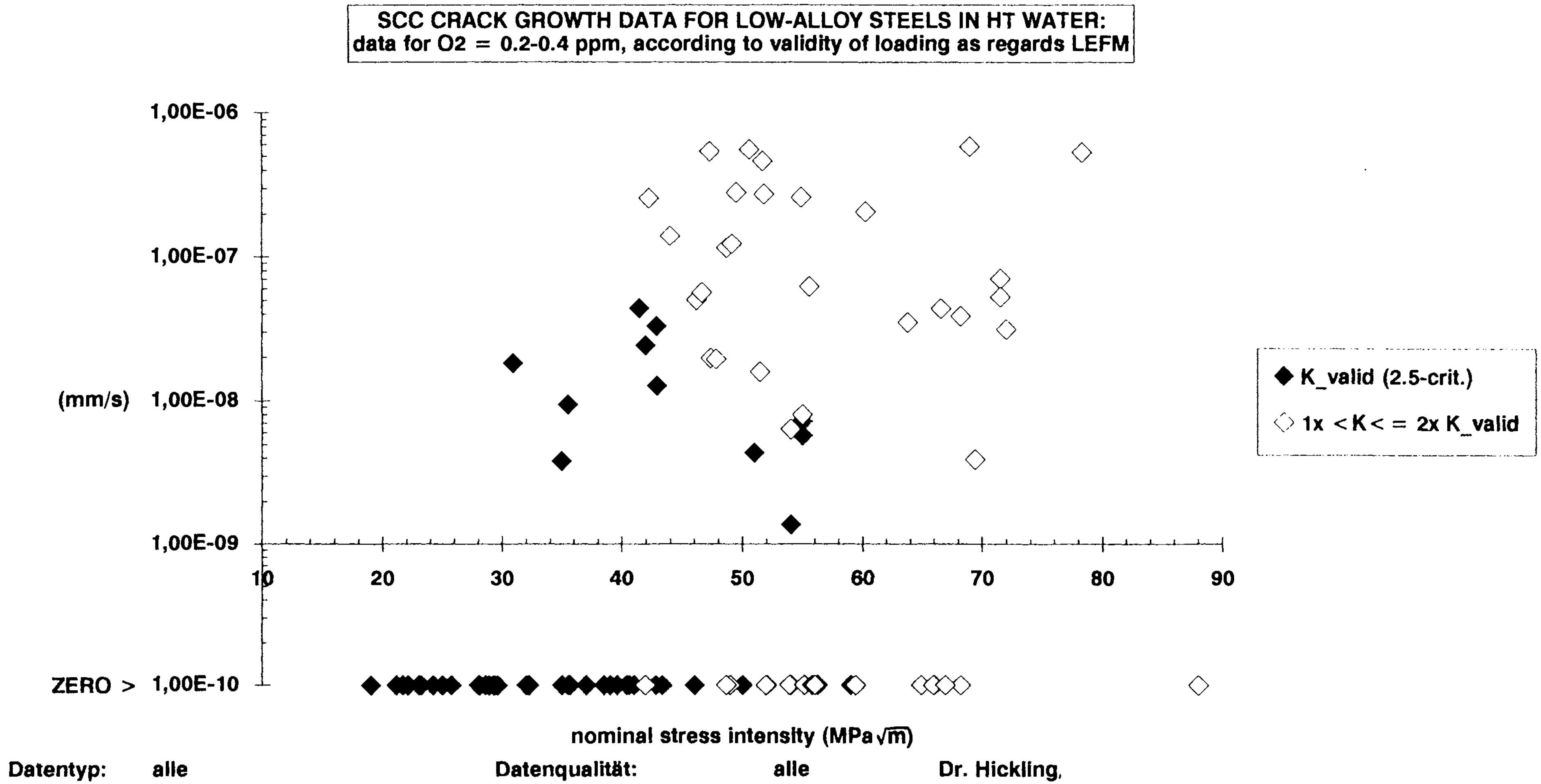
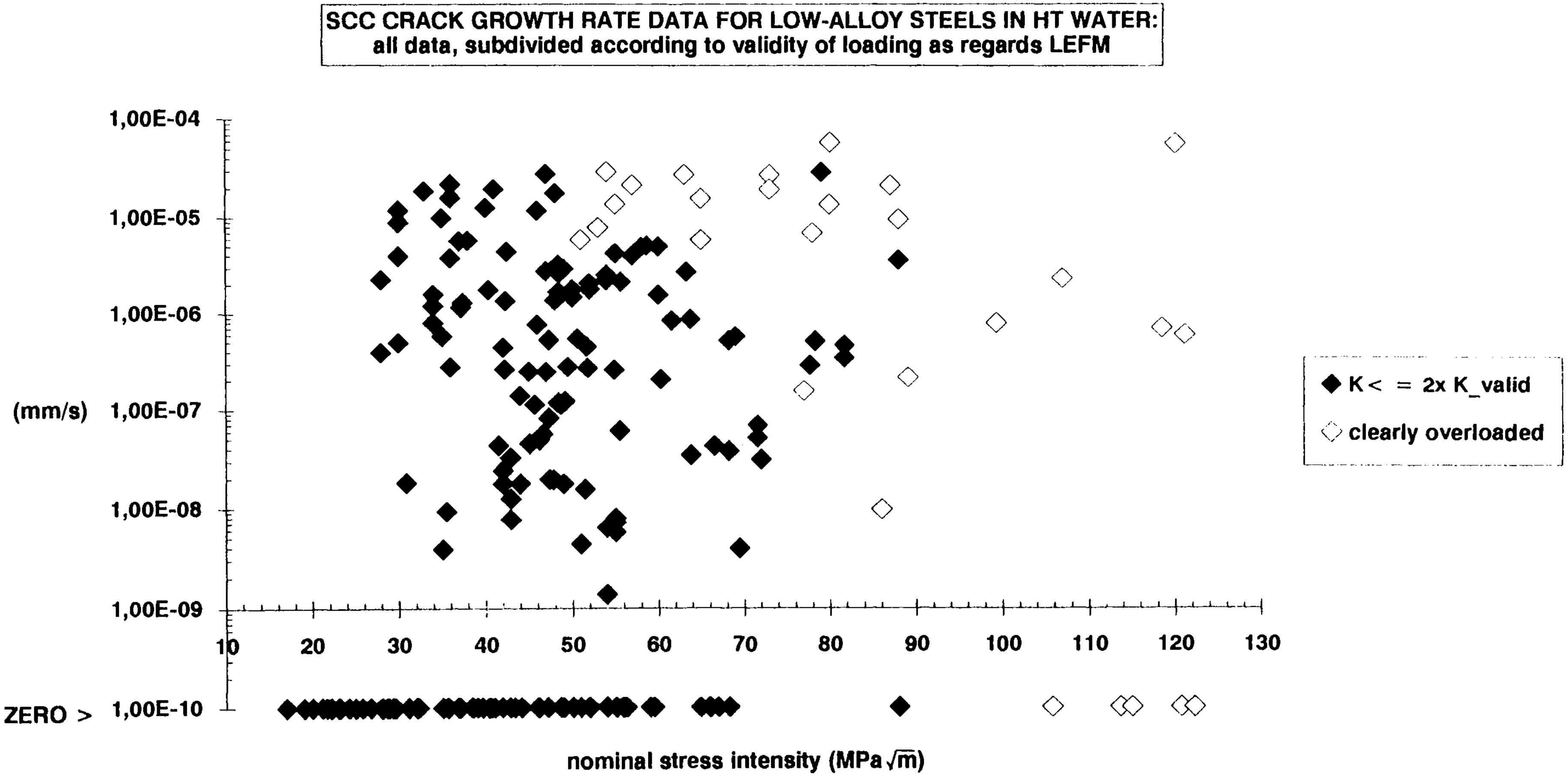
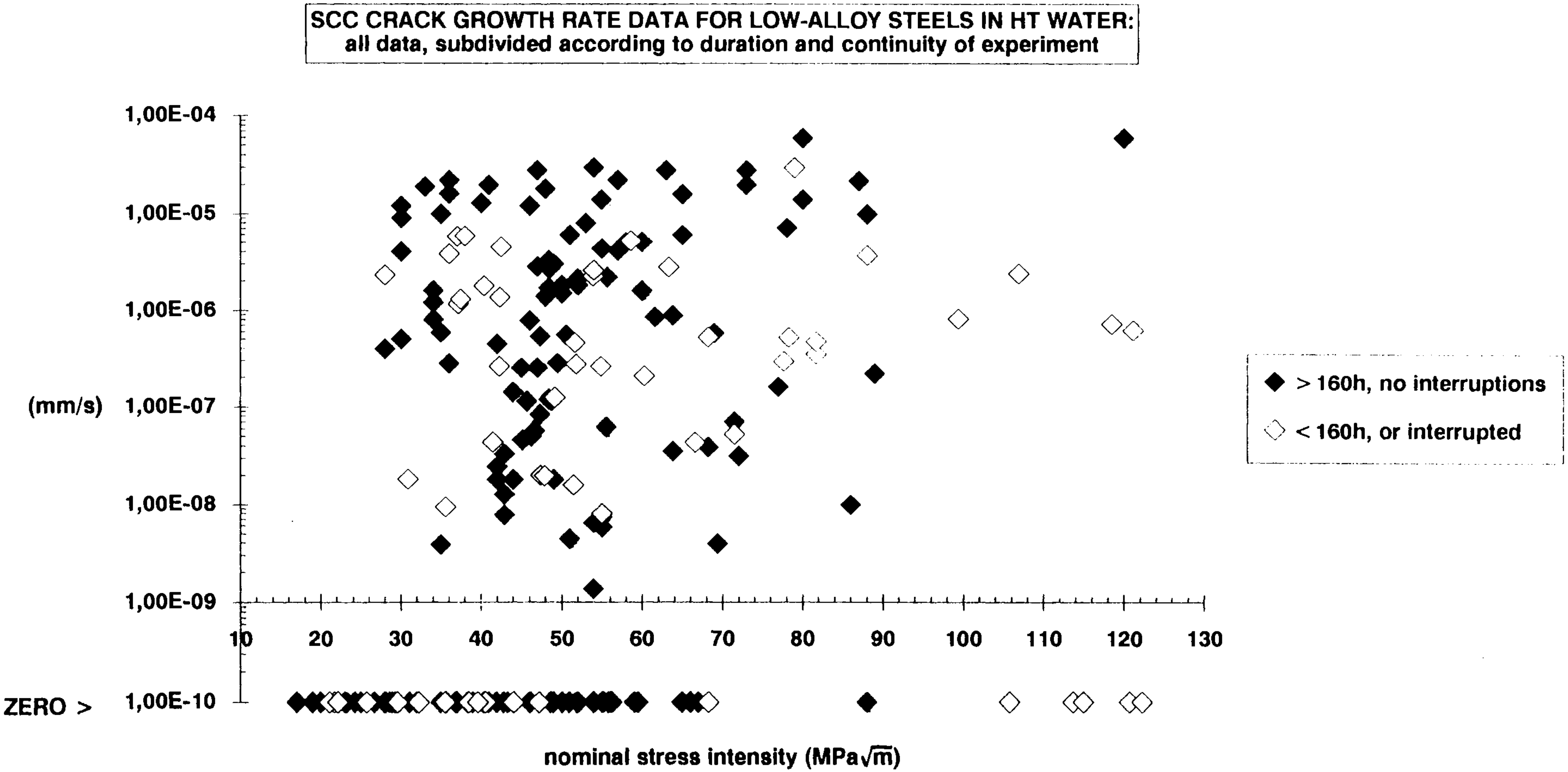

SCC CRACK GROWTH DATA FOR LOW-ALLOY STEELS IN HT WATER:
data for O2 = 0.2-0.4 ppm, according to validity of loading as regards LEFM
1,00E-06
1,00E-07
(mm/s)
1,00E-08
1,00E-09
ZERO >
1,00E-10
10
20
30
40
50
60
70
80
90
nominal stress intensity (MPa√m)
K_valid (2.5-crit.)
1x <K< = 2x K_valid
Datentyp:
alle
Datenqualität:
alle
Dr. Hickling,

Fig. 11



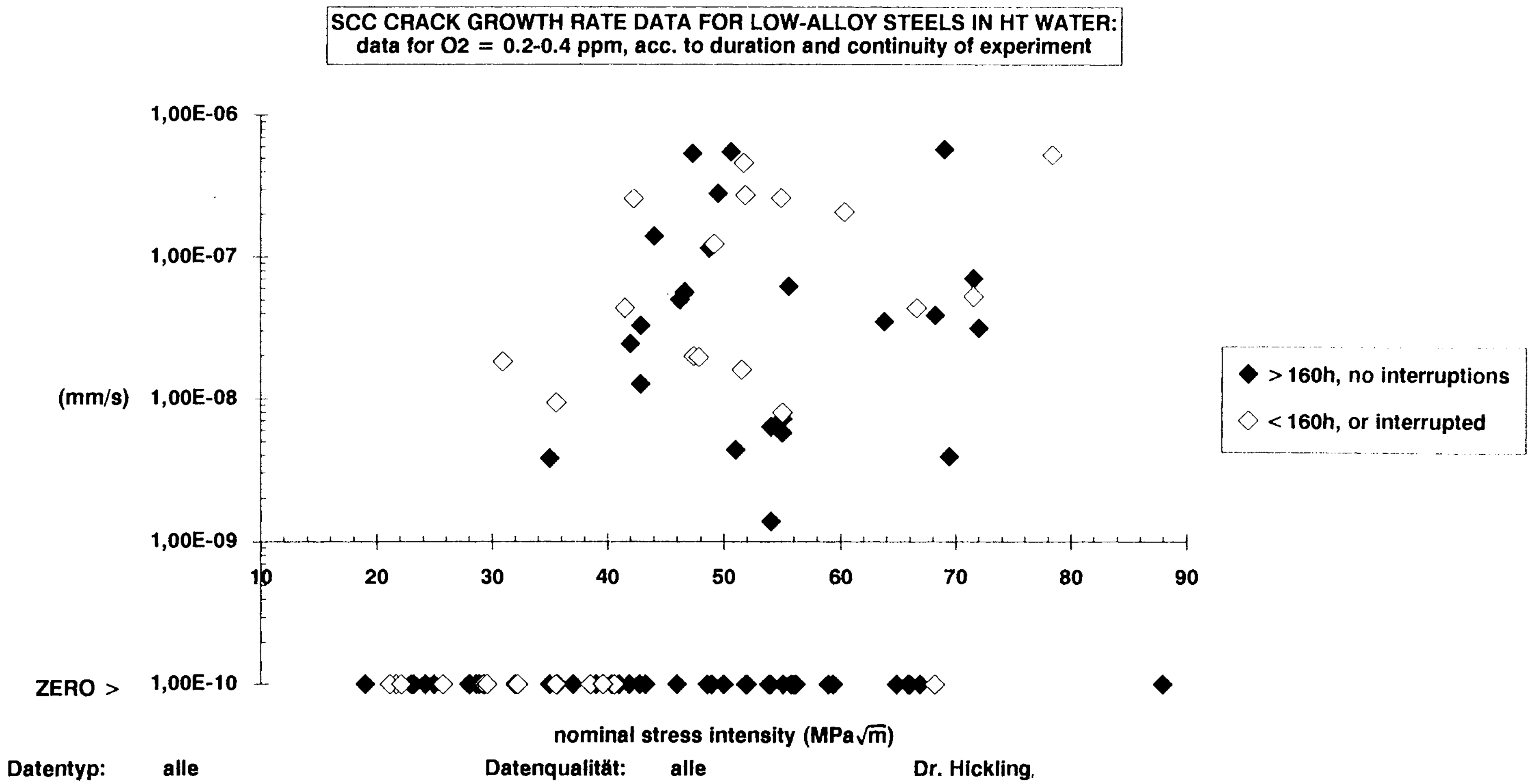
Datentyp: alle Datenqualität: alle Dr. Hickling

Fig. 12



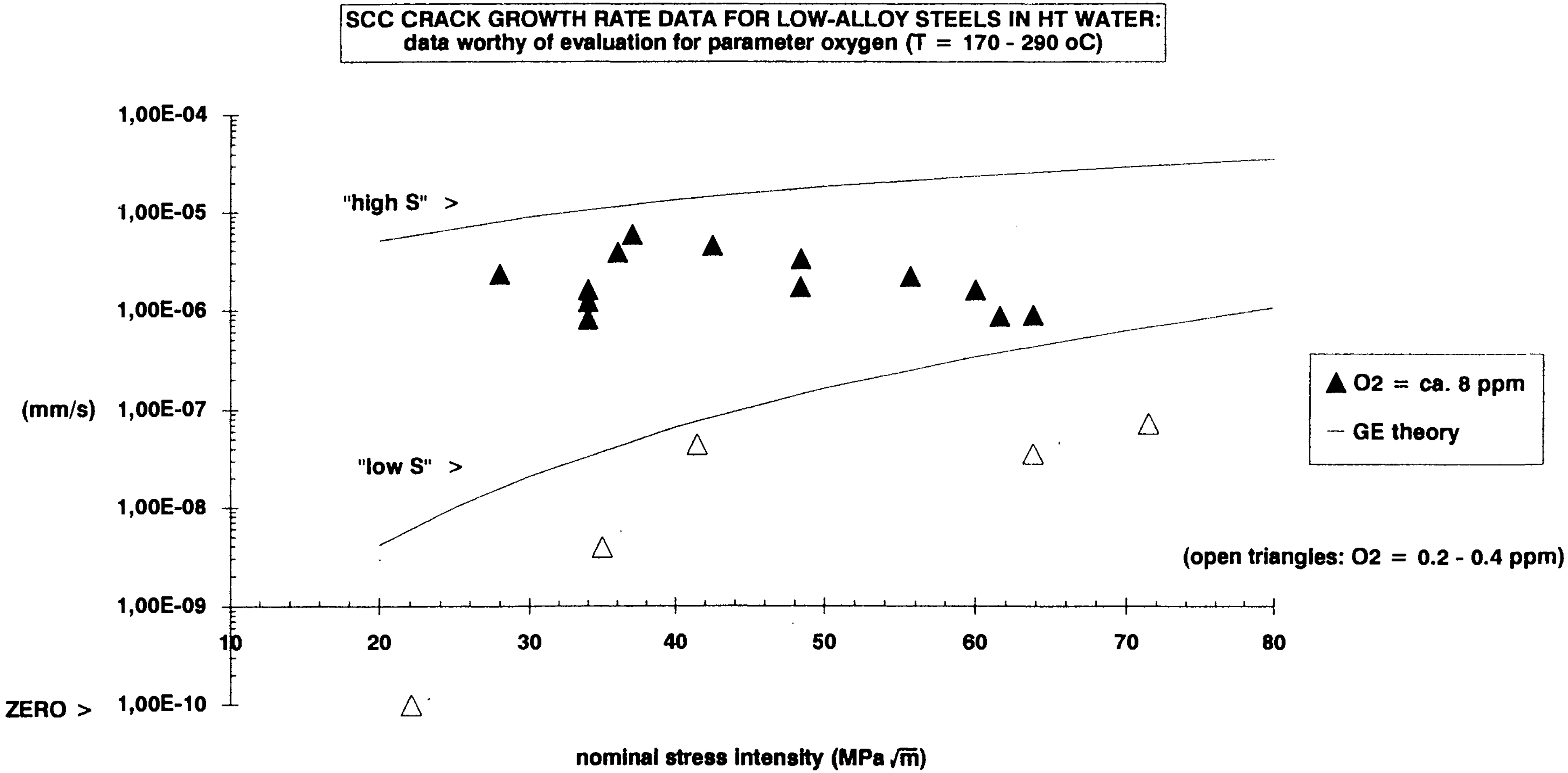
Datentyp: alle Datenqualität: alle Dr. Hickling

Fig. 13



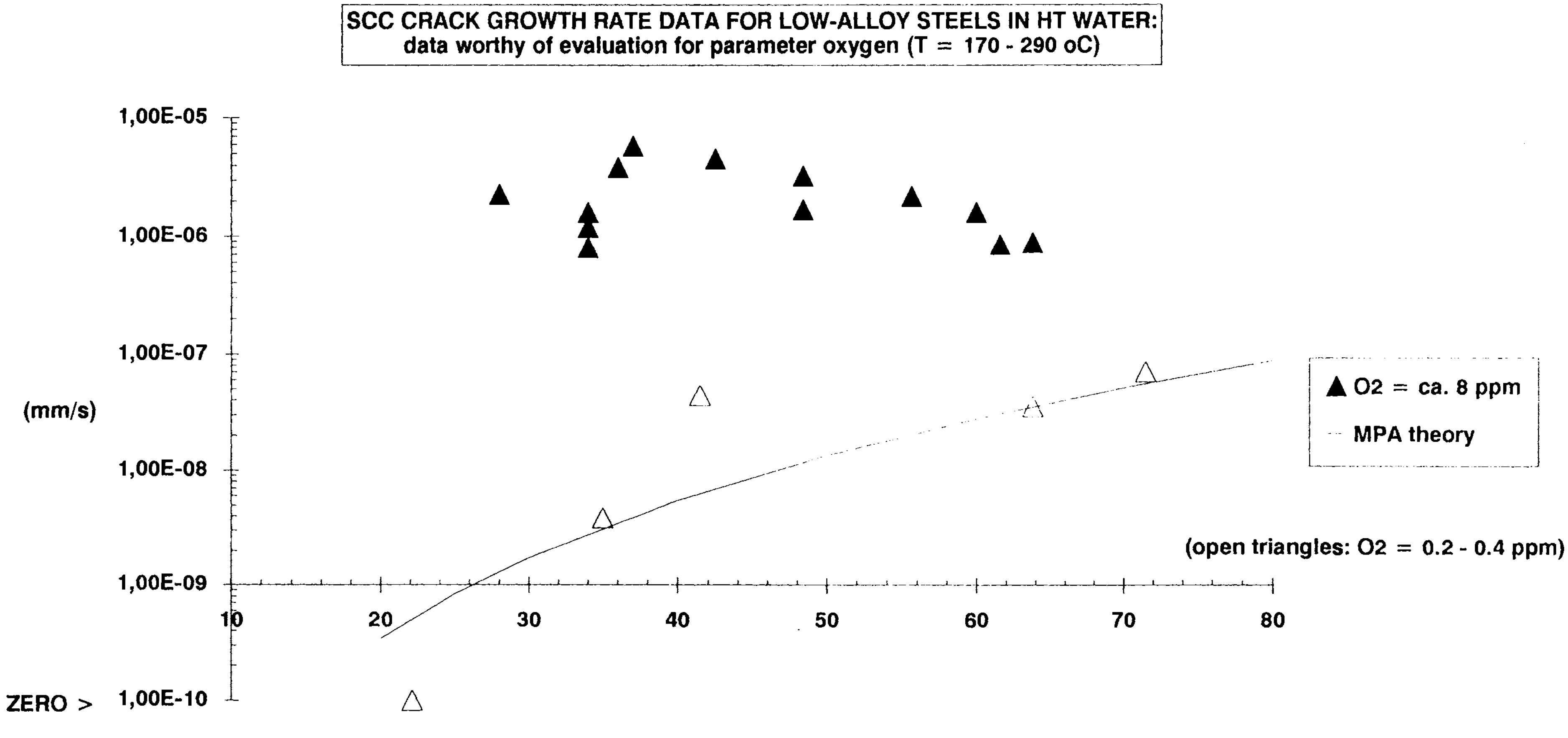
SCC CRACK GROWTH RATE DATA FOR LOW-ALLOY STEELS IN HT WATER:
data for O2 = 0.2-0.4 ppm, acc. to duration and continuity of experiment
1,00E-06
1,00E-07
(mm/s) 1,00E-08
1,00E-09
ZERO > 1,00E-10
10
20
30
40
50
60
70
80
90
> 160h, no interruptions
< 160h, or interrupted
nominal stress intensity (MPa√m)
Datentyp: alle
Datenqualität: alle
Dr. Hickling,

Fig. 14



Datentyp: W > 0/F > 0/G > 0/V < 3/O < 3/L1/S2 Datenqualität: Klassen A + B Dr. Hickling,

Fig. 15



Datentyp: W > 0/F > 0/G > 0/V < 3/O < 3/L1/S2 Datenqualität: Klassen A + B Dr. Hickling

Fig. 16

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