30 de Março

Critical Structural Integrity Challenges for the Energy Sector:

STRESS CORROSION CRACKING AND HYDROGEN EMBRITTLEMENT

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PrInt

CAPES

Fracture Mechanics and Structural Integrity Assessments in Environmentally Assisted Cracking

Daniel Correia Freire Ferreira, M.Sc. Eng. (PETROBRAS/CENPES)

March 30th, 2023

30 de Março

Critical Structural Integrity Challenges for the Energy Sector:

Fracture Mechanics and Structural Integrity Assessments in Environmentally Assisted Cracking

Structural Integrity

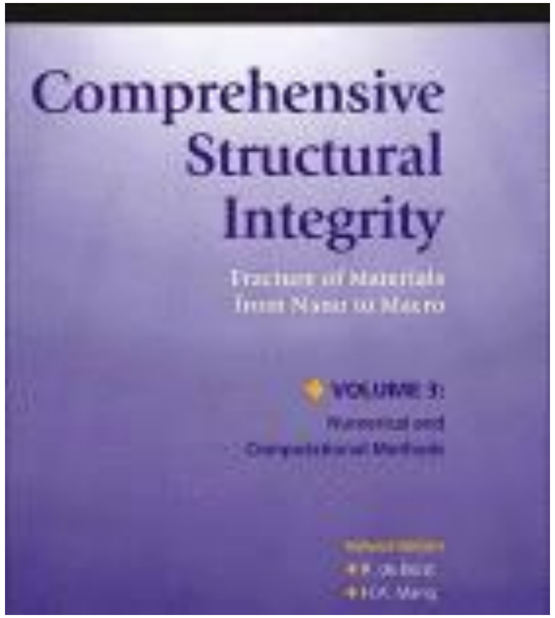
Structural Integrity is the ability of a component, structure or asset to operate at optimum level under the pressure of a load, including the weight of the asset itself. The asset needs to sustain without drastically breaking and/or deforming, whilst still being able to perform its intended use. Structural integrity is a vital consideration for structural engineering, especially when constructing plant and equipment, due to the risk of catastrophic failure from which recovery is not possible. Structural failure is the result of a loss of structural integrity.

The Welding Institute

Structural Integrity

The aim of this major reference work is to provide a **<u>first point of entry to the literature</u>** for the researchers in any field relating to structural integrity in the form of a definitive research/reference tool which links the various sub-disciplines that comprise the whole of structural integrity.

The scope of this work encompasses, but is not restricted to: **fracture mechanics**, **fatigue**, creep, materials, dynamics, **environmental degradation**, numerical methods, failure mechanisms and damage mechanics, interfacial fracture and nano-technology, structural analysis and surface behaviour.



- *Volume 1: Structural Integrity Assessment—Examples and Case Studies*
- *Volume 2: Fundamental Theories and Mechanisms of Failure*
- *Volume 3: Numerical and Computational Methods*
- *Volume 4: Cyclic Loading and Fatigue*
- *Volume 5: Creep and High-temperature Failure*
- *Volume 6: Environmentally Assisted Fatigue*
- *Volume 7: Practical Failure Assessment Methods*
- *Volume 8: Interfacial and Nanoscale Fracture*
- *Volume 9: Bioengineering*
- *Addendum 2007: Mechanical Characterisation of Materials*

Structural Integrity Assessments

BS 7910:2019

Guide to methods for assessing the acceptability of flaws in metallic structures

FITNESS-FOR-SERVICE

API 579-1/ASME FFS-1, December 2021

American Petroleum Institute

The American Society of Mechanical Engineers

The fracture mechanics based **fitness-for-purpose (FFP) approach**, also referred to as **Engineering Critical Analysis (ECA)**, enables the significance of flaws to be assessed in terms of structural integrity. The ECA concept has undergone extensive developments in the past 30 years or so and the widely used PD6493 procedure has been produced in the UK. The document has recently been revised and is now published as BS 7910 'Guide on methods for assessing the acceptability of flaws in metallic structures'

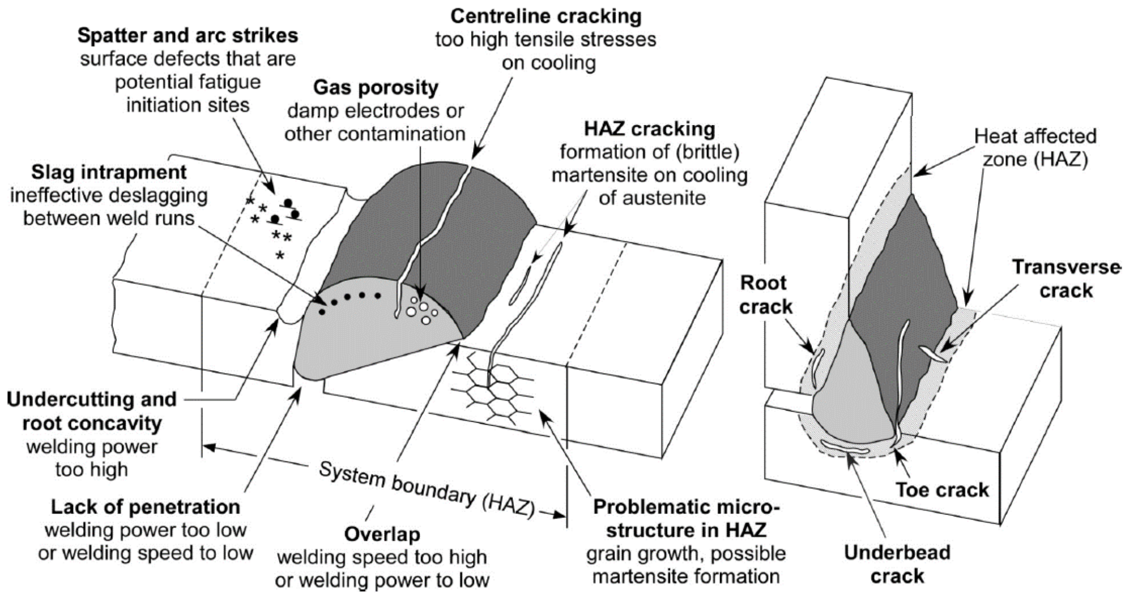
TWI

ENGINEERING CRITICAL ANALYSES TO BS 7910

http://www.eurofitnet.org/sintap_index.html

Flaws and Fracture Mechanics

Any given welded equipment (pressure vessel, pipeline, offshore structure) may have flaws – inherent to the fabrication method applied. According to the NDT techniques employed and their PoD – a maximum flaw size may be expected.



fracture toughness—a generic term for measures of resistance to extension of a crack.

Designation: E1823 – 21

Safe life design vs. Damage tolerant Design

Flaws and Fracture Mechanics

Failure mechanisms not predicted during design – fatigue, ductile to brittle transition, stress corrosion cracking

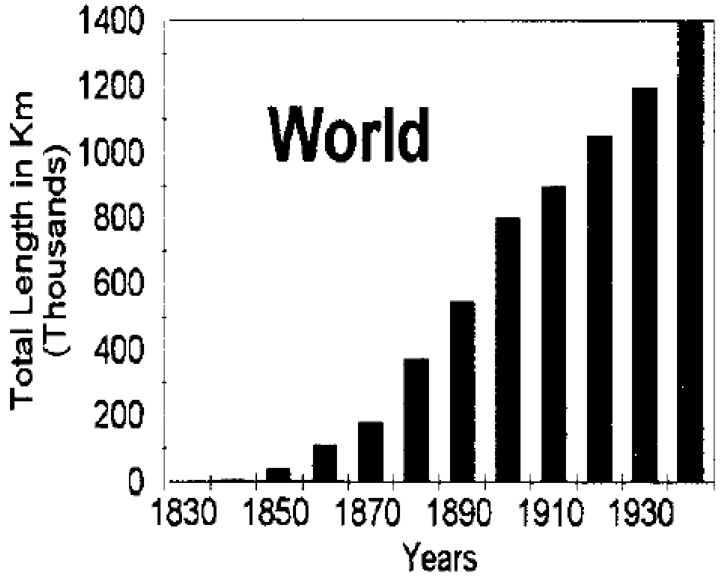


Figure 4. The growth of railway network in the world

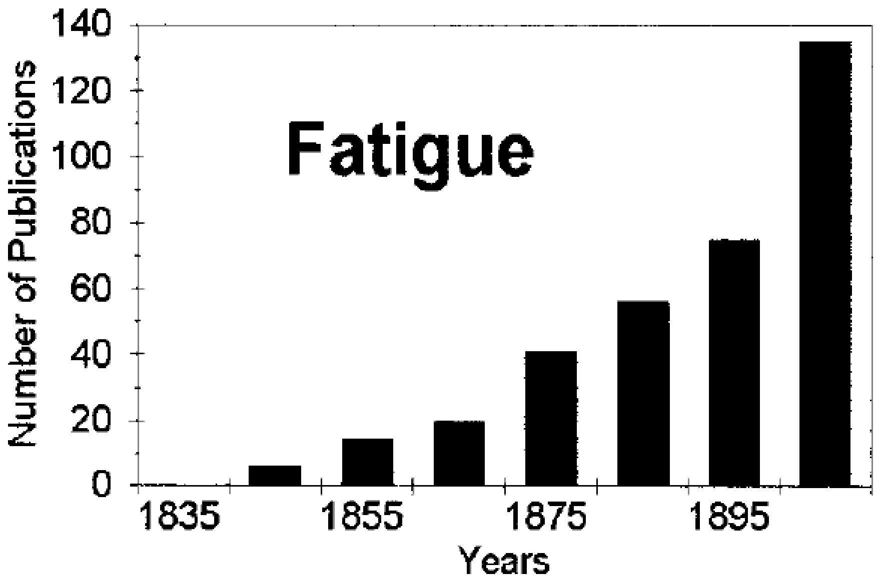


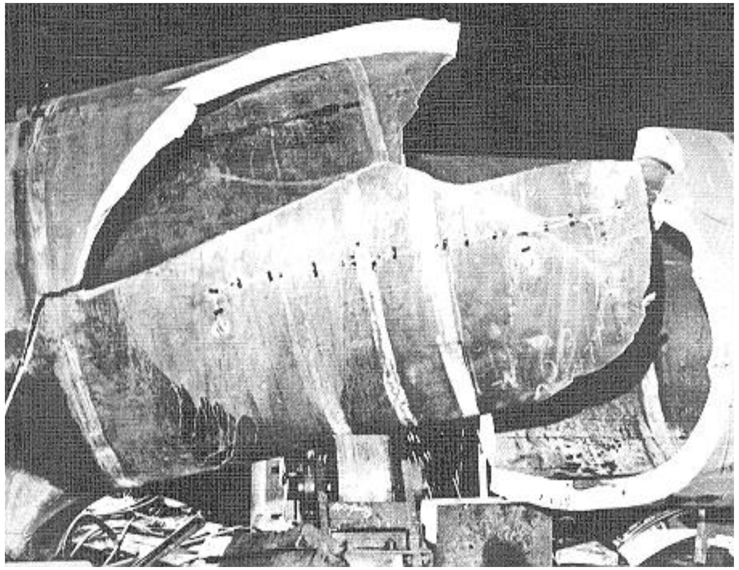
Figure 5. Total number of publications related to fatigue failures in the 19th century

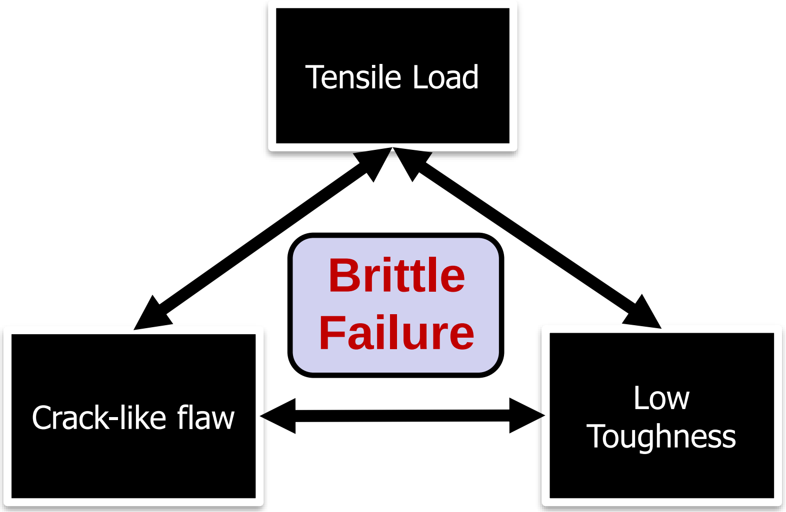
Tóth et al. (2001) – From Charpy to Modern Impact Testing

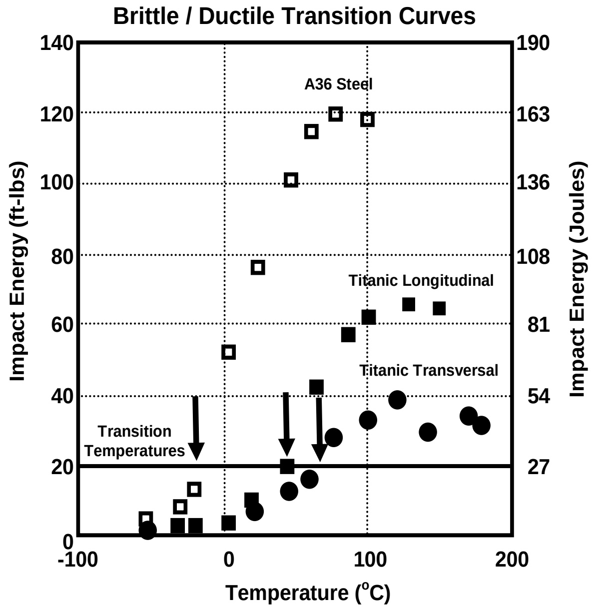
Brittle failure

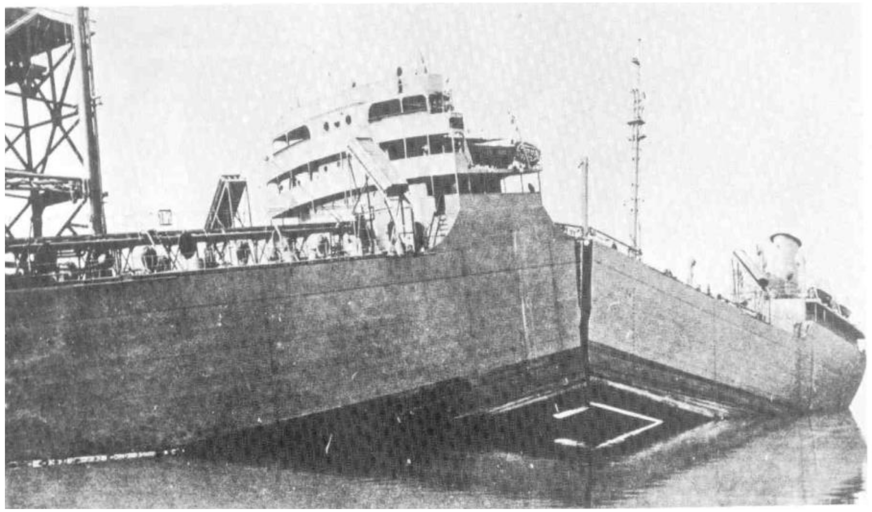
- A brittle failure takes place in an abrupt manner, usually with catastrophic consequences

- Usually requires the combination of 3 factors:
  - *Crack-like flaw* (ex. lack of fusion, lack of penetration in welded joints)
  - Applied tensile load (even if only residual stresses);
  - Low fracture toughness

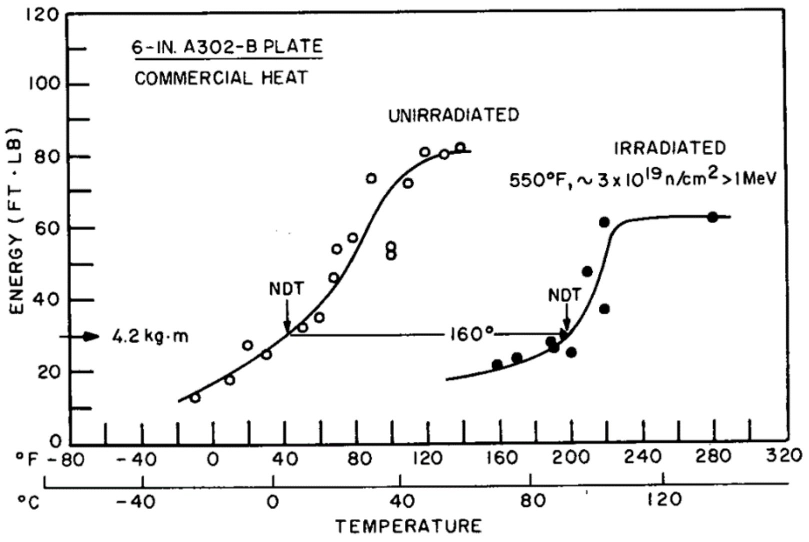








Brittle failure vs. 'embrittlement'



- Brittle failure → low fracture toughness ('abrupt failure')

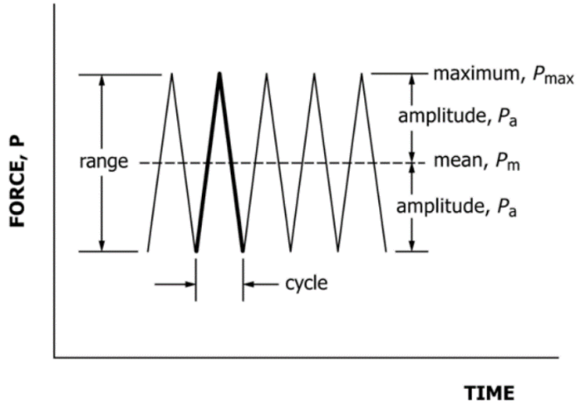
  - Low alloy steels displaying cleavage at the lower shelf;
  - (Super)duplex stainless steels with high sigma-phase fractions;
  - Nuclear reactor pressure vessel steels under radiation embrittlement;
  - Temper embrittled Cr-Mo steels with high antimony, phosphorus, tin and arsenic content displaying intergranular fracture surfaces (Watanabe J factor or Bruscato X factor);

- Some environmentally assisted cracking (EAC) types apply the term 'embrittlement' in a more general sense – meaning that failure can occur with applied stresses significantly below those expected in air or an inert environment (e.g., Hydrogen Embrittlement).

- Nevertheless, EAC does not necessarily leads to actual embrittlement – i.e. lowering of the fracture toughness of the bulk material. Quite often, the phenomena is rather of crack initiation followed by subcritical crack growth – until an abrupt failure takes place with a 'final' fracture toughness similar to that measured in inert environment.

Similar to fatigue!

Fatigue crack initiation and subcritical growth



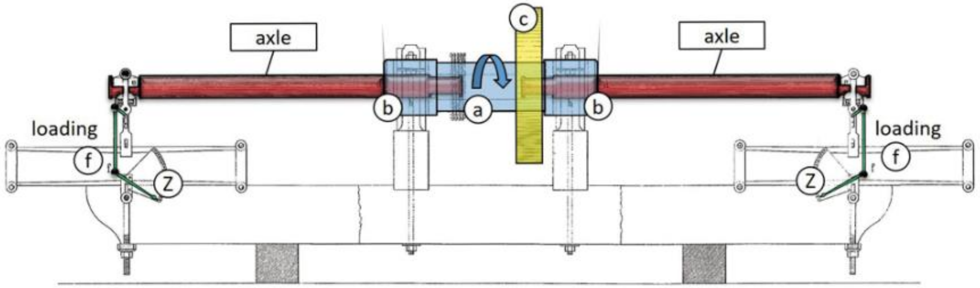
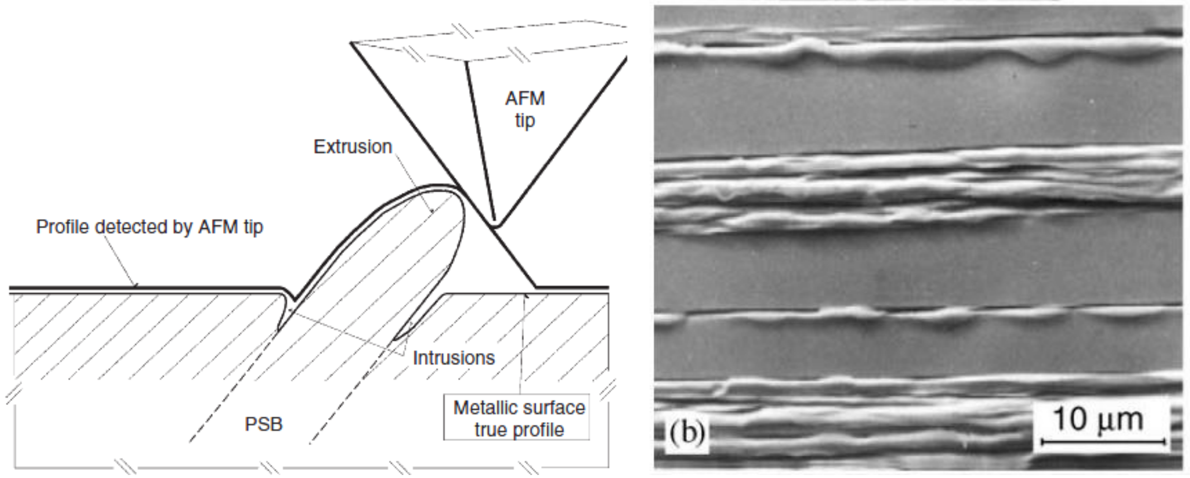


Fig. 5. First rotating-bending test machine developed by August Wöhler: in 1860

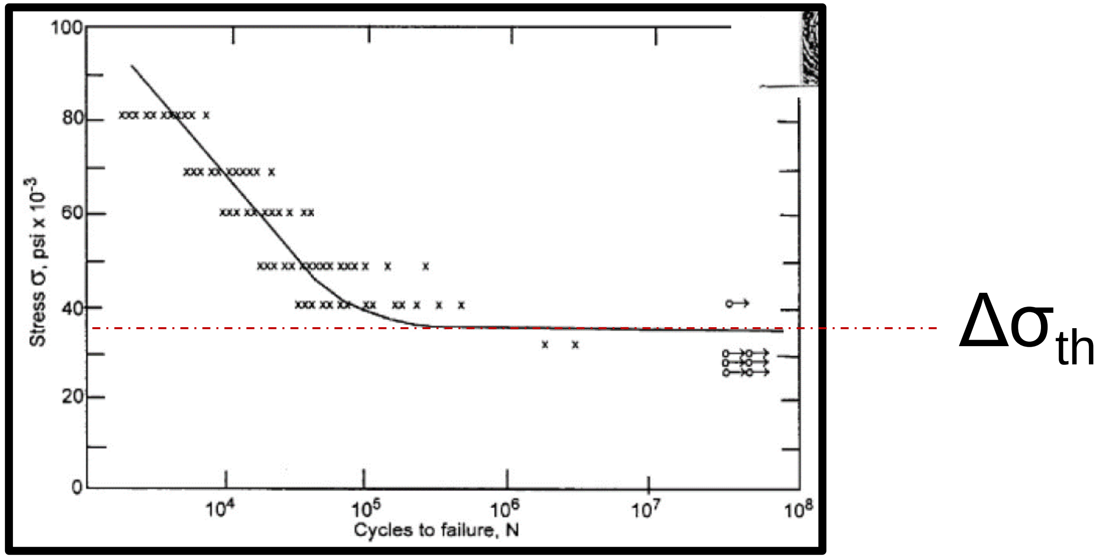
fatigue life, N_f —the number of cycles of a specified character that a given specimen sustains before failure of a specified nature occurs. Fatigue life, or the logarithm of fatigue life, is a dependent variable. **E1823**

fatigue limit, S_f [FL^{-2}]—the limiting value of the median fatigue strength as the fatigue life, N_f, becomes very large.

Discussion—Certain materials and environments preclude the attainment of a fatigue limit. Values tabulated as "fatigue limits" in the literature are frequently (but not always) values of S_N for which 50 % of the specimens survive a predetermined number of cycles. These specimens are frequently tested at a mean stress of zero. **E1823**



J. Polák, V. Mazánová, M. Heczko, R. Petráš, I. Kuběna, L. Casalena, J. Man,
The role of extrusions and intrusions in fatigue crack initiation
Engineering Fracture Mechanics, Volume 185, 2017, Pages 46-60, ISSN 0013-7944
https://doi.org/10.1016/j.engfracmech.2017.03.006.
(https://www.sciencedirect.com/science/article/pii/S0013794416307305)



Fatigue crack initiation and subcritical growth

API 579-1/ASME FFS-1 2016 Fitness-For-Service

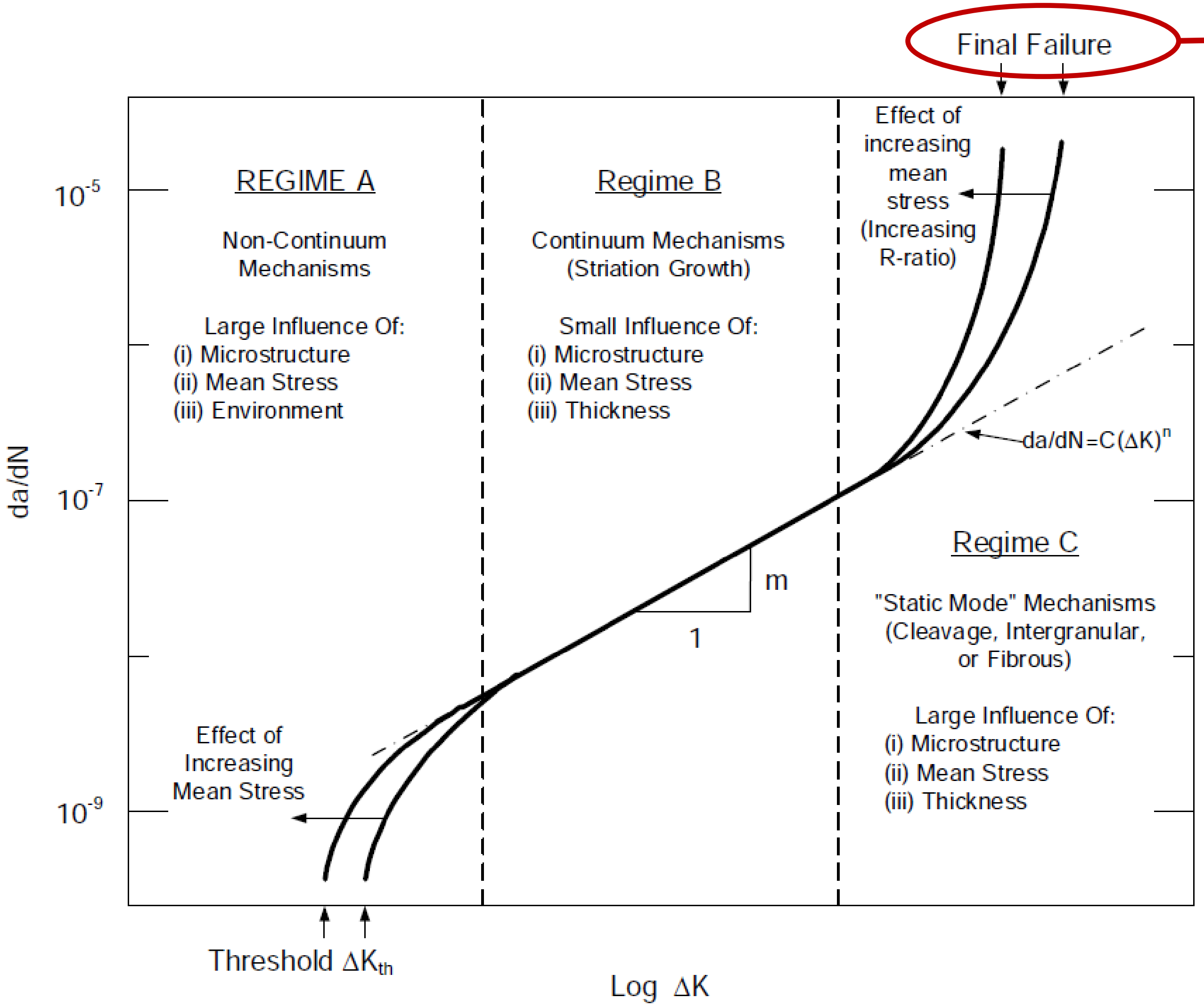


Figure 9F.4 – Crack Growth Behavior – Fatigue

Final or Fast Fracture (Air)

Fracture Toughness

K_{Ic}

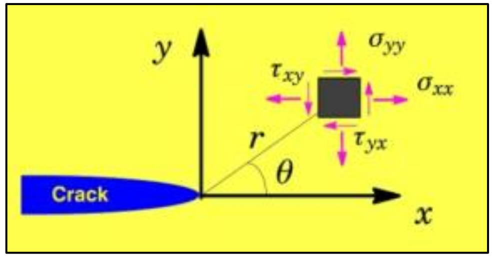
$J_{0,2mm}$ or $KJ_{0,2mm}$

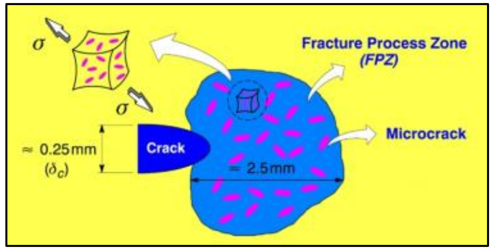
K_{mat}

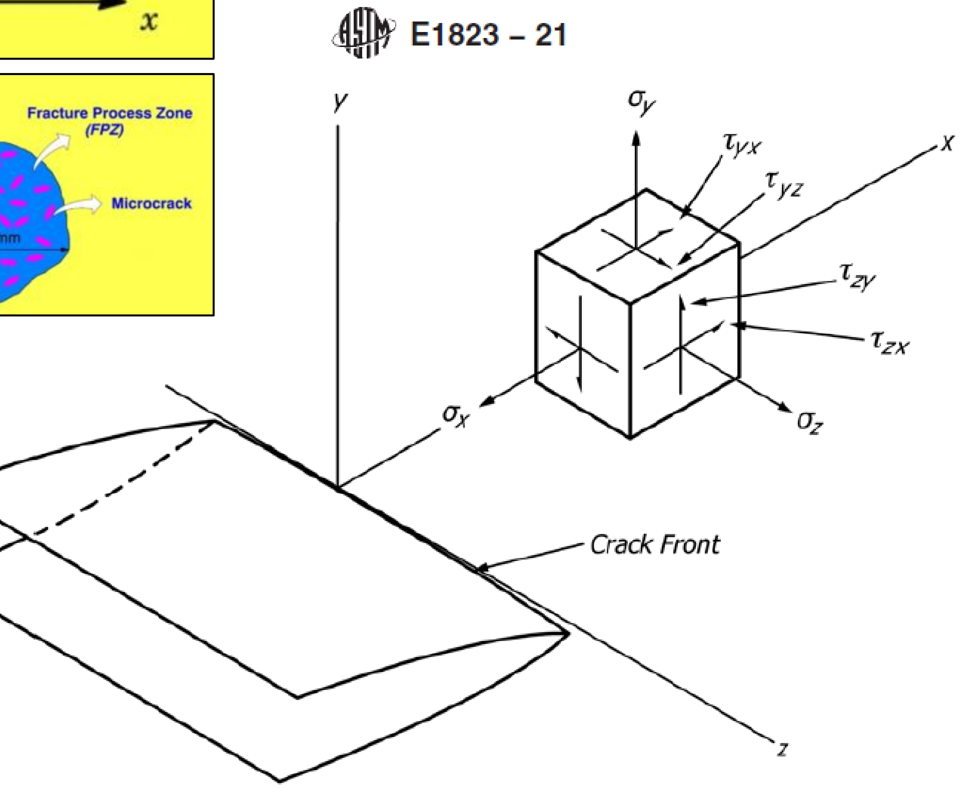
ΔK_{th} - value of ΔK which requires a significant high amount of cycles for the crack to propagate (~10^4)

May be difficult to establish in the lab

Fracture Process Zone and Crack-tip Conditions







NOTE 1—See definition of mode.

K – Stress Intensity Factor

CTOD (δ) – Crack Tip Opening Displacement

J-Integral and J-Resistance Curve

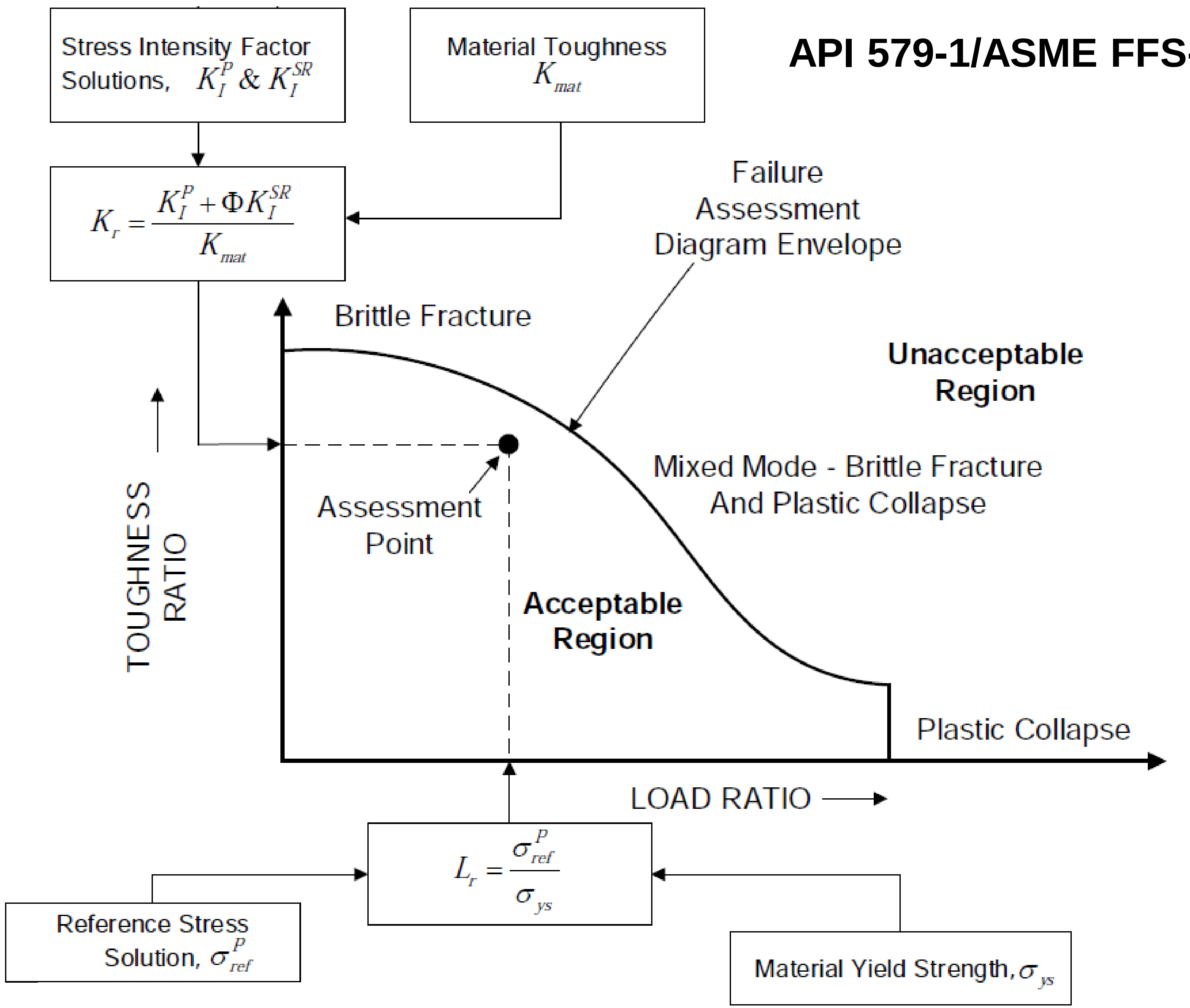
$$K_I = Y\sigma\sqrt{\pi a}$$

$$K_I \leq K_{mat}$$

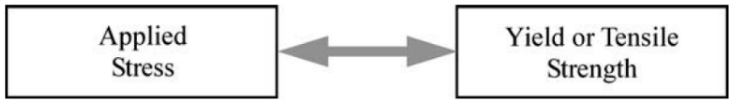
Applied K (Structure) **Material Fracture Toughness**

Failure Assessment Diagram - FAD

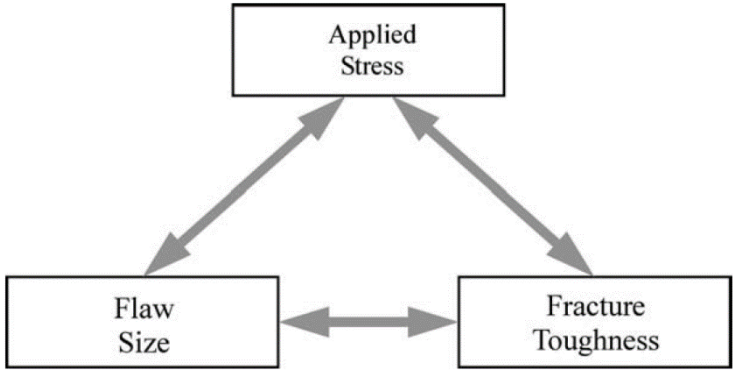
API 579-1/ASME FFS-1 2016



Strength of Materials Approach



Fracture Mechanics Approach



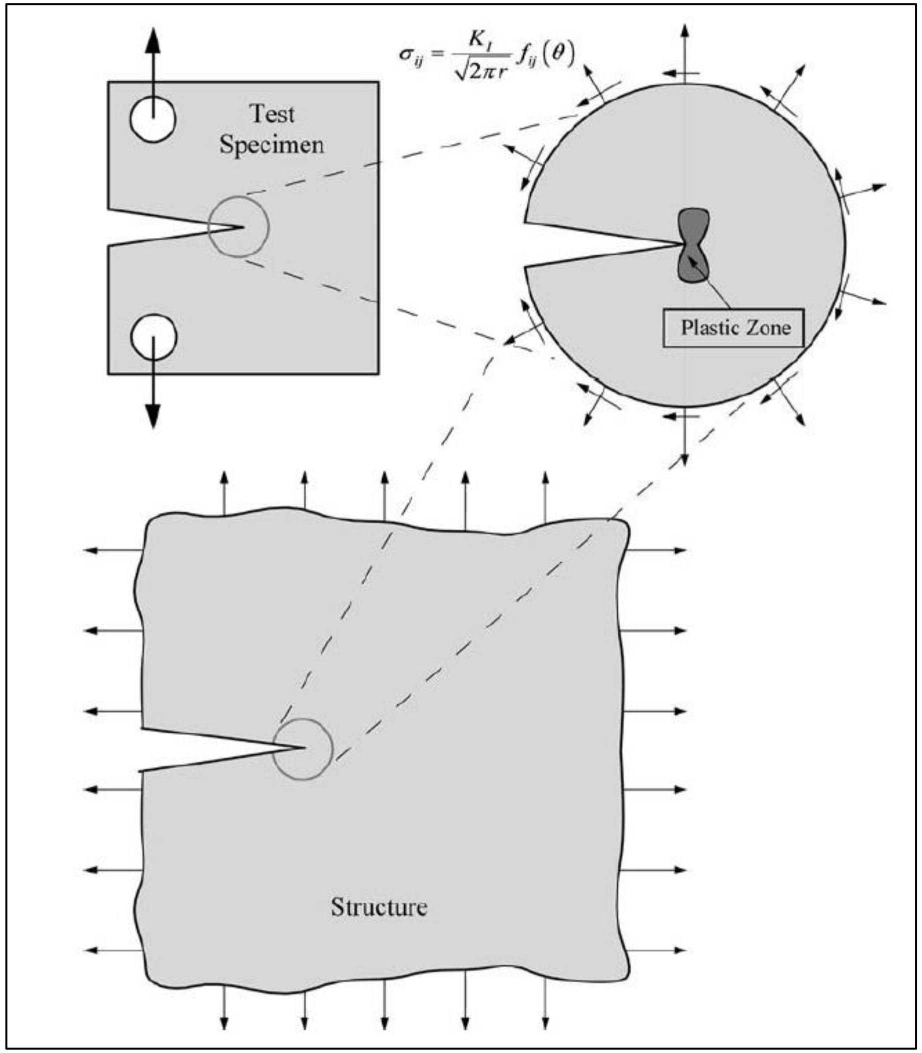
$$K_I = Y\sigma\sqrt{\pi a}$$

T.L. Anderson – Fracture Mechanics – Fundamentals and Application 3rd Edition

Similitude

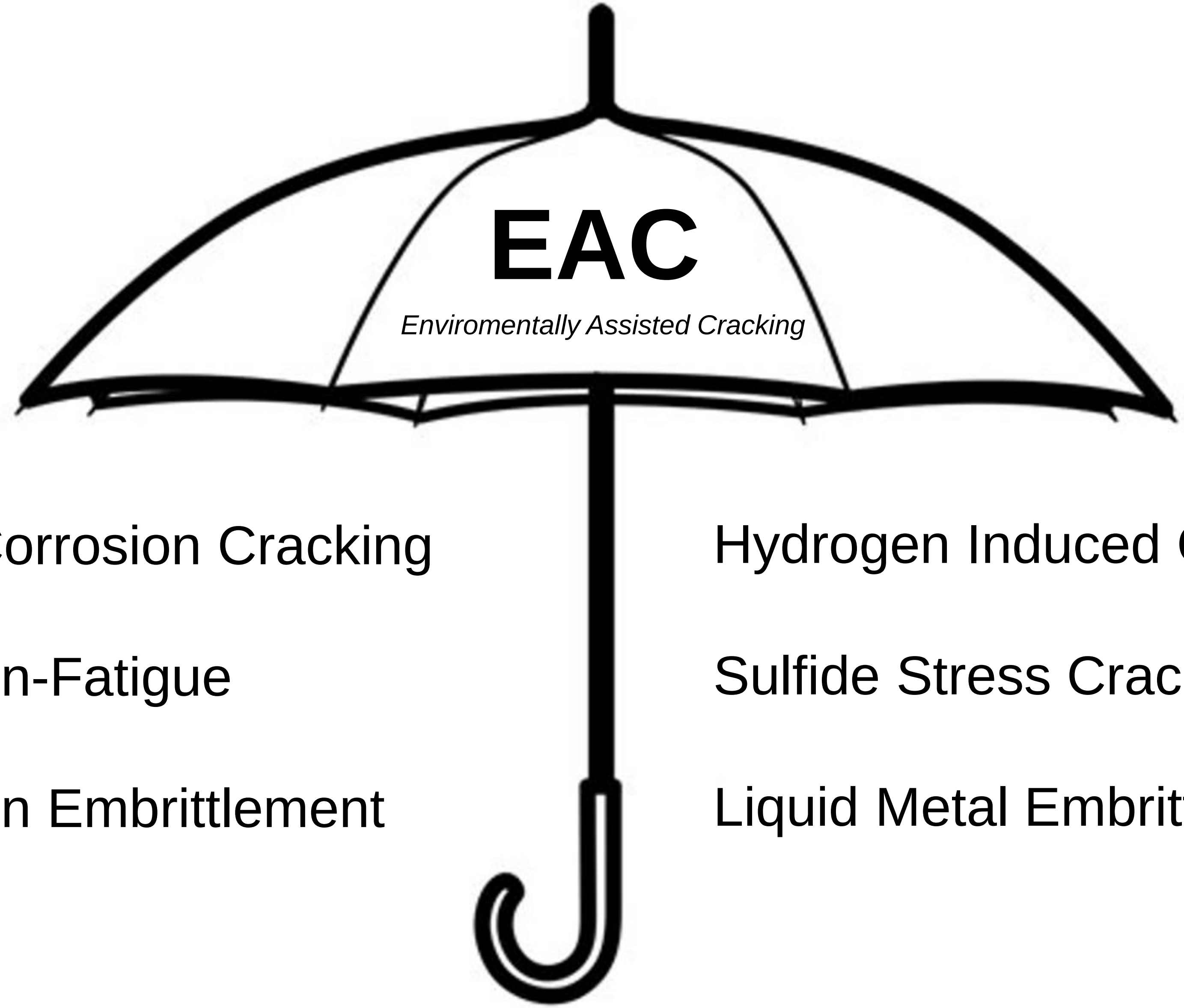
"The concept of similitude, when it applies, provides the theoretical basis for fracture mechanics. Similitude implies that the **crack-tip conditions are uniquely defined** by a **single loading parameter** such as the stress-intensity factor (K)."

T.L. Anderson – Fracture Mechanics – Fundamentals and Application 3rd Edition



T.L. Anderson – Fracture Mechanics – Fundamentals and Application 3rd Edition

Environmentally Assisted Cracking (EAC)



Stress Corrosion Cracking

Corrosion-Fatigue

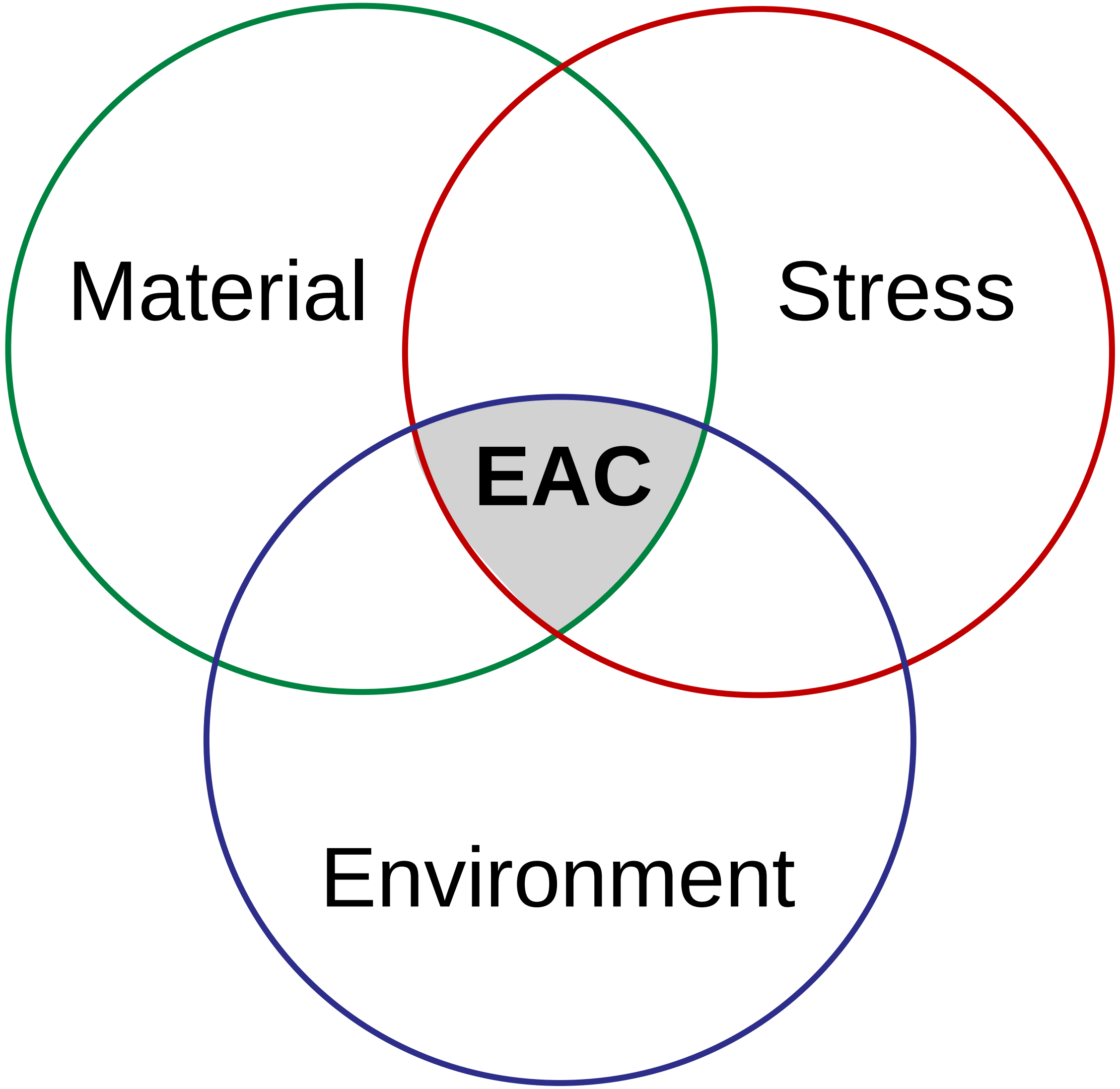
Hydrogen Embrittlement

Hydrogen Induced Cracking

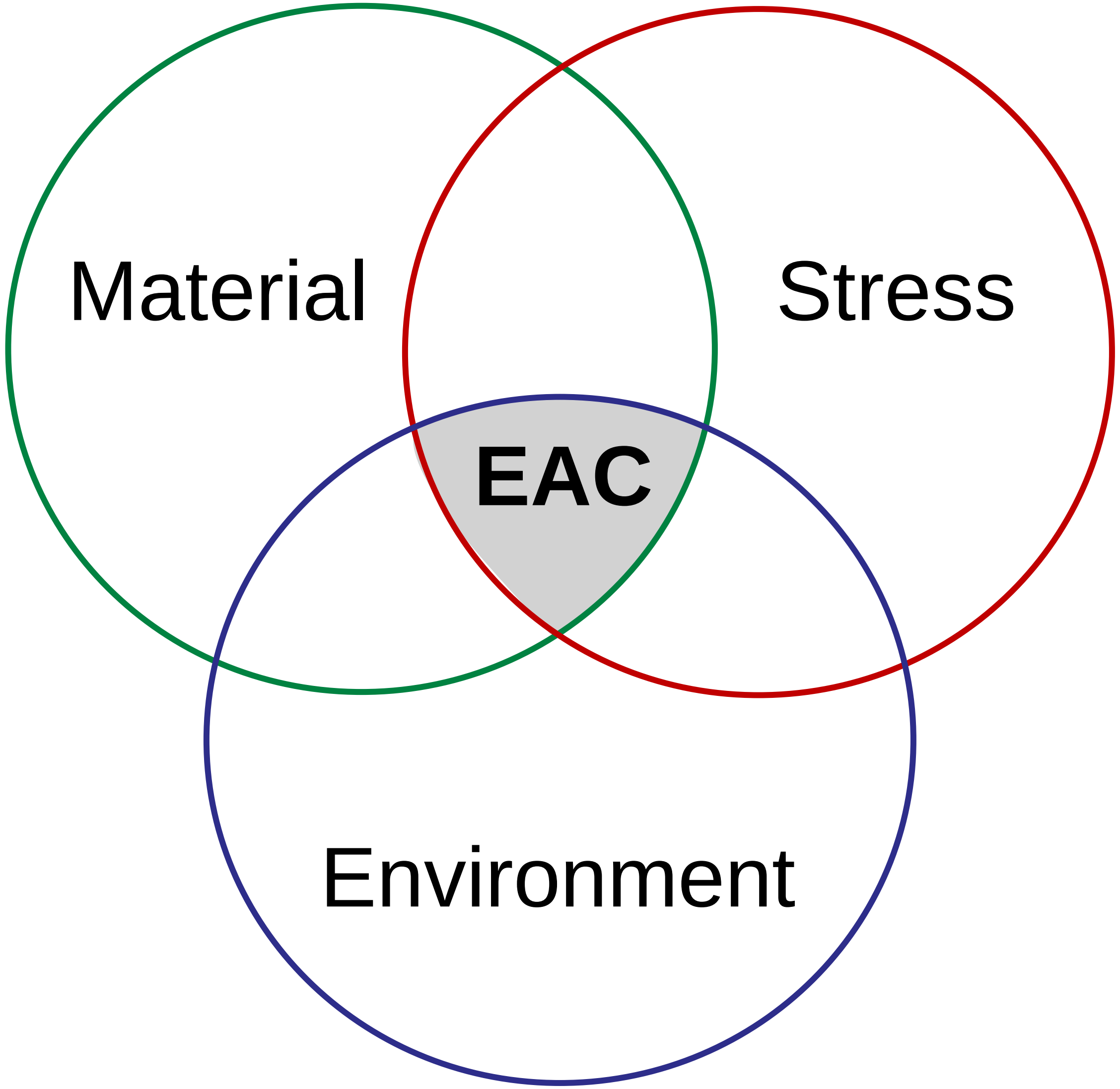
Sulfide Stress Cracking

Liquid Metal Embrittlement

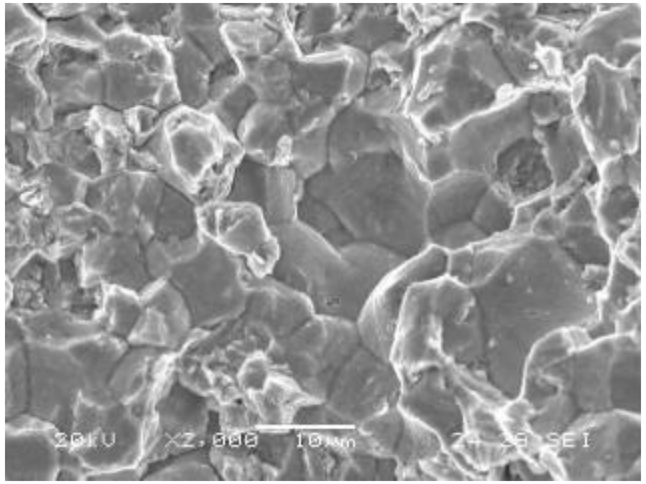
Environmentally Assisted Cracking (EAC)

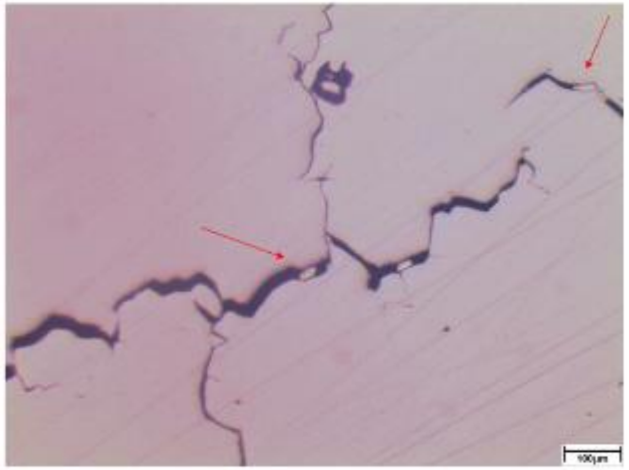


Environmentally Assisted Cracking (EAC)

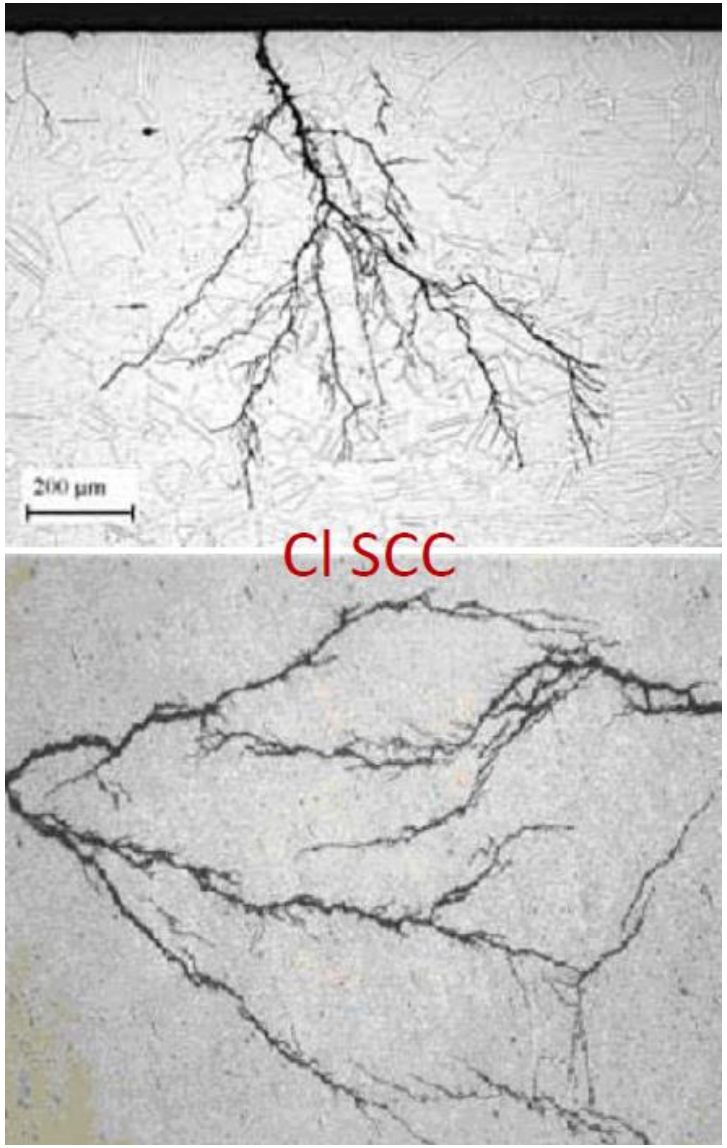


Environmentally Assisted Cracking (EAC)

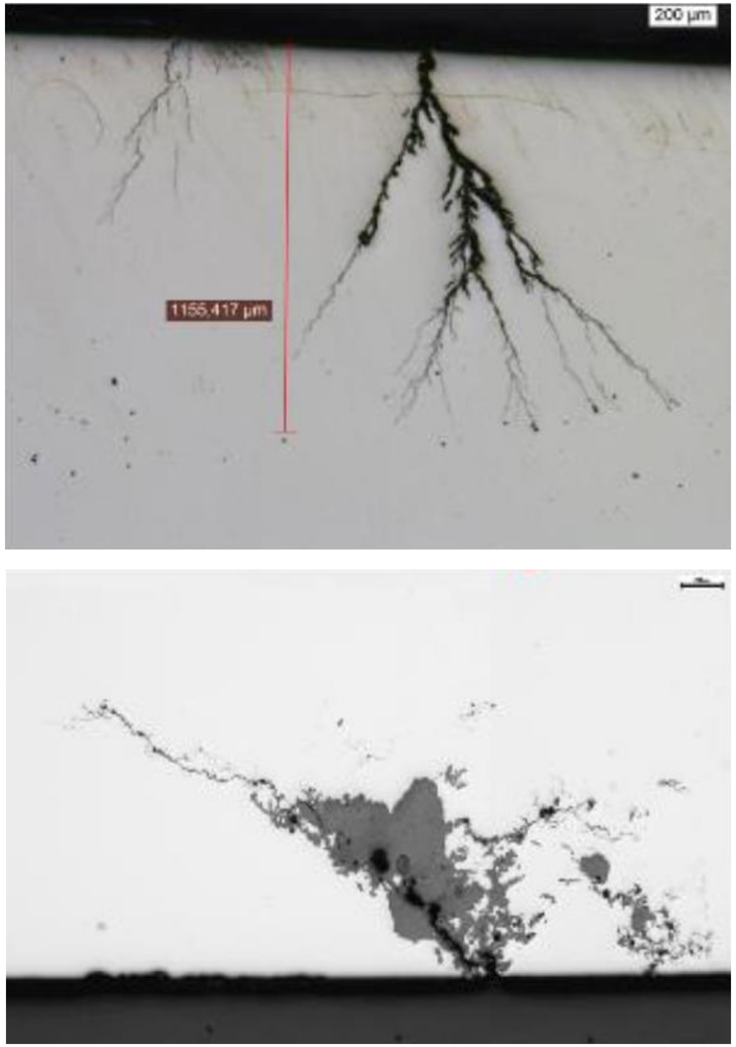




Environmentally Assisted Cracking (EAC)



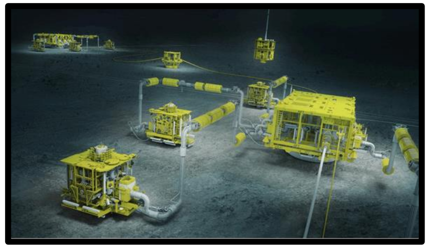
Cl SCC

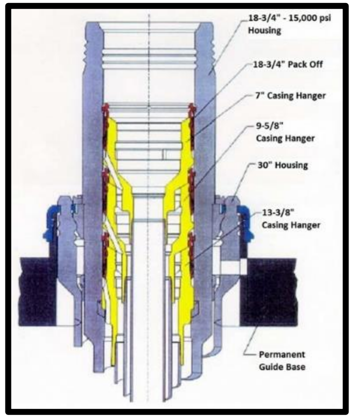


SCC CO_2

HE

General view of SCC and HE in the Energy Sector





Topside

Subsea

Downhole

Transport

Refinery

H2 Energy Transition

Carbon Capture Utilization and Storage

Nuclear

Solar

Wind

Refining industry

Damage Mechanisms Affecting Fixed Equipment in the Refining Industry

ANSI/API RECOMMENDED PRACTICE 571
THIRD EDITION, MARCH 2020

Wind Turbines and Wind Farms

- Fast growing number of offshore platforms and wind power facilities globally;
- Long-period service with limited access for inspection and interventions;
- High humidity, salinity, and long wetting times near sea level especially in subtropical and tropical sea areas;
- SCC/EAC conditions not fully mapped – on going work;
- Fatigue is deemed the main failure mechanism and can be aggravated by corrosion-fatigue;

https://petrobras.com.br/fatos-e-dados/firmamos-acordo-com-a-equinor-para-avaliar-sete-projetos-de-eolica-offshore-no-brasil.htm

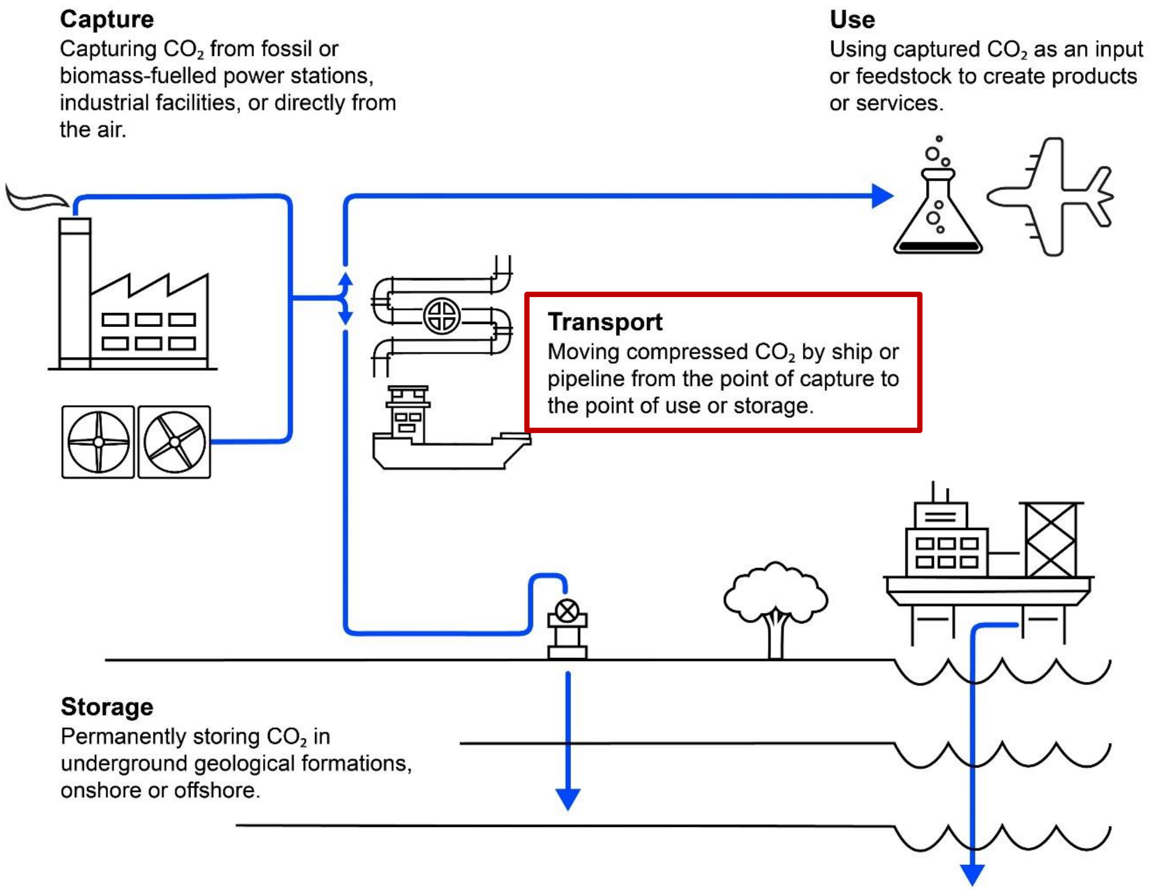
Solar Energy and Solar Power Plants

Ivanpah Solar Electric Generating System

- SCC/EAC conditions not fully mapped;
- High thermal gradients, specially in Concentrated Solar Power;
- Challenges with molten-salt and thermal-energy storage;

https://nossaenergia.petrobras.com.br/energia/de-olho-na-energia-do-futuro/

Carbon Capture Utilisation and Storage (CCUS)



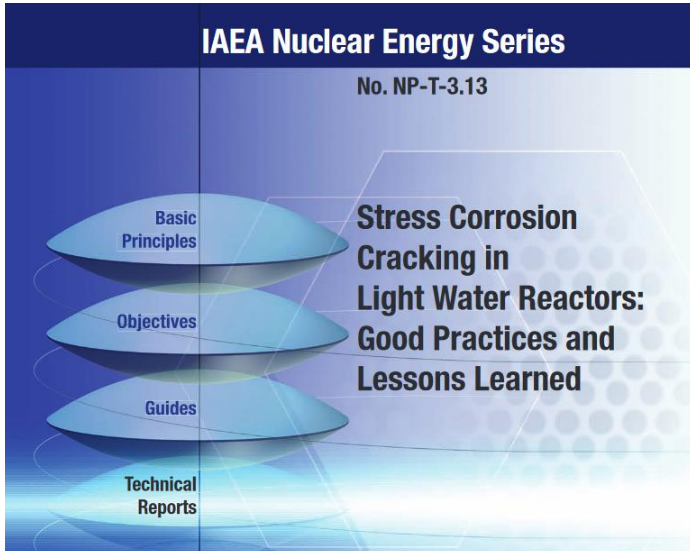
- Main SI challenges: transport of CO_2 rich fluids;
- Dense phase or gas phase CO_2;
- Impurity elements and risk of corrosion and material degradation;
- Arresting running ductile fractures in pipelines transporting CO_2 has proven to be more challenging than in transporting natural gas (NG);

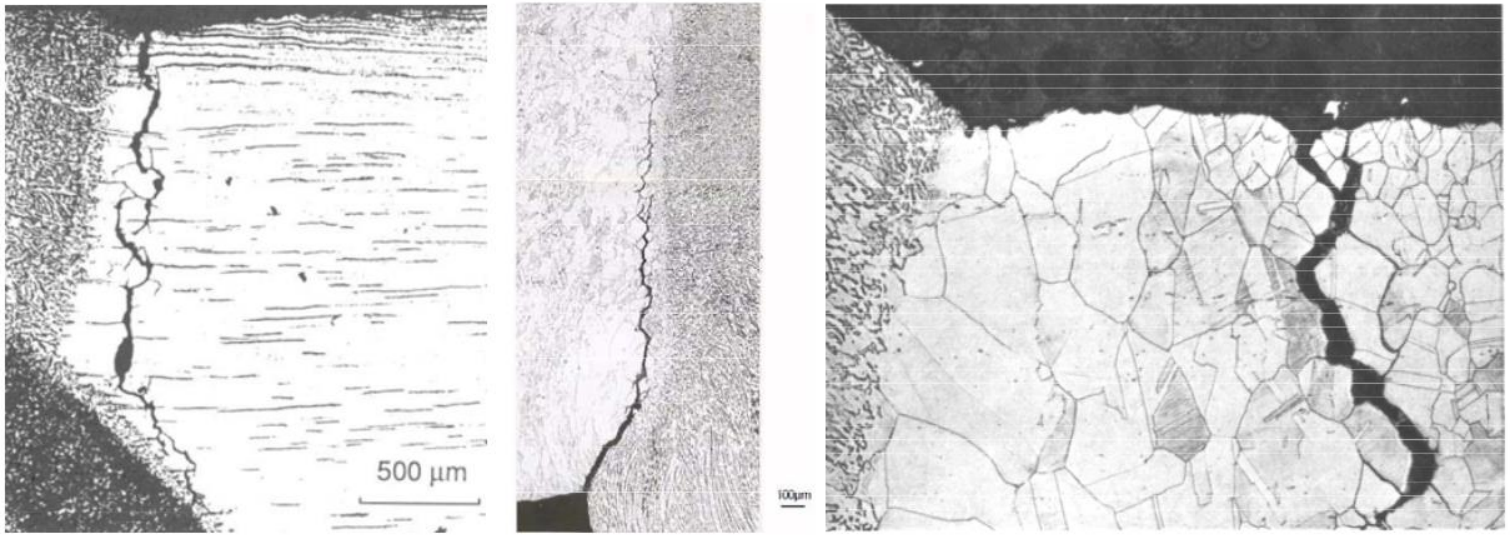
DNV **CO2SafePipe JIP**

https://www.dnv.com/article/design-and-operation-of-co2-pipelines-co2safepipe-240345

https://petrobras.com.br/fatos-e-dados/programa-de-ccus-da-petrobras-no-pre-sal-e-o-maior-do-mundo-em-volume-de-gas-carbonico-co2-reinjetado.htm

Nuclear Power Plants





Stress Corrosion Cracking of Current Structural Materials In Commercial Nuclear Power Plants
Peter L. Andresen
Paper presented at the CORROSION 2012, Salt Lake City, Utah, March 2012.
Paper Number: NACE-2012-1929

P.L. Andresen,
9 - Stress corrosion cracking (SCC) of austenitic stainless steels in high temperature light water reactor (LWR) environments,
Editor(s): Philip G. Tipping, In Woodhead Publishing Series in Energy,
Understanding and Mitigating Ageing in Nuclear Power Plants, Woodhead Publishing,
2010, Pages 236-307, ISBN 9781845695118, https://doi.org/10.1533/9781845699956.2.236.
https://www.sciencedirect.com/science/article/pii/B9781845695118500093

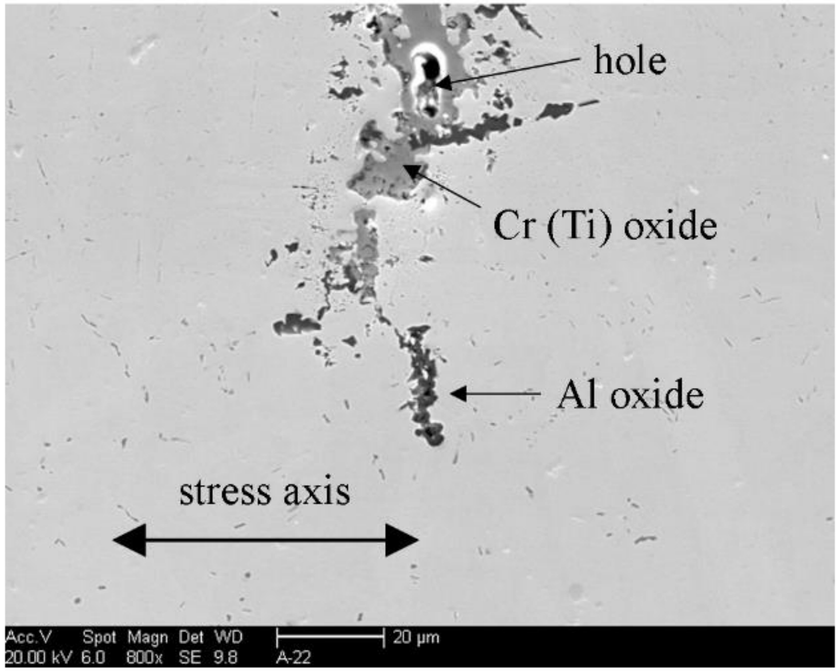
G.S. Was, P.L. Andresen,
6 - Irradiation assisted corrosion and stress corrosion cracking (IAC/IASCC) in nuclear reactor systems and components,
Editor(s): Damien Féron,
In Woodhead Publishing Series in Energy, Nuclear Corrosion Science and Engineering, Woodhead Publishing, 2012,
Pages 131-185, ISBN 9781845697655, https://doi.org/10.1533/9780857095343.2.131.
https://www.sciencedirect.com/science/article/pii/B9781845697655500068

Nuclear Power Plants

Laura Carroll
e-mail: Laura.Carroll@INL.gov
Idaho National Laboratory

THE ROLE OF ENVIRONMENT ON HIGH TEMPERATURE CREEP-FATIGUE BEHAVIOR OF ALLOY 617

Alloy 617 is the leading candidate material for an intermediate heat exchanger (IHX) application of the Very High Temperature Nuclear Reactor (VHTR), expected to have an **outlet temperature as high as 950°C**. Acceptance of Alloy 617 in Section III of the ASME Code for nuclear construction requires a detailed understanding of the creep-fatigue behavior. Initial creep-fatigue work on Alloy 617 suggests **a more dominant role of environment with increasing temperature and/or hold times** evidenced through changes in creep-fatigue crack growth mechanisms and failure life



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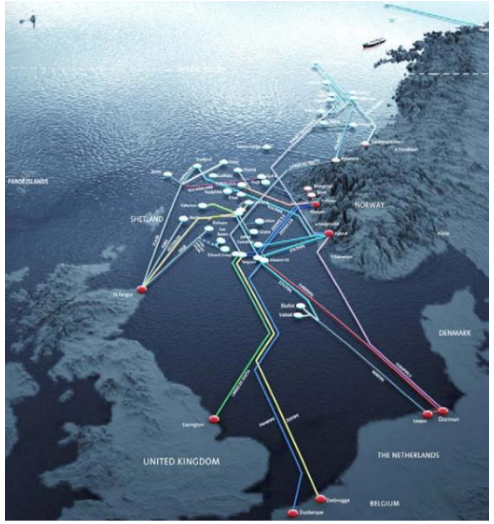
https://inldigitallibrary.inl.gov/sites/sti/sti/5698712.pdf

https://www.osti.gov/servlets/purl/1168621

https://www.osti.gov/servlets/purl/1363883

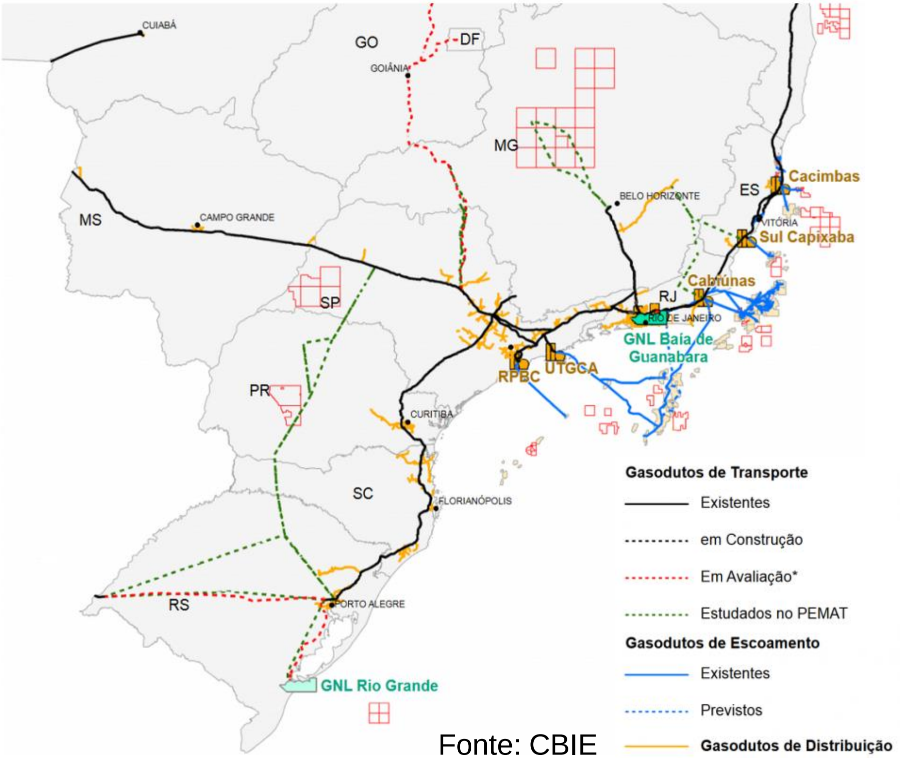
https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=f23fbe30397fcc2063c13c9f9daa82a377897d9a

Energy Transition – Hydrogen gas transport and storage

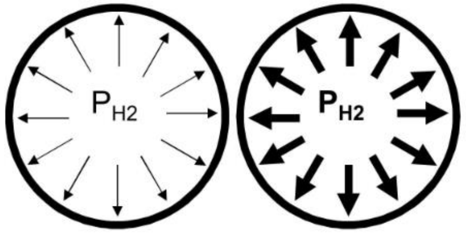


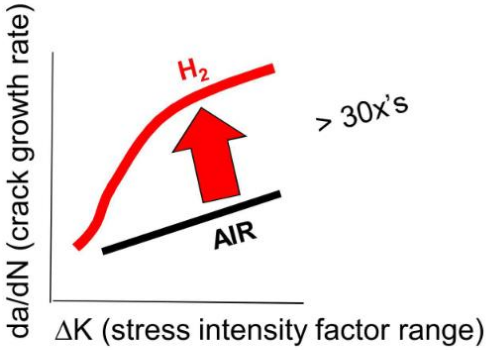
Malha de transporte de gás no Mar do Norte (8800 km), operado pela Gassco

- Worldwide trend for transition to low carbon energy grid and economy;
- Hydrogen as energy vector and means of storage is a critical part of this process;
- In this complex utilization and supply chain for hydrogen, transport and storage of hydrogen gas at high pressures is crucial to lower costs and ensure safe operation;
- Transport in existent facilities (‘vintage’ re-purposed pipelines) is one of the best cost-effective solutions – but risk of vintage material degradation under high pressure hydrogen gas must be assessed;



Fonte: CBIE





Sandia National Laboratories - Hydrogen Effects on Pipeline Steels and Blending into Natural Gas

Energy Transition – Hydrogen gas transport and storage

DNV

Transportation of hydrogen gas in offshore pipelines: H2Pipe

Joint industry project

1 Background

Background for Phase 1 of the Joint Industry Project H2Pipe was to develop a Guideline for design and operation of hydrogen pipelines.

List of deliverables Phase 1:

- FMECA Design and Operation of Hydrogen Pipelines
- State-of-the-Art for Material Aspects Related to Transport of Hydrogen Gas in CMn-Pipelines
- Guideline Design, Construction and Operation of Hydrogen Pipelines
- Technical report Initial Mechanical Test Program
- Initial assessment Running Fracture

2 Objectives of Phase 2

The objectives of Phase 2 are to build on Phase I of the H2Pipe JIP and to develop the guideline to a level where it can offer direct and detailed support in design and re-qualification of offshore hydrogen pipelines.

3 Scope Phase 2

The Phase 2 will focus on the following areas:

- Special design scenario considerations
- Effect of H2 on crack growth resistance and deformation capacity
- Hydrogen uptake
- Risk assessment study
- Update of Guideline document

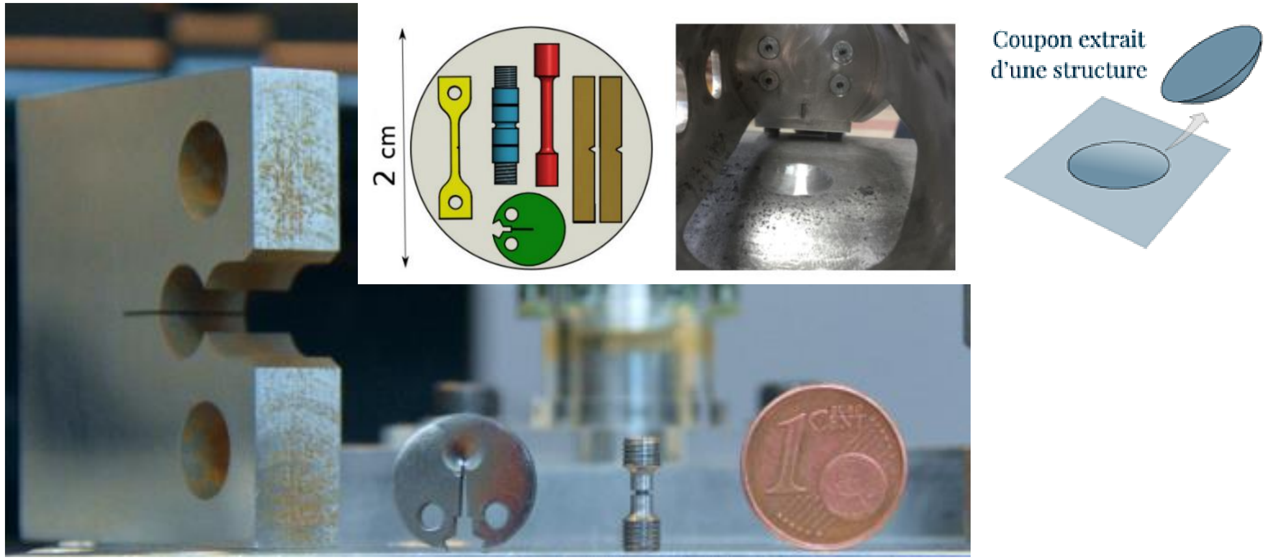
Table 5-1 List of participants Phas

Company	Country*
Aker Solutions	Norway
Allseas	Netherlands
Ansteel	China
ArcelorMittal	Belgium
BP	United Kingdom
Corinth Pipeworks	Greece
Energinet	Denmark
Equinor	Norway
ExxonMobil	United Stated of America
Gassco	Norway
Gasunie	Netherlands
Hyundai Steel	South Korea
Intecsea	Netherlands
JFE Steel	Japan
Jindal Saw	India
Neptune Energy	Norway
Nippon Steel	Japan
Rosen	Germany
Saipem	Italy
Shell	Netherlands
Subsea 7	United Kingdom
Tata Steel	India
TechnipFMC	United Kingdom
Tenaris	Italy
TotalEnergies	Norway
Trans Adriatic Pipeline	Switzerland
Vallourec	France
Welspun	India
Wintershall Dea	Germany
Wood	United Kingdom
Ørsted	Denmark

Energy Transition – Hydrogen gas transport and storage

MESSIAH
Chaire ANR industrielle

MINES ParisTech | PSL

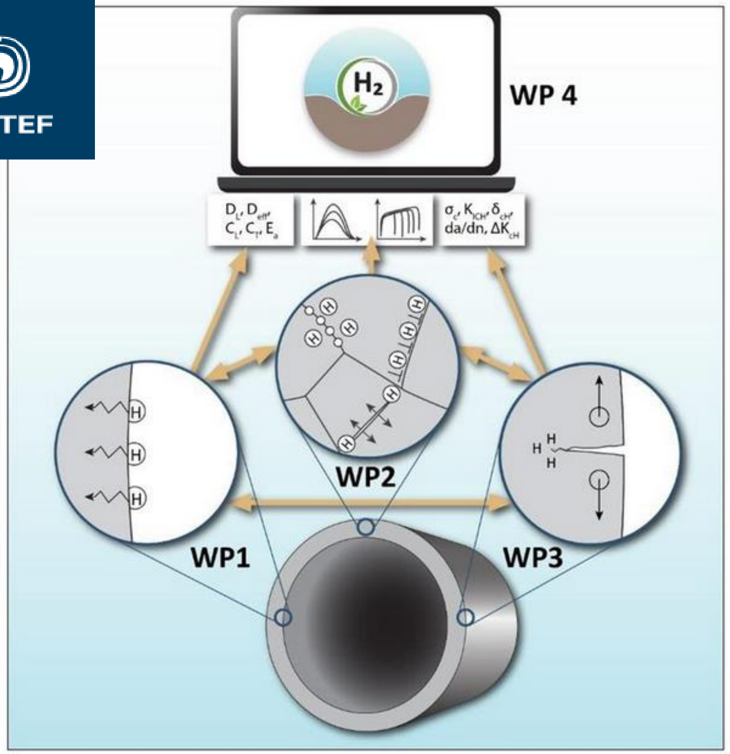


Air Liquide creative oxygen | MANNESMANN PRECISION TUBES | TRANSVALOR | RICE GRTgaz | EDF | ANR

The aim of the **ANR Industrial MESSIAH Chair** is to understand the effect of hydrogen on the mechanical behavior of transport facilities and the risks of rupture. More specifically, the project will study the toughness of gas transport facilities in service by using mini-test pieces machined in coupons from the facilities.

https://messiah.minesparis.psl.eu/en/home/

SINTEF

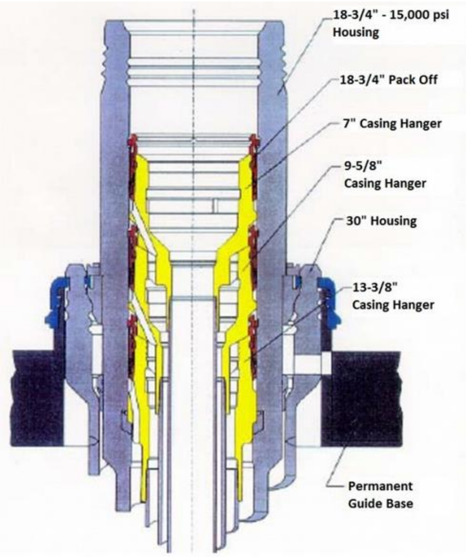


HyLINE - Safe Pipelines for Hydrogen Transport

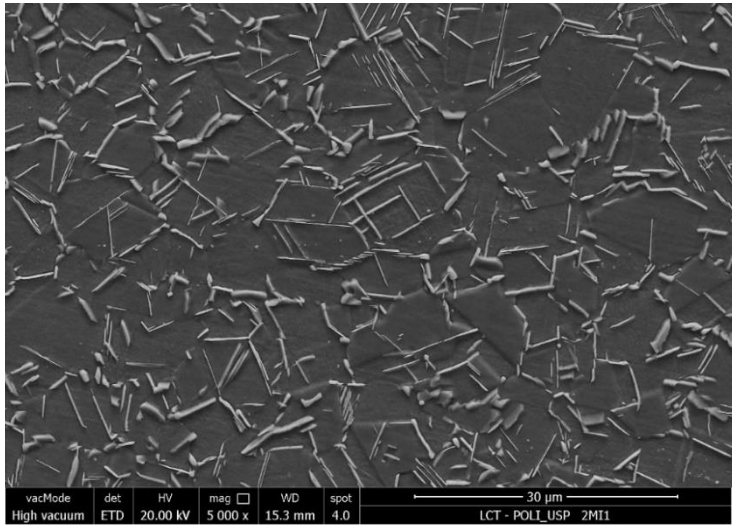
Hydrogen, the most abundant chemical substance in the universe, may, as an energy carrier hold the key to the inevitable and needed transition from fossil fuels to renewable energy. Together with Norway's important role as a major energy provider in Europe comes the obligation to be a main player in this transition.

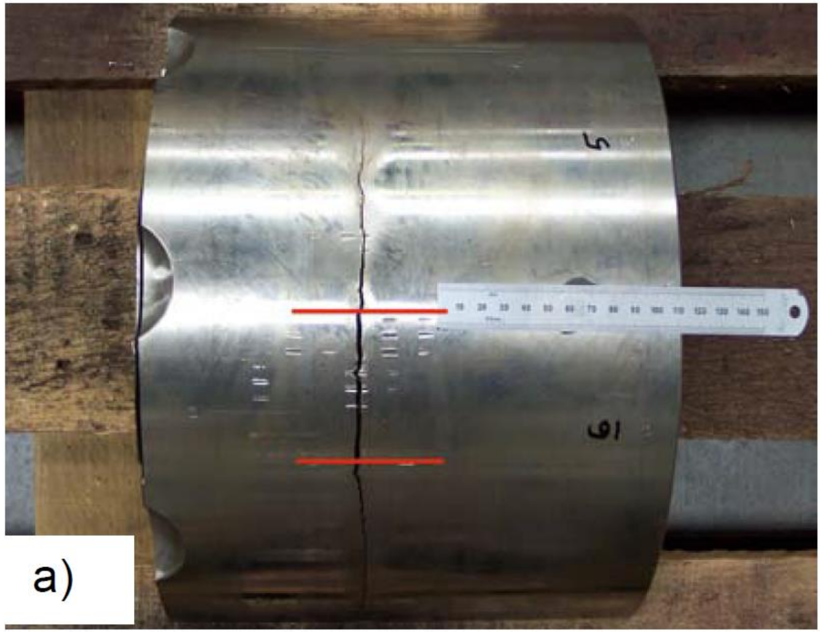
https://www.sintef.no/en/projects/2019/hyline-safe-pipelines-for-hydrogen-transport/

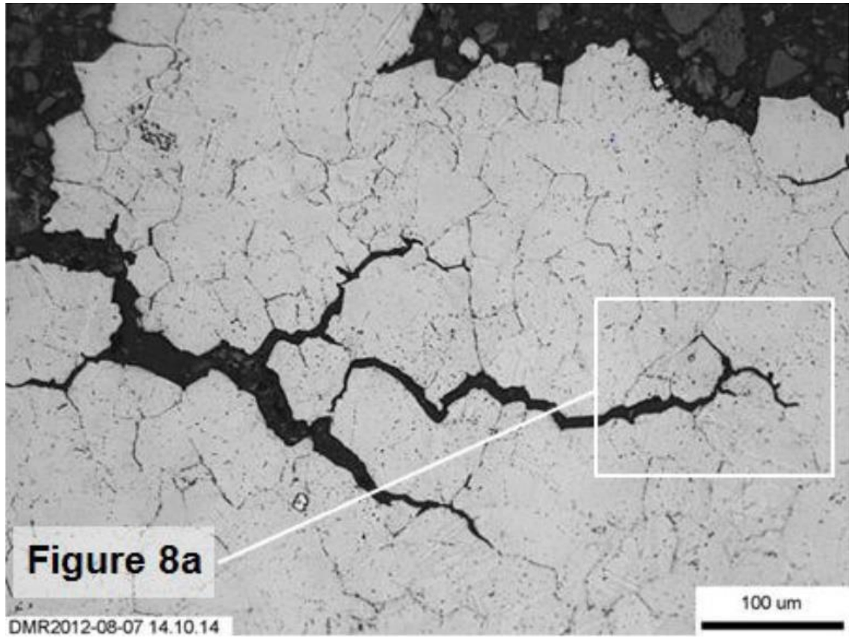
Downhole Components (DHSV, Locators, Tubing Hangers, Casing Hangers)



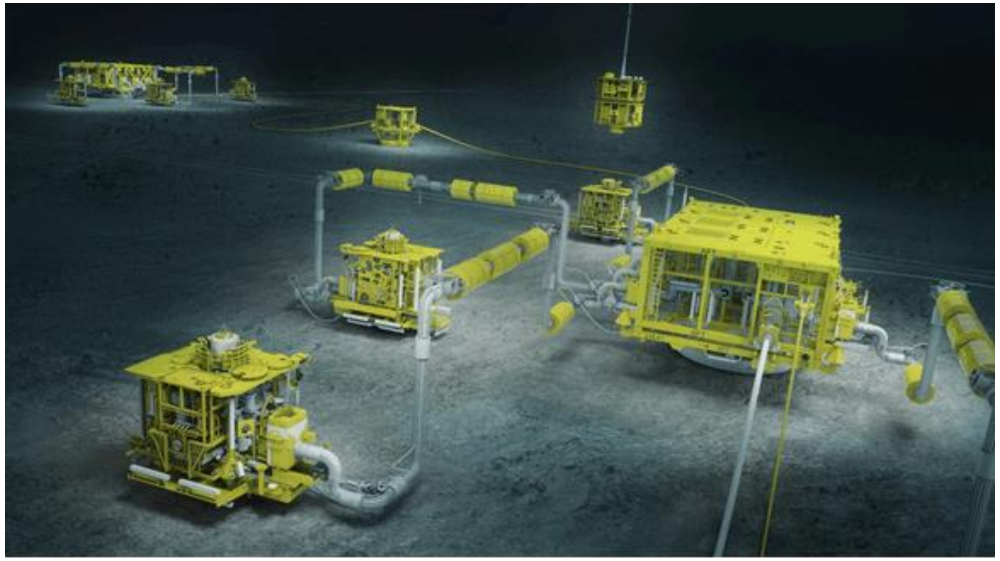
Downhole Components (DHSV, Hangers, etc.)
HISC on Precipitation Hardened Nickel Alloys (ex. 716, 718, 725)
Agressive brine solutions for packer fluids (+ CO_2, + H_2S)
Failures on out of standard SMSS (S13Cr, 13Cr)
Transient operations such as well acidizing
Production fluid with high salinity and high CO_2







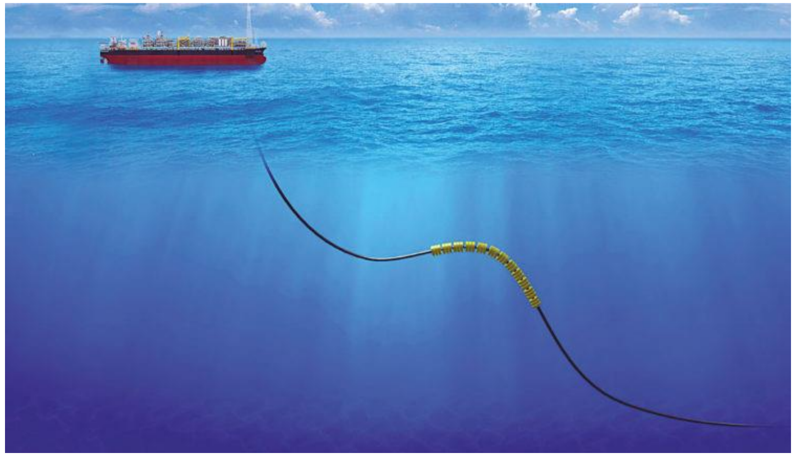
Subsea equipment, risers and flowlines



Subsea equipment

Hydrogen Embrittlement from cathodic protection (anodes)
Low alloy steel fasteners on Manifolds, PAB, XT, BOP (GoM)
Dissimilar welded joints – LAS/IN625 (GoM and North Sea)
HISC on Precipitation Hardened Nickel Alloys fasteners (mainly IN718)
HISC on Duplex and Martensitic Stainless Steels (13Cr and S13Cr)

[New Challenge] Subsea Factory Requirements / High CO_2 pressures



Risers and Flowlines
SN Fatigue (flexible and rigid)
da/dN FCG (rigid)
SCC CO_2 (flexible)
Mainly carbon steel, pipeline steel (X65 and Alloy 625 CRA)

HIC, SSC qualification for Sour Service

Upstream and Transport

Topside

Baking issues on high strength fasteners
HIC, SSC qualification for Sour Service (H_2S)
Duplex and SDSS equipment subject to hydrogen
Chloride Stress Cracking on SS fasteners (not Petrobras)
Hydrogen Embrittlement on 17-4 PH fasteners

[New Challenge] Fasteners for splash zone flanged connections

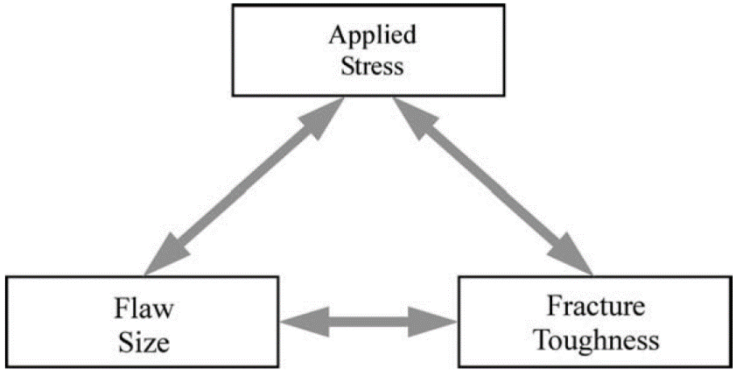
Transport – Onshore and Offshore

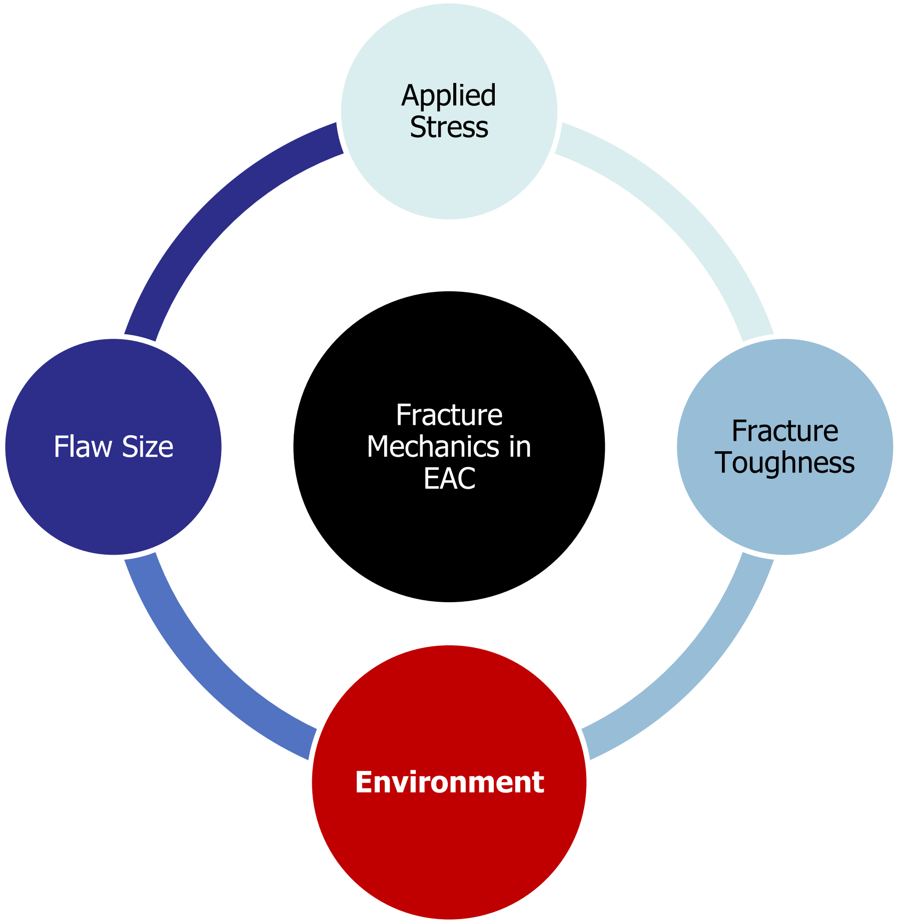
Export gas with H_2S (risk of wet H_2S sour service)
Internal fluid EAC is mainly due to H_2S (SSC)
External on-shore SCC (soil as electrolyte):
Near-neutral pH SCC
High pH SCC

[New Challenge] Hydrogen gas transport
[New Challenge] High CO_2 CCUS applications

Fracture Mechanics in Environmentally Assisted Cracking

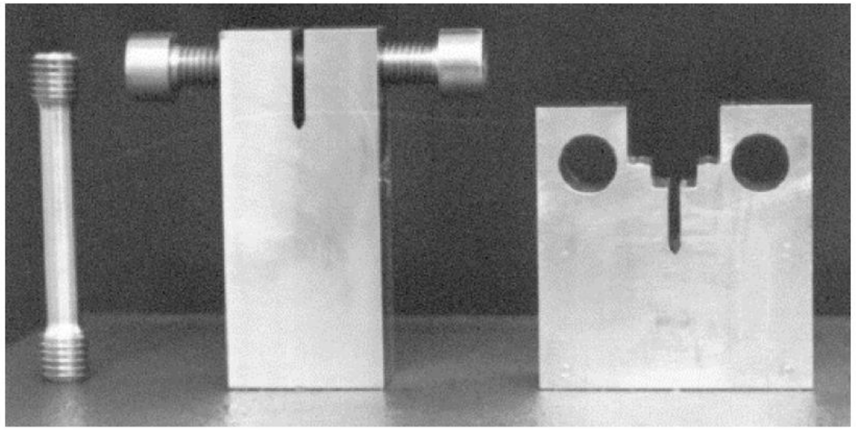
Fracture Mechanics Approach

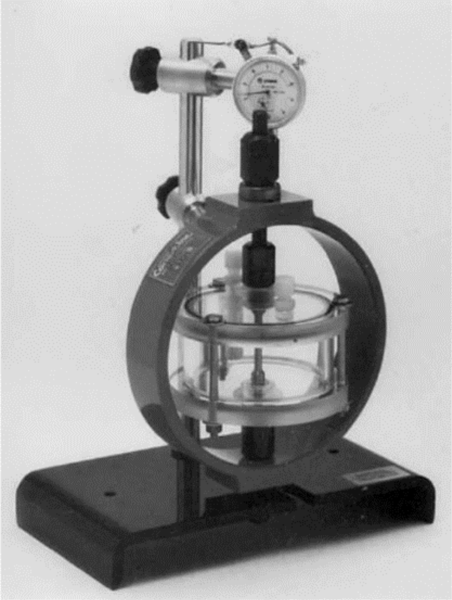


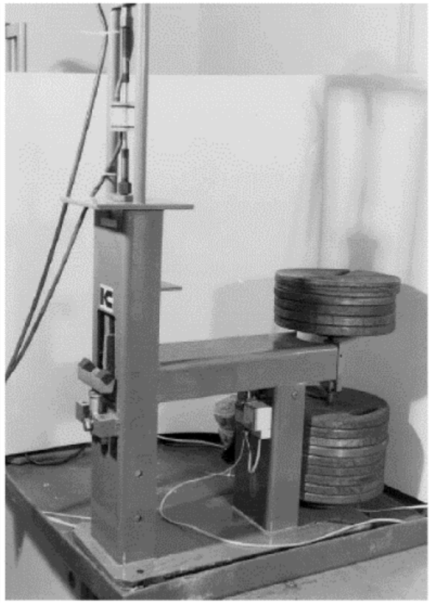


Similitude and applicability of lab tests

Fracture Mechanics in Environmentally Assisted Cracking



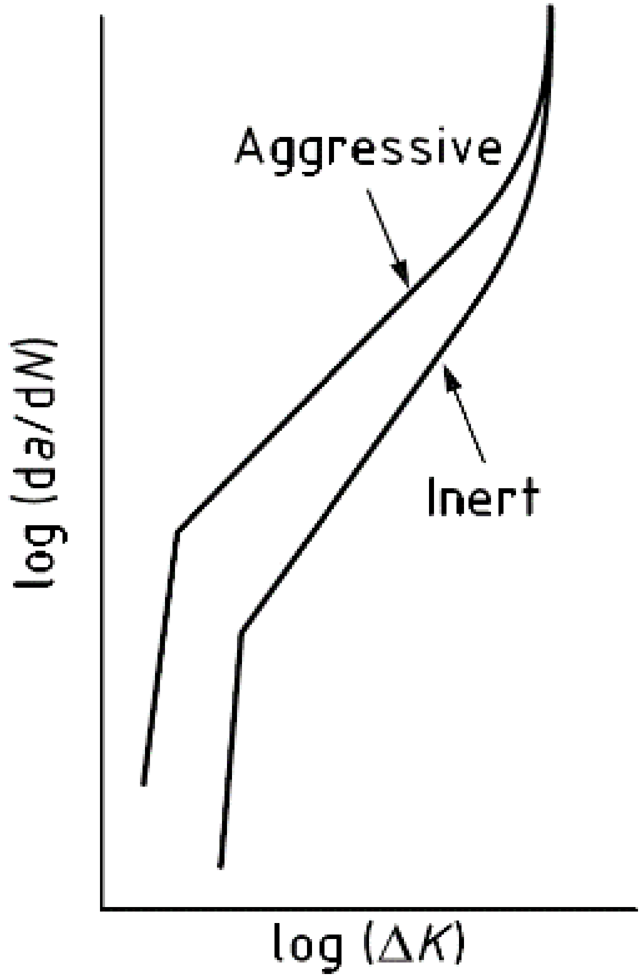




Fracture Mechanics in Environmentally Assisted Cracking

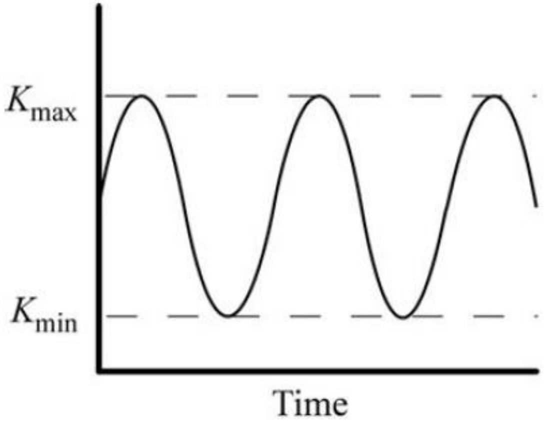
- Damage tolerant design
  - Use of SN or da/dN curves at the design stage;
  - Limit acceptable flaw size (with NDT) and assume ‘no-initiation’ behaviour;
- Safe life design
  - Without fracture mechanics, test smooth specimens;
  - Assume no pre-existing flaws;
  - Design for no crack nucleation;
- Stress-based and Strain-based design (ex. duplex stainless steels HISC and DNV RP F-112)
- Fitness-for-service requirement
  - After failure or identification of risk – how to address operating equipment?
  - How to compare different components and establish a probability of failure ranking?

EAC - Corrosion-Fatigue or Hydrogen Assisted Fatigue



(a) True Corrosion Fatigue (TCF)

- Damage tolerant design
- Assuming pre-existing crack-like flaws
- Lowering of ΔK threshold values (ΔK_{th})
- Higher crack growth rates lead to much shorter lives
- Risk of ‘fatigue exemption’ by codes



Fatigue Crack Growth Rate - Hydrogen Gas

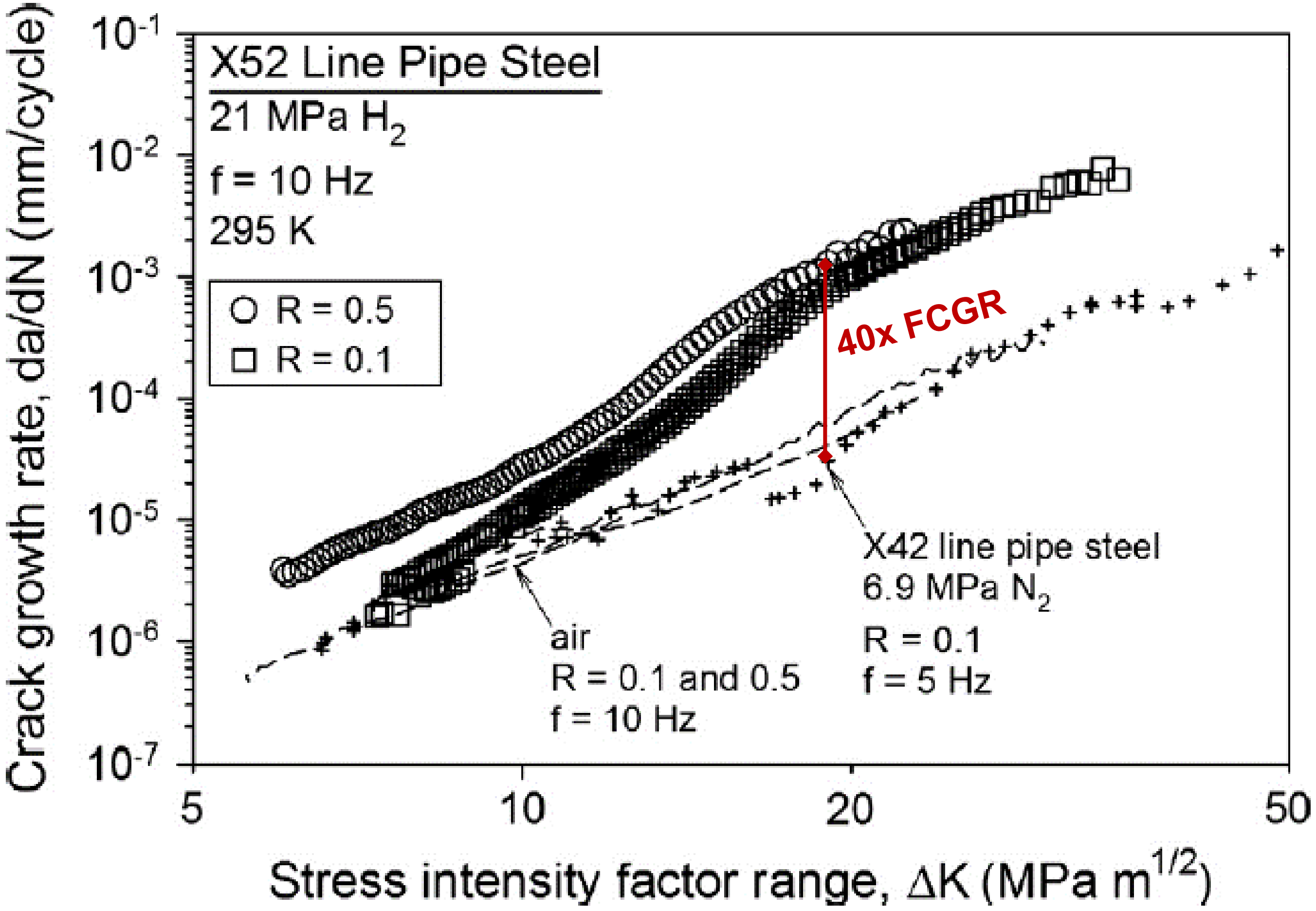


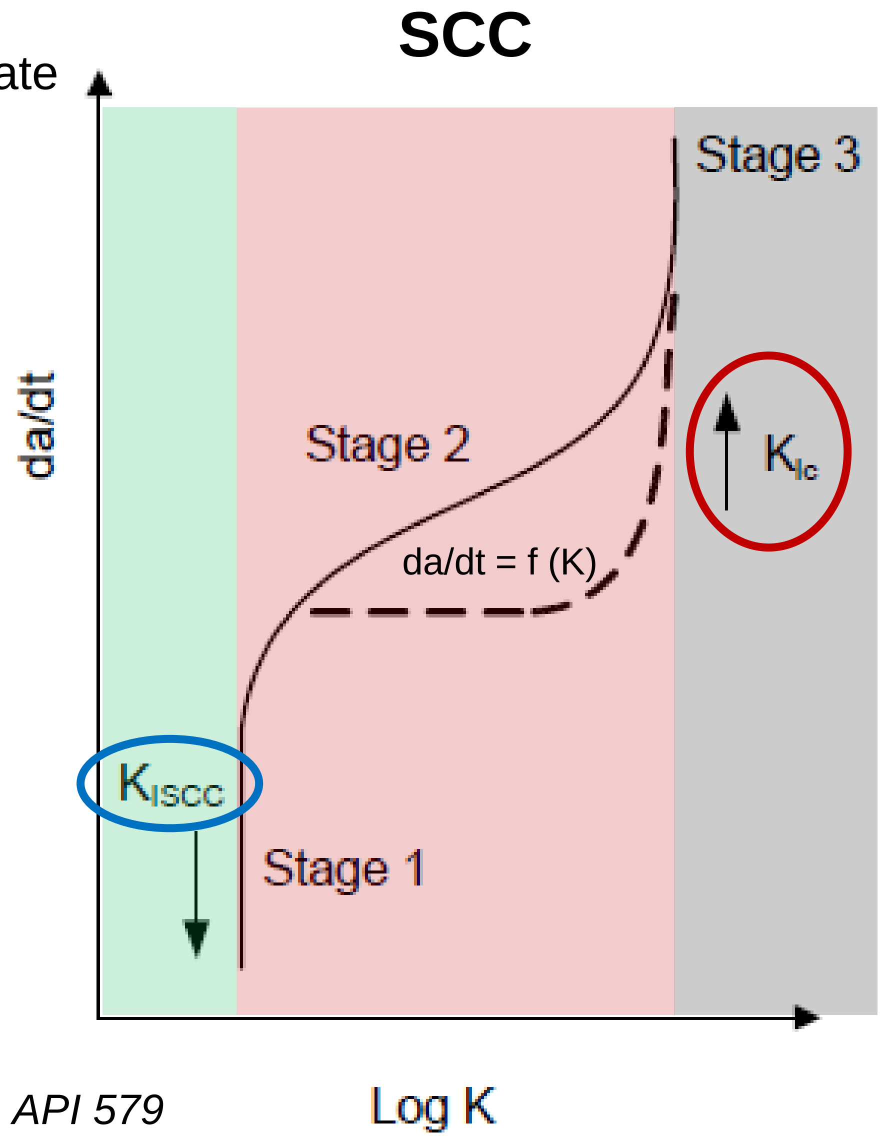
Fig. 2. Fatigue crack growth rate (da/dN) vs. stress intensity factor range (ΔK) relationships for X52 line pipe steel in high-purity hydrogen gas and ambient air. The da/dN vs. ΔK relationships in hydrogen and air were measured at both $R = 0.1$ and $R = 0.5$. Two datasets are plotted for high-purity hydrogen at $R = 0.1$. Fatigue crack growth data for X42 line pipe steel measured in high-pressure nitrogen gas [12] are included for comparison with the X52 data in air.

B.P. Somerday, P. Sofronis, K.A. Nibur, C. San Marchi, R. Kirchheim,
Elucidating the variables affecting accelerated fatigue crack growth of steels in hydrogen gas with low oxygen concentrations,
Acta Materialia, Volume 61, Issue 16, 2013, Pages 6153-6170, ISSN 1359-6454, https://doi.org/10.1016/j.actamat.2013.07.001.

Subcritical crack growth - Static Loading only

Threshold
Fracture Toughness

K_{ISCC}
K_{TH}
K_{IEAC}



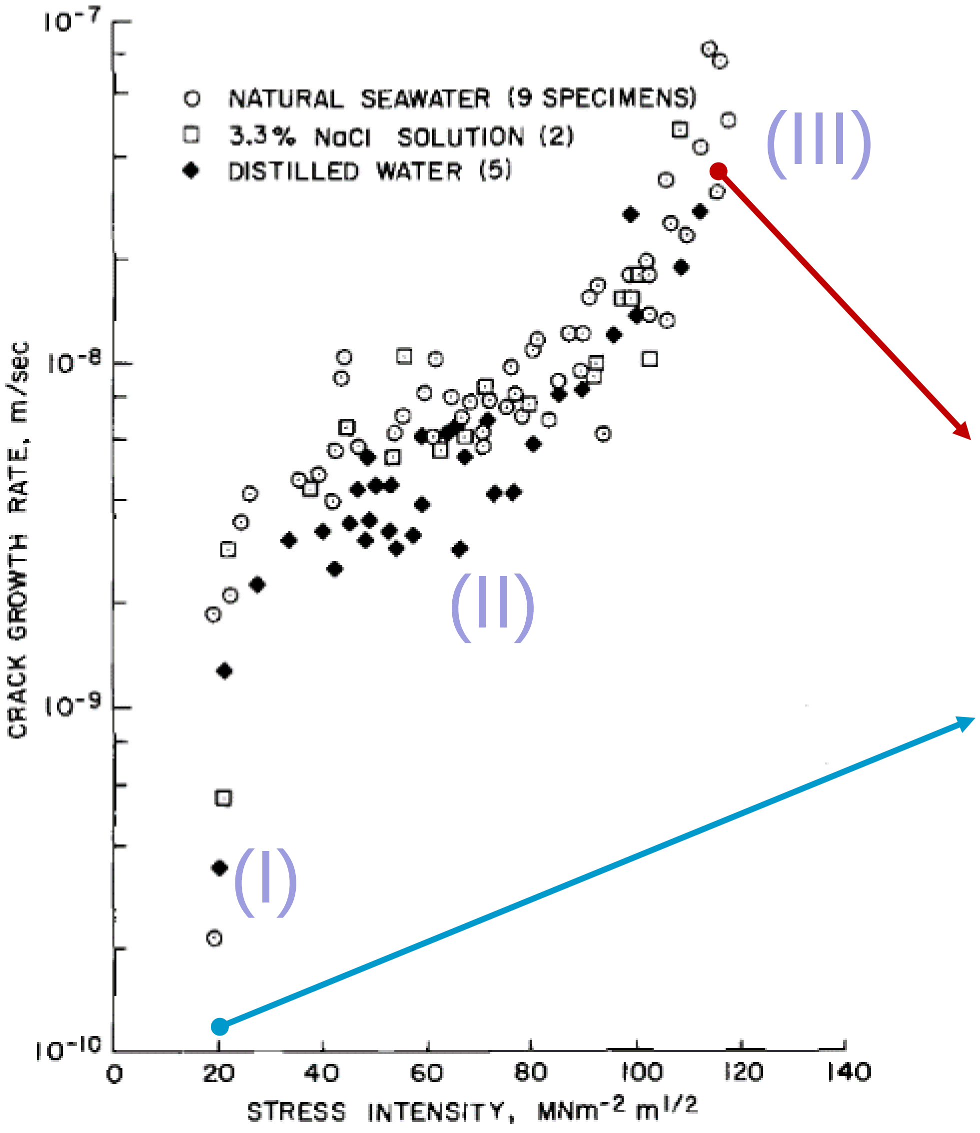
API 579

Final/Fast Fracture (Air)
Fracture Toughness

K_{Jc}
K_{Ic}
K_{mat}

Subcritical crack growth - Static Loading only

Low alloy steel 1400 MPa YS



K_{mat} = 120 MPa.m$^{1/2}$

6x

K_{TH} = 20 MPa.m$^{1/2}$

Low allow steel is not 'embrittled'
Final toughness is similar to air value

$$K_I = Y\sigma\sqrt{\pi a}$$

$$a_{air} \propto \left(\frac{K_{mat}}{\sigma}\right)^2$$

36x

$$a_{scc} \propto \left(\frac{K_{TH}}{\sigma}\right)^2$$

Failure Analysis Diagram (FAD) - EAC

BS 7910:2019

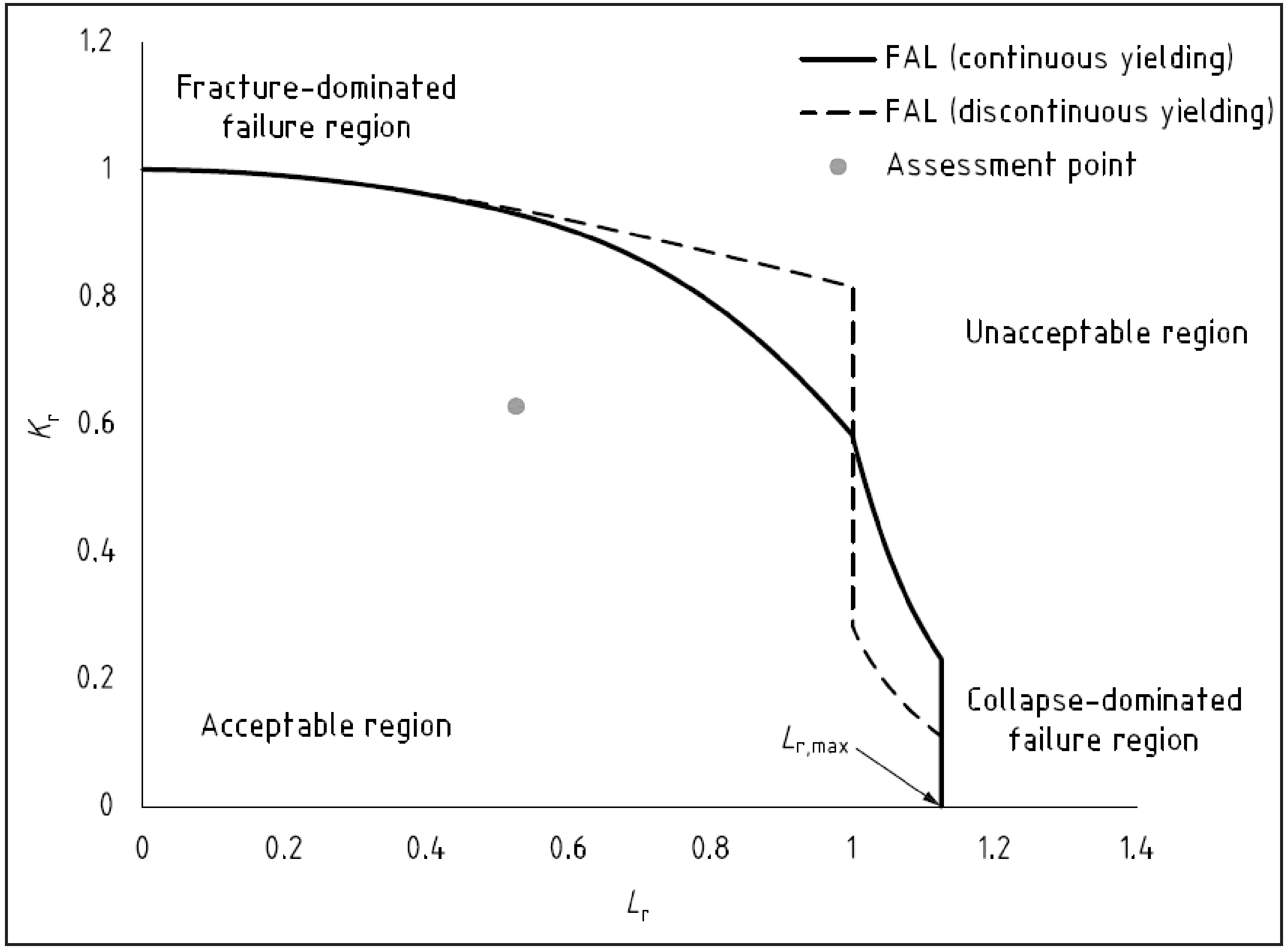
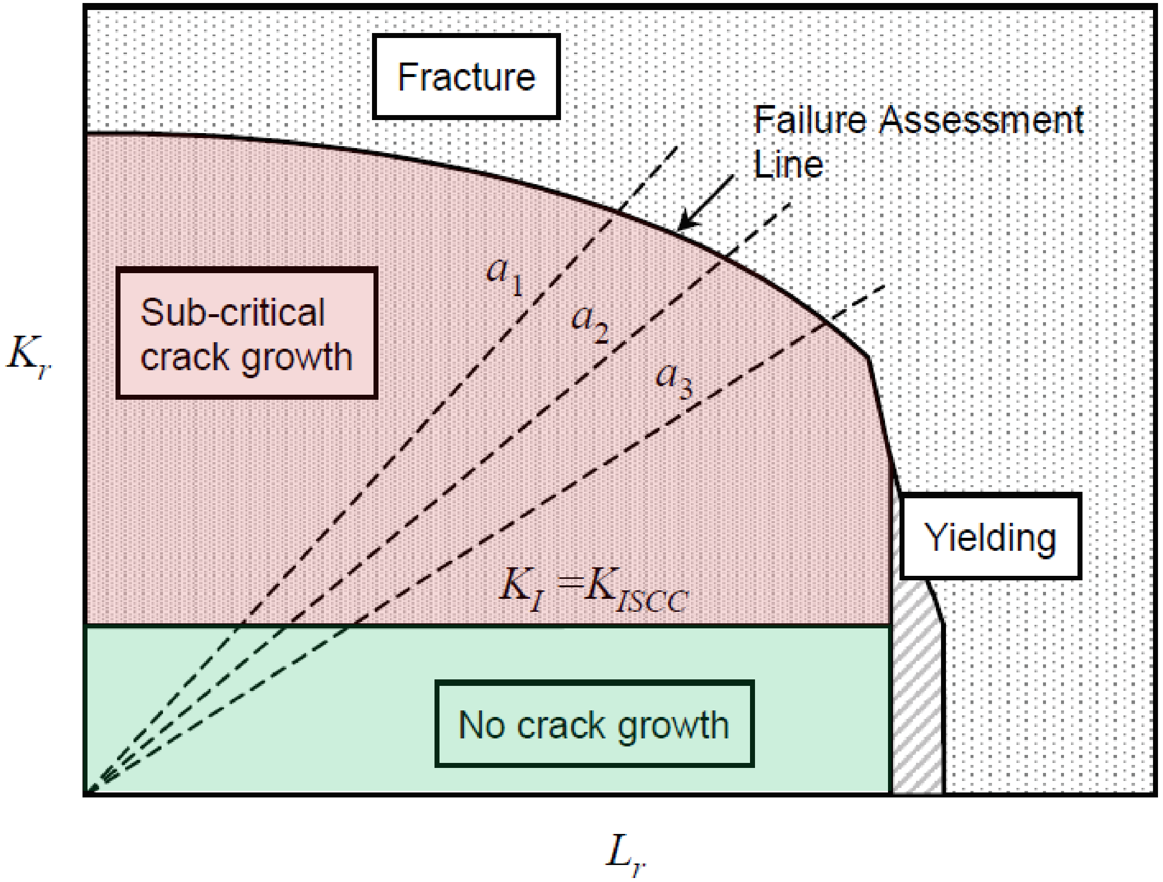


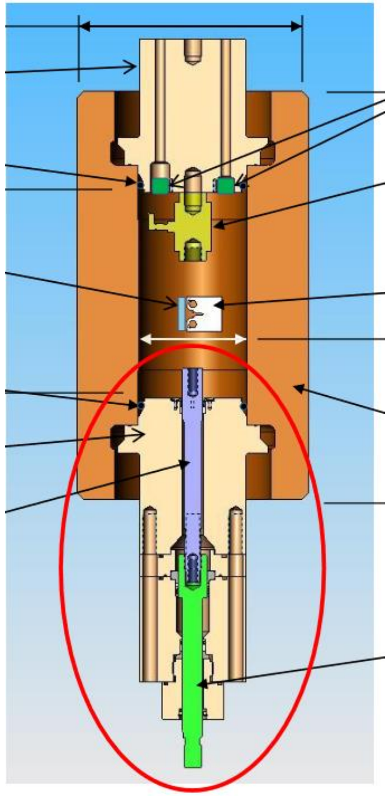
Figure 7.13 **Example of a Failure Assessment Diagram**

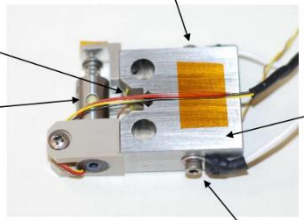
SINTAP/FITNET



http://www.eurofitnet.org/sintap_index.html

Main Challenges for EAC Testing



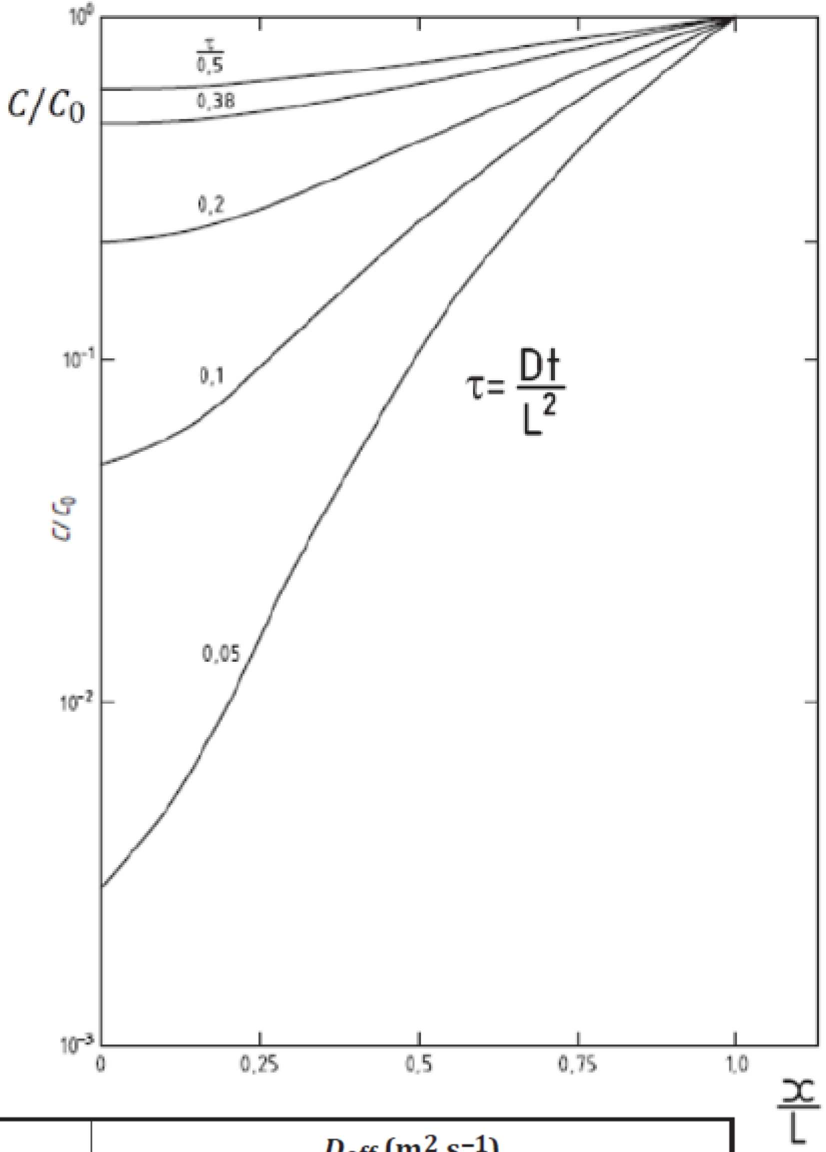


- Lack of specific and detailed test standards (*niche* topic);
- Similitude (reproduction of test environment and loading);
- Hydrogen pre-charging (+ austenitic alloys, + transient testing);
- Long test times and/or incubation period for crack initiation;
- In-situ testing always preferable to ex-situ testing;
- High pressure conditions ($100\ bar < P_{OP} < 1000\ bar$);
- With CO_2, H_2S and H_2;
- Contamination of test environment (O_2, CO);
- High temperature conditions affect test system setup and control;

Typical hydrogen sources

- Cathodic Protection (sacrificial anodes or impressed current);
- Corrosion reactions (even atmospheric corrosion);
- Coatings (Cd, Zn, Zn-Ni) that require baking procedures;

- Hydrogen pre-charging in test specimens;
- Bulk material diffusion to replicate field;
- 20 to 30 years design life;
- Testing in-situ;
- Incubation time;
- Slower loading rates (K-rate or ε-rate);
- Austenitic alloys (SS, PH Ni);



Material	D_{eff} ($m^2 s^{-1}$)
Pure iron	$7,2 \times 10^{-9}$
BS 4360 50D (S355J2G3, 1.0577)	$1,7 \times 10^{-10}$
AISI 4340 (1.6565)	$1,7 \times 10^{-11}$
3,5 % Ni-Cr-Mo-V	$5,3 \times 10^{-12}$

Fatigue Crack Growth Rate - Hydrogen Gas - Effect of impurities

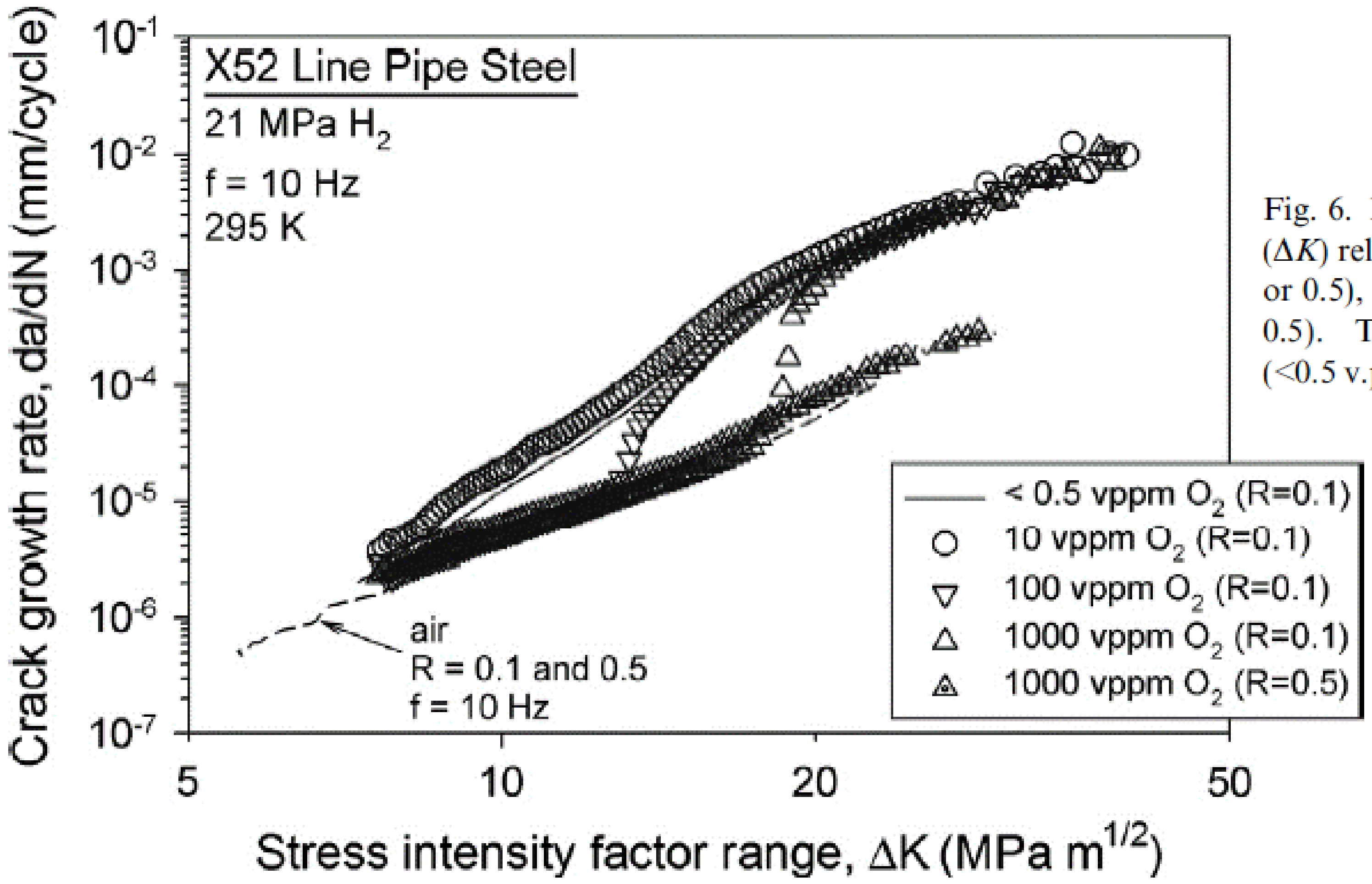


Fig. 6. Fatigue crack growth rate (da/dN) vs. stress intensity factor range (ΔK) relationships for X52 line pipe steel in mixed $H_2 + O_2$ gases ($R = 0.1$ or 0.5), high-purity hydrogen gas ($R = 0.1$), and ambient air ($R = 0.1$ and 0.5). The da/dN vs. ΔK relationships in high-purity hydrogen (<0.5 v.p.p.m. O_2) and air are from Fig. 2.

B.P. Somerday, P. Sofronis, K.A. Nibur, C. San Marchi, R. Kirchheim,
Elucidating the variables affecting accelerated fatigue crack growth of steels in hydrogen gas with low oxygen concentrations,
Acta Materialia, Volume 61, Issue 16, 2013, Pages 6153-6170, ISSN 1359-6454, https://doi.org/10.1016/j.actamat.2013.07.001.

EAC Modelling and Database Building

- Underlying EAC mechanistic phenomena is often under ‘current’ investigation and require a multi-physics, complex modelling approach;
- Fitting of test data with current models is fairly feasible – the main challenge is to extrapolate to other scenarios, heats, material specs, etc;
- Testing laboratory infrastructure is expensive (high pressure, safety issues, complex monitoring);
- Long testing times, need for test frames long-term availability and risk of losing tests increase costs considerably;
- Test results reliability (repeatability and reproducibility) is also challenging, as the number of labs running this type of tests at a high quality level is quite small, which hinders massive round-robin efforts;
- Nevertheless, hydrogen gas and energy transition has been given significant funding and effort, specially in Europe, US and Japan. This has been crucial to the current state-of-the-art;

EAC Modelling and Database Building

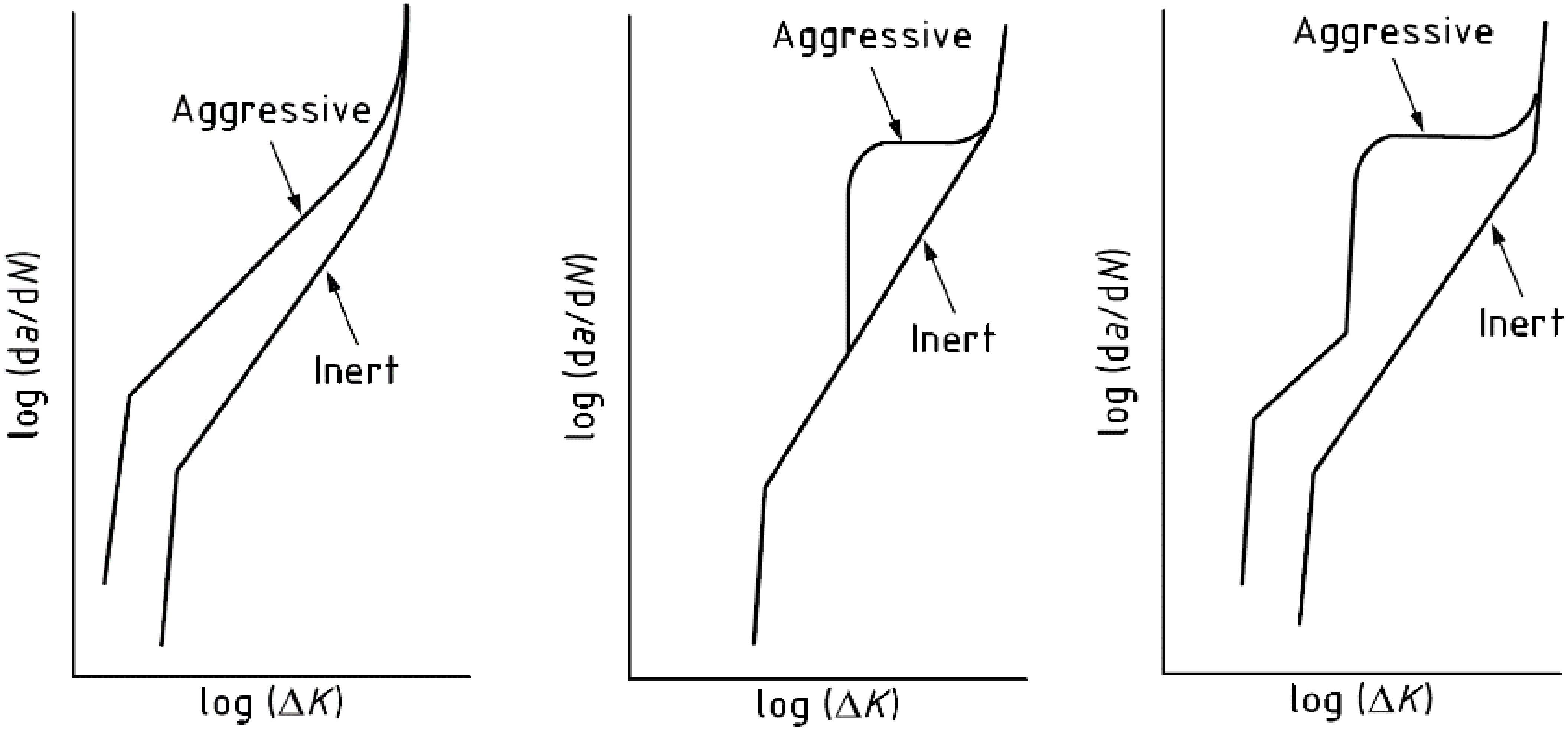
Several approaches for EAC modelling have been applied in the literature. They differ mainly in:

- Learning curve requirements;
- Proprietary softwares or solvers;
- Capability to address different type of material/environment scenarios;
- Number of parameters that require fitting;
- Parameters that can be obtained in tests or other characterization approaches;

We can list:

- Diffusion and Trapping models (Oriani and McNabb-Foster) for ECP/TDS (several authors)
- Phase-field model (Emilio Martínez-Pañeda – Imperial College)
- Crack-tip strain-rate model (Nuclear industry – Peter Andresen / Ramgopal Thodla at DNV Ohio)
- Modified ductile-damage Gurson–Tvergaard–Needleman model (several authors)
- Cohesive Zone Model (mainly SINTEF/NTNU)
- WARP 3D approach (Illinois research group / NAMEF/USP – Claudio Ruggieri)
- Modified Abaqus with UMATHT routines (several authors)

Static EAC + Fatigue



(a) True Corrosion Fatigue (TCF)

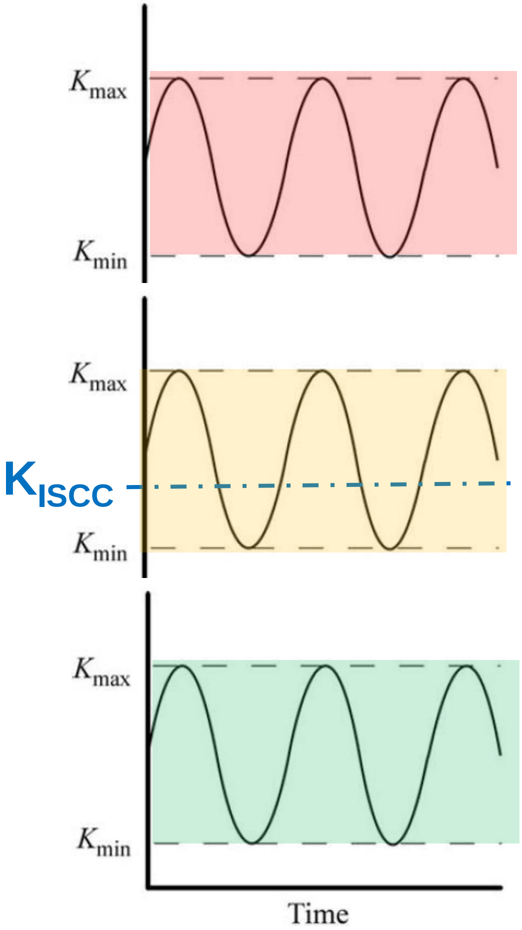
(b) Stress Corrosion Fatigue (SCF)

(c) SCF with TCF

Static EAC + Fatigue

ΔK always the same, K_{max} and K_{min} change

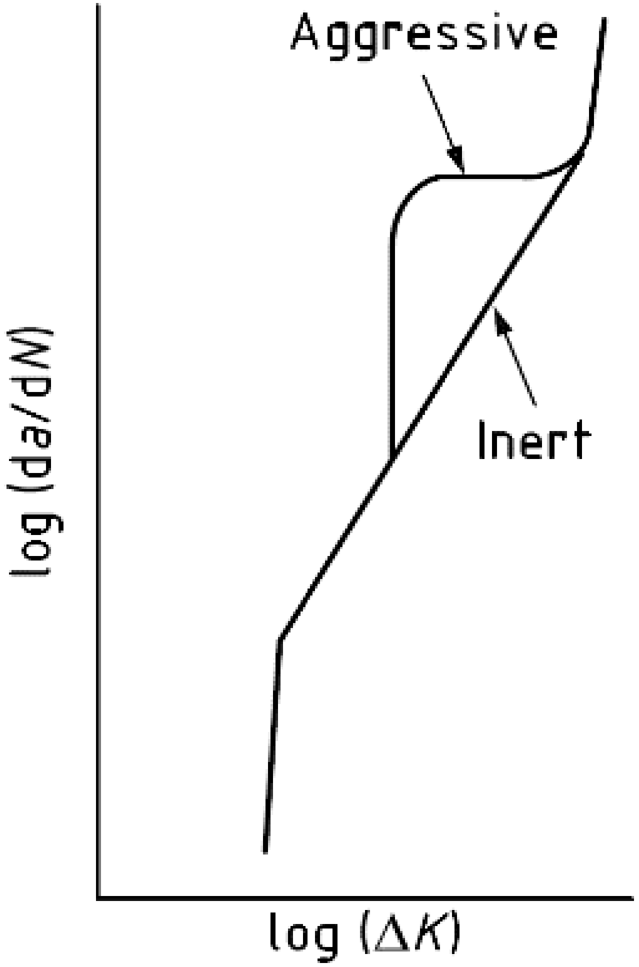
Influence of R (mean stress)



Full cycle above SCC threshold ↑CGR

Cycle partially above SCC threshold ↑CGR

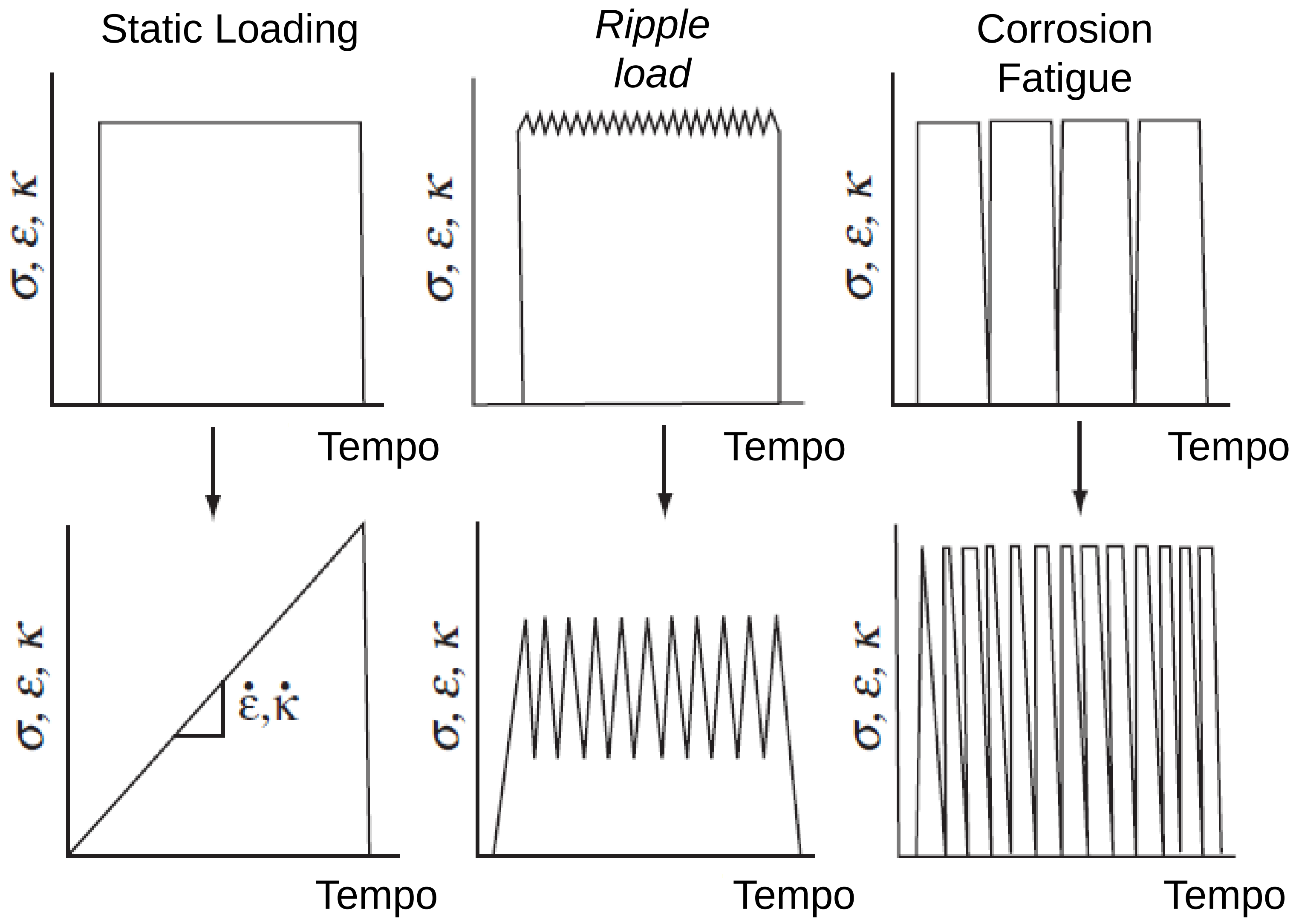
Full cycle below SCC threshold



EAC/SCC/HE vs. Corrosion-Fatigue or Hydrogen Assisted Fatigue

Actual Load Scenarios

Loading protocol for testing



K threshold (K_{EAC})

High mean stress
High R ratio

Corrosion-Fatigue

$$R = S_{mín} / S_{máx}$$

EAC/SCC/HE vs. Corrosion-Fatigue or Hydrogen Assisted Fatigue

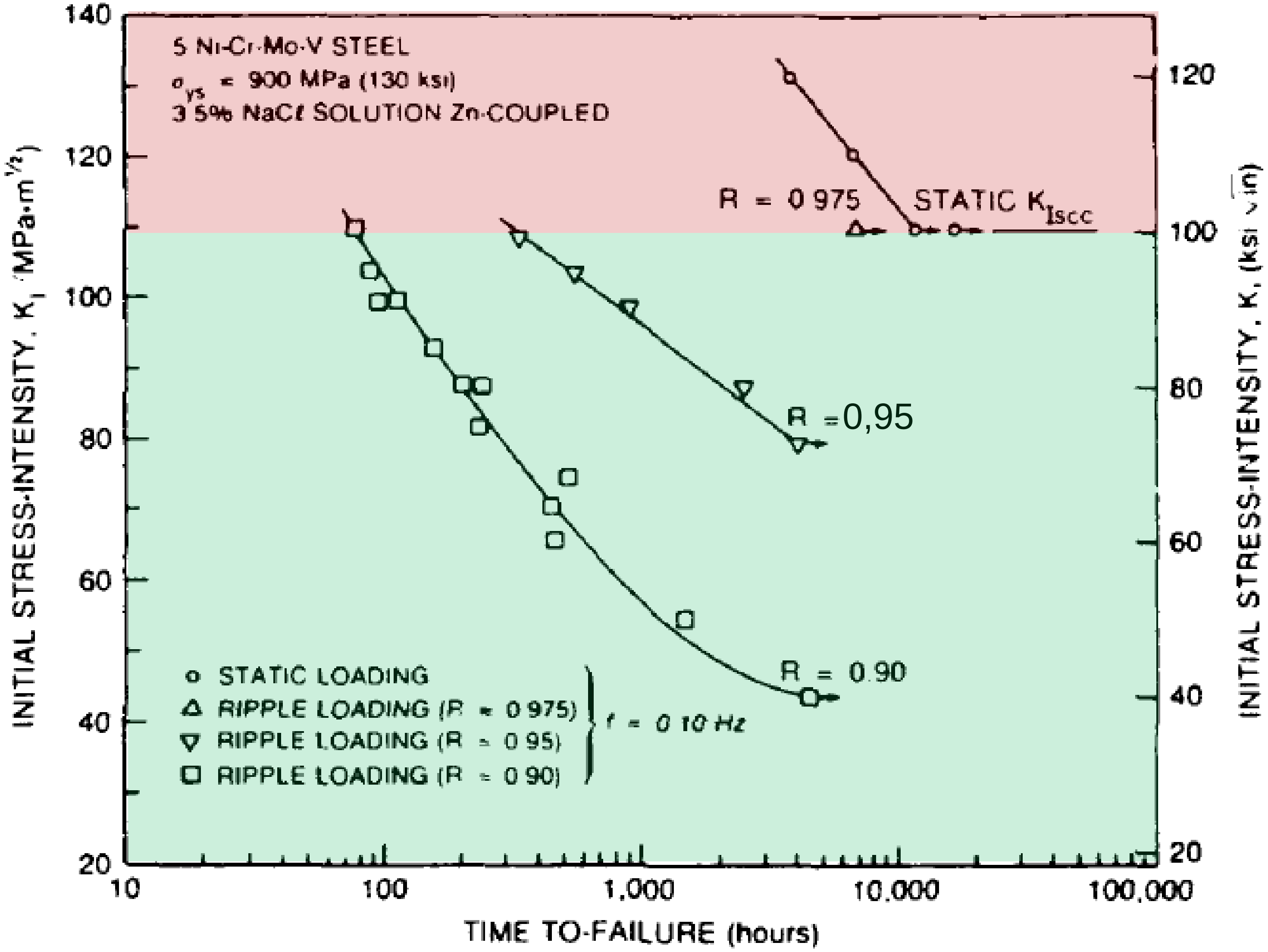


Fig. 1 — Initial stress-intensity (K_I) versus time-to-failure data for 5Ni-Cr-Mo-V steel under static loading and ripple-loading [5].

?

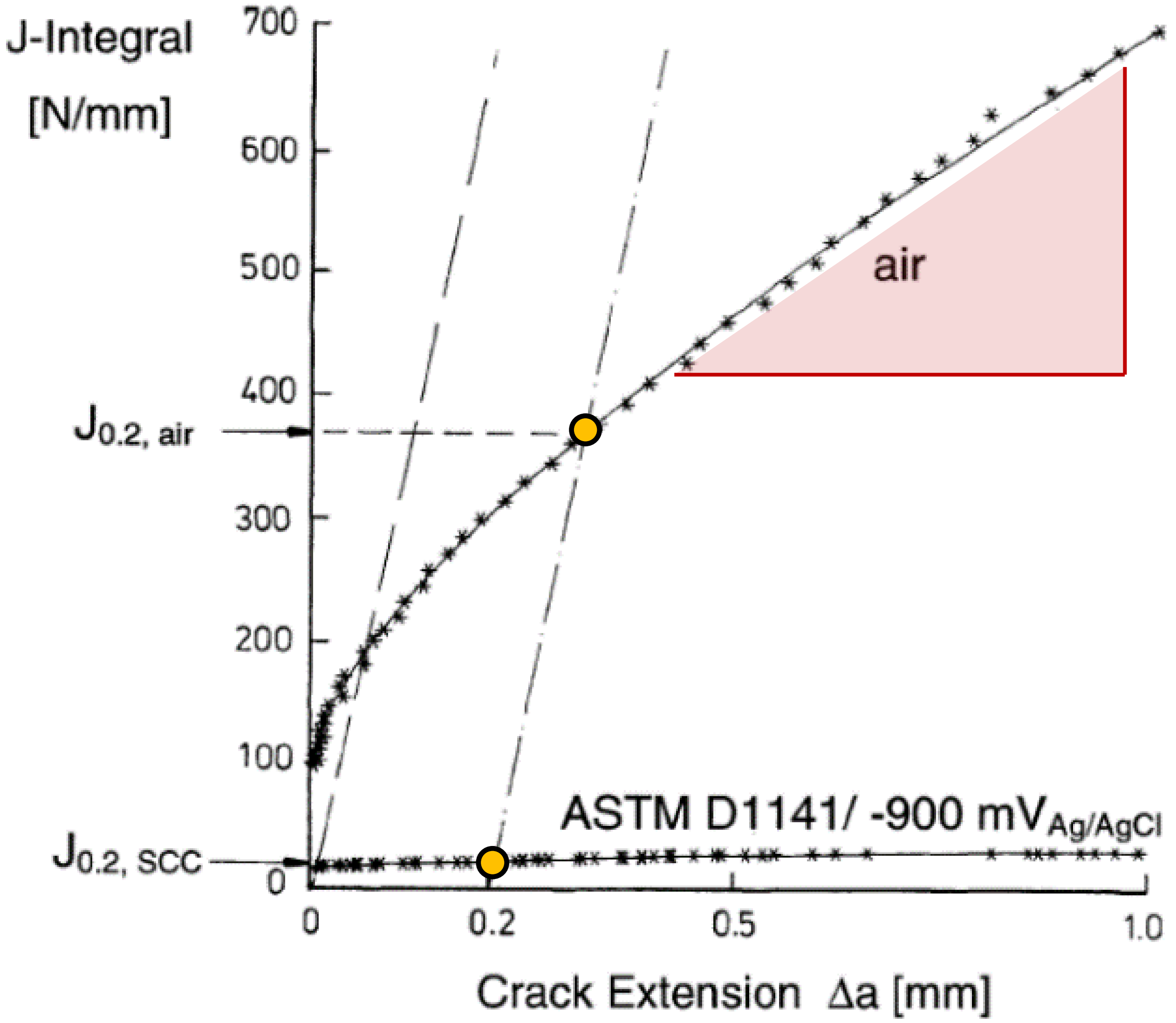
How design codes deal with Ripple Loads?

(Pao & Bayles, 1991) (Yoder et al., 1988)

Static EAC + Fatigue Parameters

	Static Loading Only	*Ripple load*	(Corrosion) Fatigue
Inert Environment	σ_{YS}		$\Delta\sigma_{TH}$ e ΔK_{TH} da/dN
Agressive Environment	σ_{TH} e K_{TH} da/dt		$\Delta\sigma_{TH}$ e ΔK_{TH} da/dN

Rising displacement test and Elasto-plastic behaviour



Rising displacement test vs. Constant Displacement Tests for lower YS

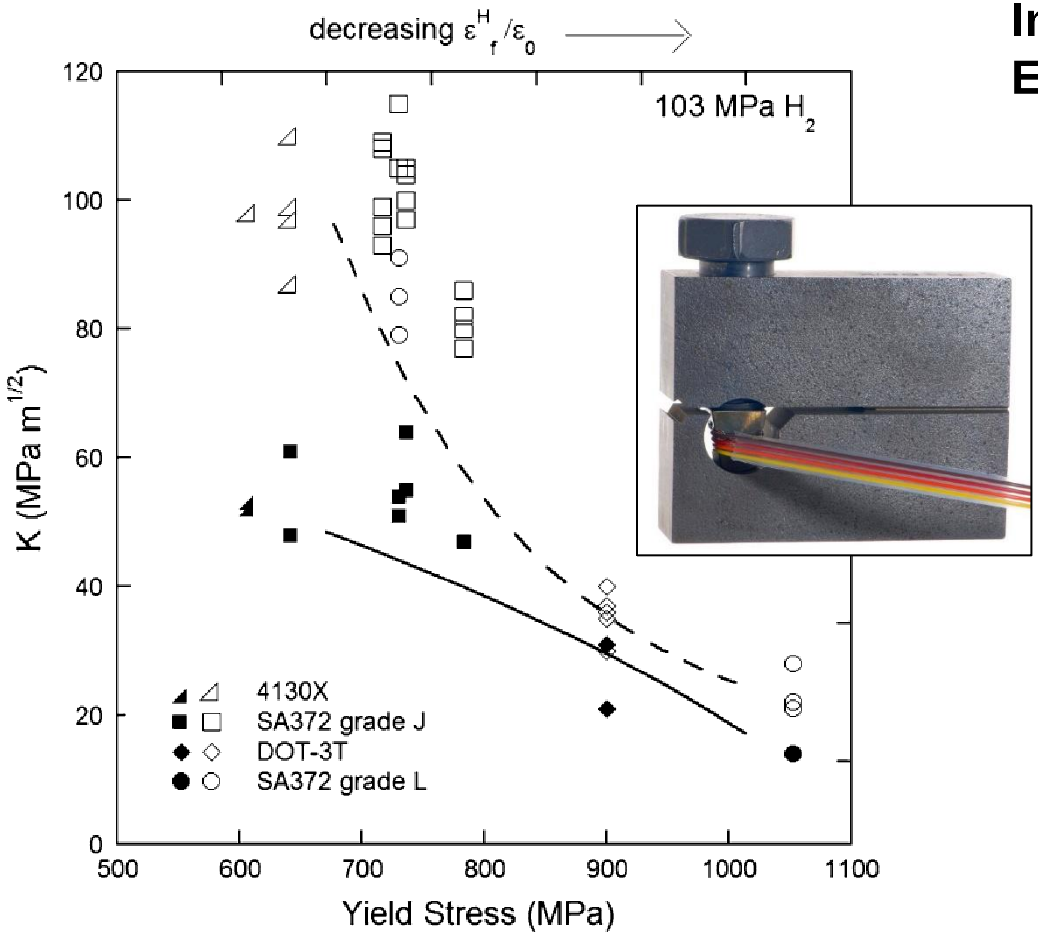


Fig. 3—Crack arrest thresholds in 103 MPa H_2 gas from constant-displacement tests (K_{THa}), open symbols, and crack initiation thresholds from rising-displacement tests (K_{THi}), filled symbols, plotted as a function of yield strength. The solid and dashed lines show general trends of Eqs. [3] and [7], respectively, as a function of $\varepsilon_f^H/\varepsilon_0$.

DOI: 10.1007/s11661-012-1400-5

In-situ vs. Ex-situ
Estático vs. Monotônico Crescente

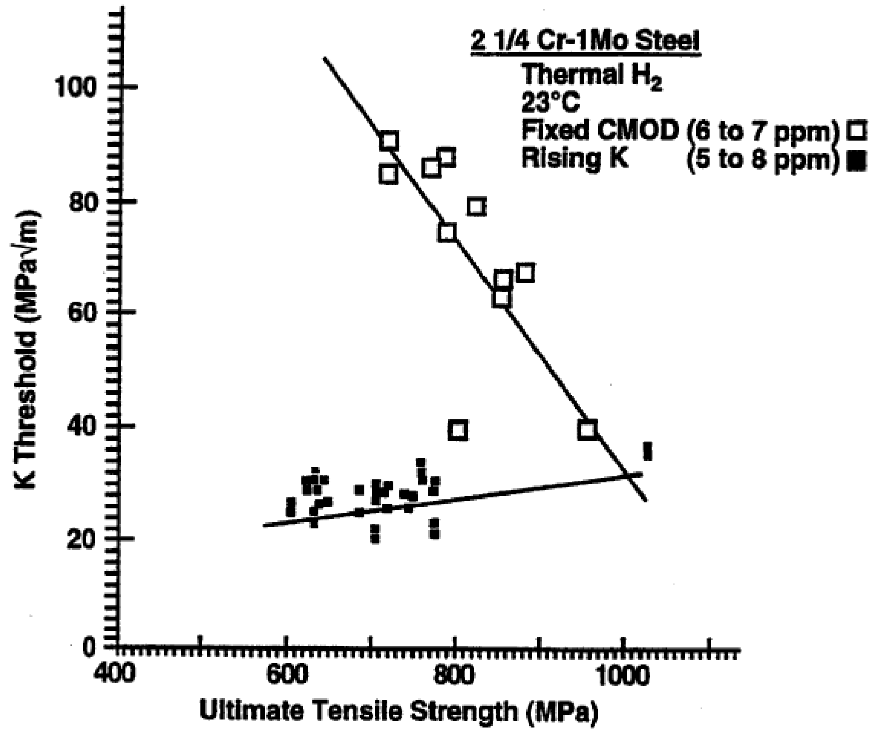


Figure 7 The effect of loading format, including fixed-CMOD yielding crack arrest under falling *K* (□) and rising-CMOD causing crack growth initiation under rising *K* (■), on IHAC of a tempered bainitic alloy steel containing a given constant amount of pre-charged H (source Gangloff, 1998).

FFS Standards (BS 7910 / API 579 / FITNET)

BS 7910:2019

10.3.3 Environmentallv assisted cracking

10.3.3.2 Stress corrosion cracking (SCC)

10.3.3.2.2 K_{ISCC} determination

NOTE

The fracture toughness at initiation of stable tearing can be defined using R-curve data obtained from tests performed using specific material-environmental combinations. However, **the use of tearing resistance curves for the assessment of ductile tearing in an aggressive environment is still the subject of ongoing research**.

Test Standards

ASTM F1624 - 12(2018)

ASTM INTERNATIONAL

Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique

ASTM F519 - 18

Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments

ASTM G129 - 00(2013)

Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking

ASTM E1681 - 03(2020)

Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials

NACE INTERNATIONAL

TM0177-2016-SG, Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H2S Environments

TM0198-2020, “Slow Strain Rate Test Method for Screening Corrosion-Resistant Alloys for Stress Corrosion Cracking in Sour Oilfield Service”

TM0316-2016-SG, “Four-Point Bend Testing of Materials for Oil and Gas Applications”

Inert Environment Fracture Toughness

ASTM E1820 - 20b
Standard Test Method for Measurement of Fracture Toughness

ISO 12135:2016
Unified method of test for the determination of quasistatic fracture toughness

ISO 15653:2018
Method of test for the determination of quasistatic fracture toughness of welds

ASTM E1921 - 20
Reference Temperature, To, for Ferritic Steels in the Transition Range

ISO

ISO/TR 20491:2019
Fasteners — Fundamentals of hydrogen embrittlement in steel fasteners

ISO 16573-1:2020
Steel — Measurement method for the evaluation of hydrogen embrittlement resistance of high strength steels — Part 1: Constant load test

ISO/DIS 16573-2
Steel — Measurement method for the evaluation of hydrogen embrittlement resistance of high strength steels — Part 2: Slow stain rate test

ISO 7539 consists of the following parts, under the general title *Corrosion of metals and alloys — Stress corrosion testing*:

- *Part 1: General guidance on testing procedures*
- *Part 2: Preparation and use of bent-beam specimens*
- *Part 3: Preparation and use of U-bend specimens*
- *Part 4: Preparation and use of uniaxially loaded tension specimens*
- *Part 5: Preparation and use of C-ring specimens*
- *Part 6: Preparation and use of pre-cracked specimens for tests under constant load or constant displacement*
- *Part 7: Method for slow strain rate testing*
- *Part 8: Preparation and use of specimens to evaluate weldments*
- *Part 9: Preparation and use of pre-cracked specimens for tests under rising load or rising displacement*
- *Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen assisted cracking*