Chapter 9 – ENVIRONMENTALLY ASSISTED CRACK GROWTH OF METALLIC ALLOYS

David W. Hoeppner
Professor and Director, Quality and Integrity Design Engineering Center (QIDEC)
Mechanical Engineering Department, University of Utah
Salt Lake City, Utah
USA

9.1 INTRODUCTION

Environmentally Assisted Cracking (EAC) of metal alloys is one of the most fascinating and challenging time dependent mechanisms of degradation that may lead to failure of aircraft components in use today. The cause of environmentally assisted cracking is related to corrosion mechanisms. This effect is one of the four major time dependent or time related failure mechanisms. The other three being fatigue, creep, and wear. When combinations of the failure mechanisms occur the challenge for engineers and scientists becomes vexing. Corrosion, when combined with fatigue, produces a phenomenon that is called corrosion fatigue. It is defined as when corrosion and fatigue occur **simultaneously**. Note it does not define the sequential occurrence when corrosion may occur prior to fatigue or vice versa. The objective of this chapter is to present the key issues involved in environmentally assisted cracking and its relationship to the integrity of aircraft components.

9.2 PHENOMENOLOGICAL ASPECTS OF EAC

Environmentally assisted cracking of metal alloys used in aircraft occurs under two major conditions, viz.:

1) Sustained loading; and
2) Cyclic loading (fatigue).

For many years the former has been referred to as stress corrosion cracking. There is an effort underway throughout the technical community to refer to these as follows:

1) Environmentally assisted cracking under sustained loading; and
2) Environmentally assisted cracking under cyclic loading.

9.2.1 EAC Under Sustained Loading

The science of corrosion is very extensive and it is well known that thermodynamics and kinetics control this most interesting electrochemical phenomenon. See Roberge [1],[2],[3] and Fontana and Green [4] for detailed information about corrosion. Figure 9-1 shows a typical manner in which data are presented for environmental effects of crack growth under sustained loading. The plot represents time to failure for a defined failure condition for all conditions at a given temperature. The plot has often been referred to as the stress corrosion cracking plot, but hydrogen embrittlement data may also be presented in this manner. In the fields of both polymers and ceramics, data plotted in this manner is often referred to as "static fatigue" data but this is not recommended. The asymptote that may develop at the lower right is referred to as the stress corrosion cracking threshold. It is very important to mention that the effects are very sensitive to both chemical composition and grain orientation in most aircraft alloys. Thus, materials characterization programs must include extensive evaluation to both uncracked and precracked specimens of the alloy under consideration. In addition, evaluations of manufacturing in relation to orientation effects also must be considered. For example, when machining all care must be taken not to expose short transverse grain boundaries or parting planes in either castings or forgings. It is imperative that chemical environment maps related to positions in aircraft be prepared. These will define the severity of the chemical environment and temperature related to the location in the aircraft. Some companies actually test materials in “severe” environments to attempt to assure a “conservative” approach. Some military agencies and companies have actually attempted to do environmental tracking with various types of environmental measuring devices. This is leading to much more precise definition of the actual environment at the location of interest.

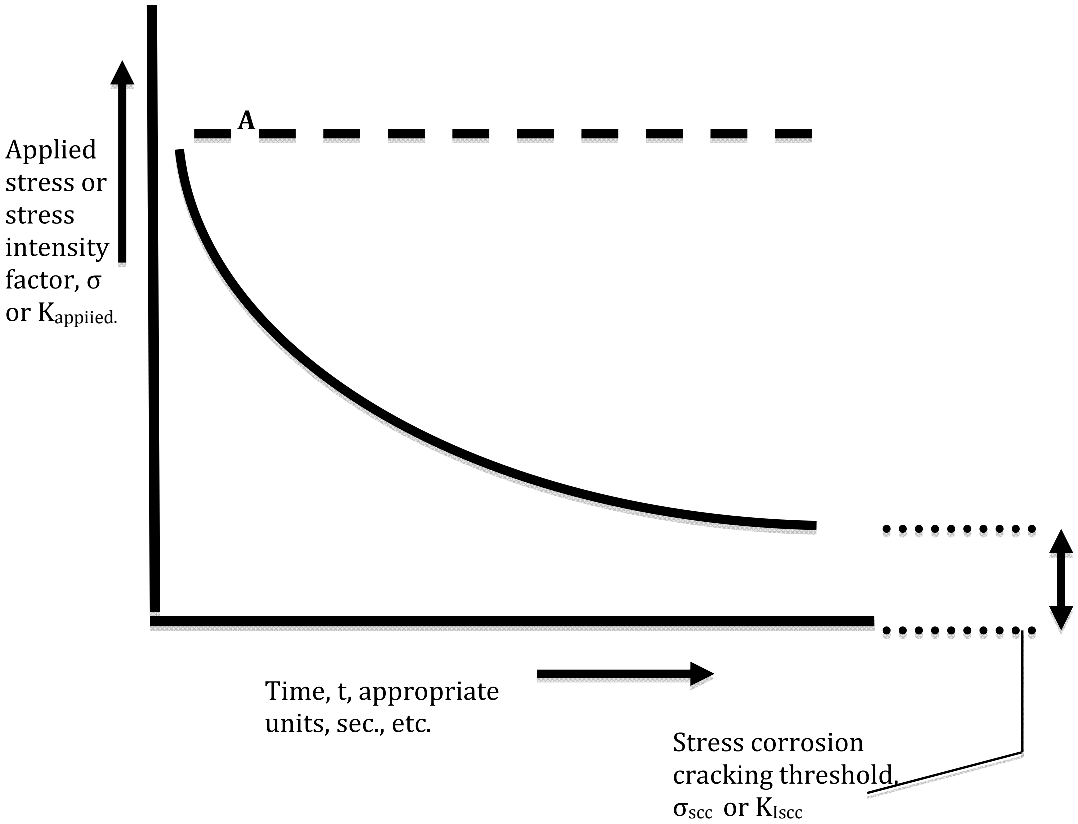

Figure 9-1: Plot of Applied Stress or Stress Intensity versus Time at Sustained Load in a Given Environment for a Given Material.

9.2.2 EAC Under Cyclic Loading

Fatigue has been studied since the early 1800 period and much of the activity has centered around mechanics applications of either stress or strain versus cycles or reversals to failure as depicted in Figure 9-2.

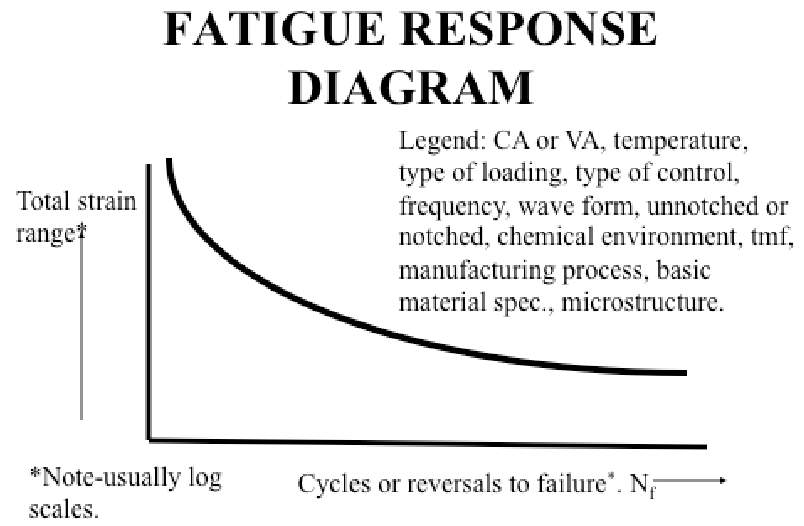

Figure 9-2: Basic Diagram for Presentation of Fatigue Response (see Hoeppner [5]).

ASTM defines corrosion fatigue in E1823 as follows:

> "Corrosion fatigue is the process by which fracture occurs prematurely under conditions of simultaneous corrosion and repeated cyclic loading at lower stress levels or fewer cycles than would be required in the absence of the corrosive environment." ASTM E1823 [6]. Note in the definition the application of corrosion and cyclic loading occurs simultaneously. Some recent studies reported in the literature actually do not apply to the process of corrosion fatigue in that they involve corrosion prior to the fatigue loading. The researchers who report this are evaluating what is often referred to as prior corrosion plus fatigue or corrosion + fatigue.

In 1972 Hoeppner [7] suggested the corrosion fatigue process needs to be evaluated in a systems framework such as shown in Figure 9-3. Later work suggested this might be referred to within a Holistic Structural Integrity Process Paradigm (HOLSIP – see www.holsip.com). The reason this is important for corrosion fatigue as well as other time dependent interactions of failure mechanisms is the complexity of the processes involved and the need to formulate methods of life estimation/prediction to establish structural integrity over the component life of interest. With corrosion this is particularly important due to the different types of corrosion that may occur on structures in the field and the insidious nature of the degradation. Furthermore, if the fatigue and corrosion fatigue processes are divided into four phases of nucleation, short crack propagation, long crack propagation, and final instability/failure as has been suggested by Hoeppner [8] then the types of corrosion important in nucleation can be different than those involved in propagation.

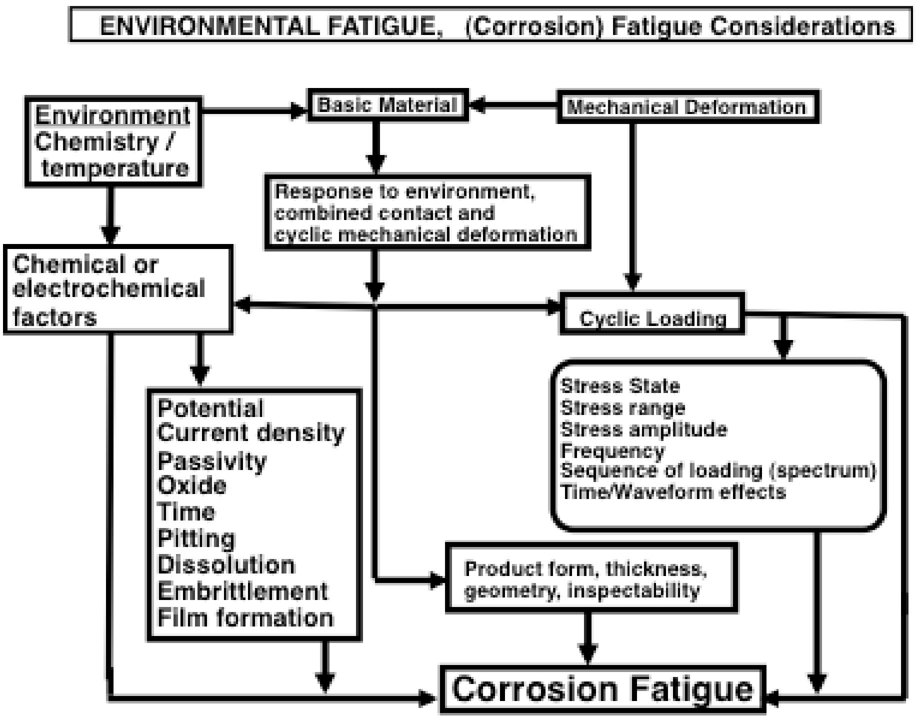

Figure 9-3: The Systems View of Corrosion Fatigue (see Hoeppner [5] and [7]).

9.2.3 Sources of Information

Corrosion fatigue studies were first reported by Haigh [9] in 1917 and followed by McAdam during 1926 – 1930 [10]-[13]. Gough and Sopwith [14]-[17] published extensively on the topic from 1932 – 1946. One of the first meetings devoted to environmental aspects of fatigue was the ASTM symposium entitled "the Effects of Complex Load Histories and Chemical Environments on Fatigue" [18]. In 1971 a major symposium sponsored by NACE was held on corrosion fatigue at the U. of Connecticut and the proceedings were published by NACE. The proceedings from that symposium contain many key papers on the work to that time [19]. Duquette provided an extensive review of corrosion in that volume [20]. In more recent years NACE has held another meeting on environmental effects and the proceedings of that symposium are noteworthy. In addition to the research work by Professor Pierre Roberge (e.g., Refs [1]-[3]) he also manages an important web site which is one of the most valuable resources on corrosion (www.corrosion-doctors.org).

9.3 THE HOLISTIC APPROACH TO EAC

The systems view, or more recently the HOLISTIC view, of corrosion fatigue [5],[7] can be viewed as shown in Figure 9-3. All of the basic elements of the fatigue systems view are included in this figure and the key issues of the chemical environment are added. It now becomes important for the engineer interested in designing a component to anticipate the chemical environments that the component will be exposed to along with the mechanical load/force spectra and these issues must be incorporated into the life estimation and all aspects related to it. In a manner similar to what the fatigue community has done to standardize load spectra for applications, and certainly as a minimum to define the force spectrum to the highest degree possible, so the chemical environmental spectrum must now be understood and defined as well. This is needed since the chemical environment composition, type of exposure, frequency of loading, and electrochemical parameters are all involved in determining the type of corrosion that will result and the resultant detailed mechanism of corrosion fatigue. To complicate matters some components will experience chemical exposure and loading where corrosion mechanism overlap will occur. In other words, pitting may be a dominant nucleation mechanism and a bona fide Mode I crack may form from the pit growth and become either an environmentally accelerated short crack or a long crack.

Although there are some laboratories in the world that control the chemical environment for “baseline” or reference fatigue data for a given set of test parameters this is rare to this writer’s knowledge. Most laboratories use the term “lab air” or some equivalent without defining what lab air means. In the fatigue test community and corrosion community this has been known to be inadequate since it has been known for many years that the chemistry of the lab air can significantly alter the quality and reliability of the resultant data. Some laboratories take great care to maintain control over the standard environment in which they obtain their baseline fatigue data.

Part of the justification for the above relates to the fact that little work has been done to either characterize the chemical environments encountered by most aircraft components or to adopt rational methods to deal with those environments in their sustained loading and fatigue design methods. This has been markedly improving in recent years. The manner in which most companies and government agencies have tried to deal with corrosion fatigue is to use a CPCP (Corrosion Prevention and Control Program). However, it is well known in the structural design community that this has serious shortcomings since the corrosion protection systems may break down and must be replaced or repaired. In addition, where corrosion is detected either by astute maintenance personnel or by failures or both the damage caused by corrosion or corrosion fatigue degradation must now be repaired or the component must be replaced. This is often referred to as the “find it and fix it approach”. Many engineers rely on the detection of corrosion as part of a poorly defined and directed maintenance and inspection program to assure the integrity of components from the ravages of corrosion fatigue. This is not an acceptable design practice and today the knowledge base on corrosion and corrosion fatigue is such that a design approach of “anticipate and manage”, similar to fatigue and damage tolerance, can and should be used. This is part of the HOLSIP approach.

9.4 IMPLICATIONS FOR AIRCRAFT STRUCTURAL INTEGRITY

Most fatigue design has been done assuming that materials used are homogeneous, continuous and isotropic media. This allows engineers to apply principles of solid mechanics and makes the challenges of design tractable using stress and strain and fracture mechanics techniques. In addition, surfaces are often assumed to be perfect or to be in an ideal state and the materials are assumed to be free of all types of corrosion. Corrosion is often thus classed as a defect or a flaw. As indicated, when corrosion is found on critical components it must either be removed or the component must be replaced, or we operate the component at much higher risk in terms of integrity. Many aspects of this idealized paradigm have been discussed by Hoeppner and others in many past and relatively recent papers [7].

In a large body of work culminating in a paper at a recent ICAF meeting (International Committee on Aeronautical Fatigue) Hoeppner pointed out that corrosion / corrosion fatigue may cause any or all of the following conditions to occur when components are operating in corrosion producing conditions:

1) Reduction of section size with a concomitant increase in stress. *Global or local*.
2) Production of stress concentration. *Local*.
3) Nucleation of cracks. *Local, possibly global. Source of multiple-site cracking*.
4) Production of corrosion debris. This may result in surface pillowing in some cases by various means, which may significantly change the stress state and structural behavior. *Local and global*.
5) Creation of a situation that causes the surfaces to malfunction. *Local and global*.

6) Cause Environmentally Assisted Crack Growth (EACG) under cyclic (Corrosion fatigue) or sustained loading (Stress Corrosion Cracking – SCC) conditions. *Local*.

7) Create a damage state that is missed in inspection when the inspection plan was not developed for corrosion or when corrosion is missed. *Local and global*.

8) Change the Structurally Significant Item (SSI) due to the creation of a damage state not envisioned in the structural damage analysis or fatigue and strength analysis. If the SSI is specified, for example, by location of maximum stress or strain, then the corrosion may cause another area(s) to become significant. *Local or global*.

9) Create an embrittlement condition in the material that subsequently affects behavior. *Local or global*.

10) Create a general aesthetic change from corrosion that creates maintenance to be done and does damage to the structure. *Local or global*.

11) Corrosion maintenance does not eliminate all the corrosion damage and cracking or the repair is specified improperly or executed improperly thus creating a damage state not accounted for in the design. *Local or global*.

12) Generation of a damage state that alters either the durability phase of life or the damage tolerant assessment of the structure or both.

13) Creation of a Widespread Corrosion Damage (WCD) state or a state of corrosion that impacts the occurrence of Widespread Fatigue Damage (WFD) and its concomitant effects. This has been observed in many applications from automobile frames to aircraft wings or fuselage segments, etc.

The types of corrosion vary widely and depending on which author you read and study it appears there are at least 8 and up to 14 types of corrosion. Thus, the thermodynamics vary widely and activation energies to nucleate a given mechanism have been found to vary with numerous input parameters. For this reason, in those cases where the attempts have been made to deal with the potential fatigue life reduction or fatigue allowable stress/strain reduction in a given environment the investigators often resort to response testing and produce results similar to those shown in Figure 9-4.

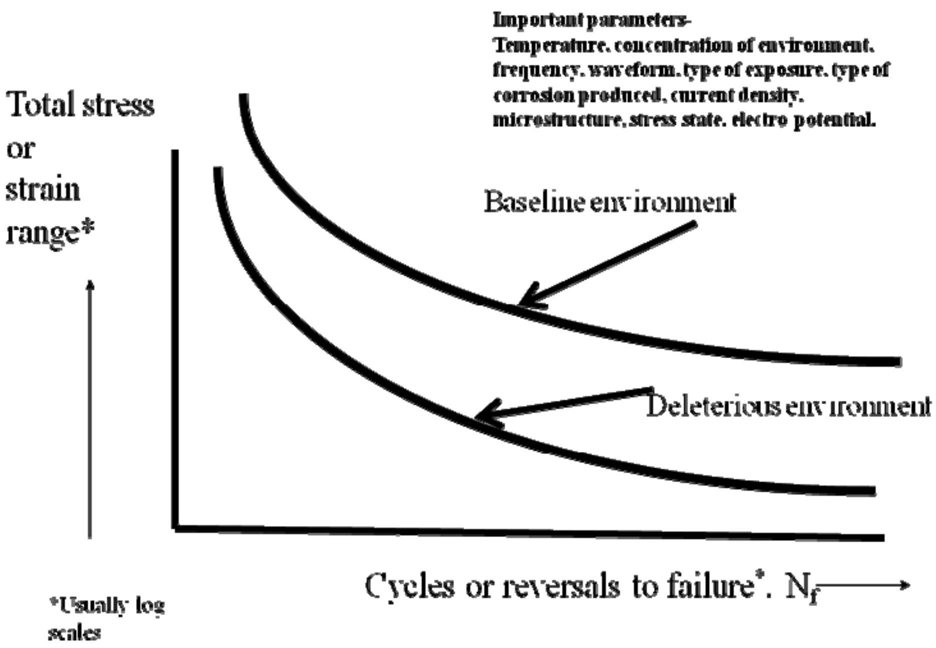

Figure 9-4: Similar to Figure 9-1 Except the Effect of a Deleterious Environment is Shown (see Hoeppner [7]).

The general effects first observed by Haigh, Gough et al., and McAdam and now many others [19]-[33] are as follows:

- The fatigue limit, if it truly existed in a baseline situation, is eliminated as depicted in Figure 9-4. The consequences of this are extremely significant if a component has been designed for "infinite life" since it now becomes a clearly finite life or limited life part.
- At a given stress or strain the expected life to failure is reduced.
- At a given life the stress or strain allowable is reduced.
- In the fatigue crack propagation realm the chemical environment accelerates fatigue crack propagation at a given stress intensity level.
- The fatigue crack propagation threshold is reduced and may not exist at all.
- Embrittlement occurs during crack nucleation and all phases of crack propagation. Thus, corrosion fatigue crack fracture surfaces take on a faceted appearance similar to Stress Corrosion Cracking (SCC). In many metallic alloys it is difficult if not impossible to determine a fractographic difference between environmentally assisted crack growth under cyclic loading and that which occurs under sustained static loading.
- The amount of scatter in data is potentially altered in various portions of the stress/strain versus cycles to failure diagram under corrosion fatigue conditions. The amount of the change has been noted to vary considerably but usually decreases.

Figure 9-5 shows the basic effect of a deleterious chemical environment on fatigue crack propagation. Extensive studies of the effect of environment and load spectra were undertaken in related to significant concern about aircraft structural integrity by Hoeppner et al. [32] and Hall et al. [22] on fatigue crack propagation in the early 1970 period. Many studies on the effect of chemical environments on fatigue crack propagation have been conducted since that time and data are now included in many handbooks.

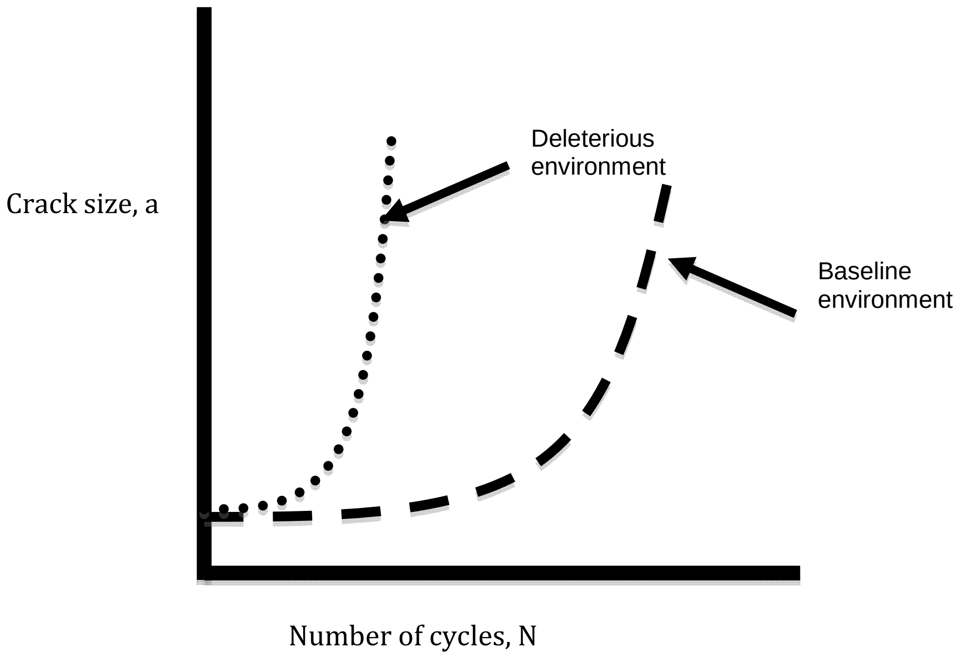

Figure 9-5: Diagram Depicting the Potential Effect of a Deleterious Chemical Environment on Fatigue Crack Propagation (the amount of the effect(s) is dependent on numerous parameters mentioned in Figure 9-4).

When fatigue crack propagation data such as shown in Figure 9-5 are evaluated using fracture mechanics concepts the data are usually plotted on a da/dN versus ΔK set of axes as shown in Figure 9-6 above.

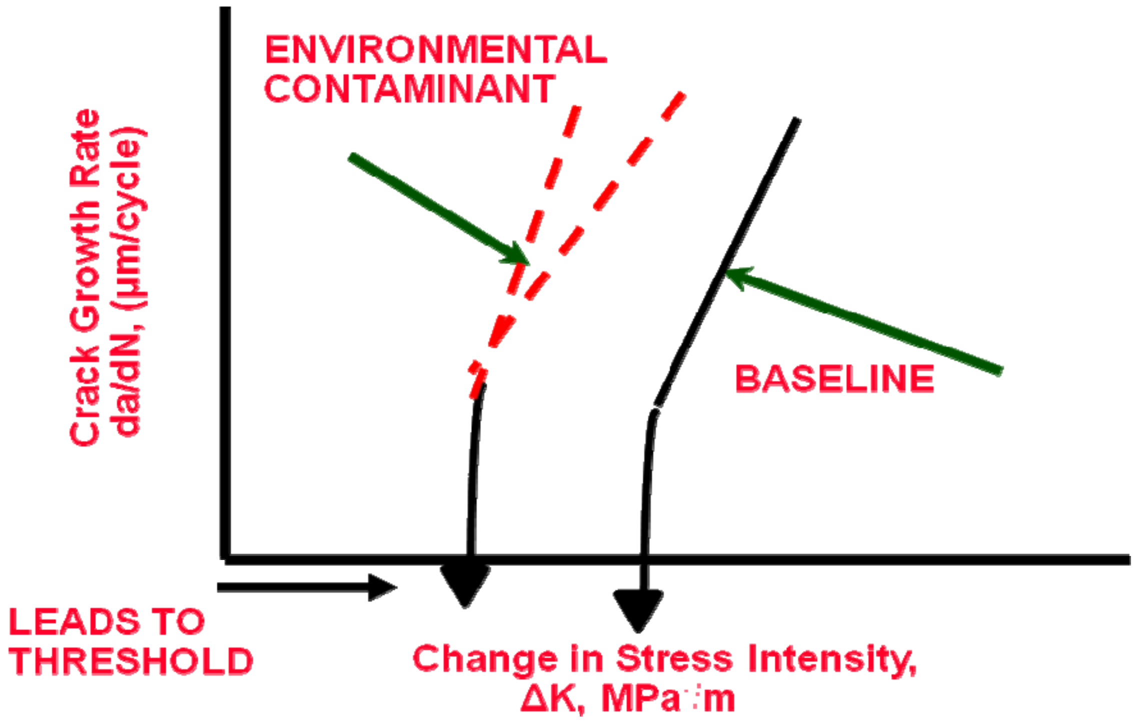

Figure 9-6: A Depiction of Fatigue Crack Propagation Data Plotted on da/dN versus ΔK Axes (Note the potentially significant effect of a chemical environment is shown in the left dashed line).

The figure shows the general trend when a chemical environment may influence the fatigue crack propagation behavior of a component in the field. The dashed red lines on the upper left of the figure indicate potential lines/bands of data from the environmental effects. In addition to the potential effects shown, the fatigue crack growth threshold also may be modified by the environment and generally lowered. Furthermore, significant effects of the environment have been observed on short crack propagation rates. This is very significant when attempting to assess the role of short cracks in Multiple Site Damage (MSD) and the potential for crack link up and the effects on structural integrity. It is clear from an observation of Figure 9-6 that a major impact from the acceleration of fatigue crack propagation may occur and alter the time or cycles between inspection intervals of components and thereby significantly alter the integrity assessment. Many ways have been proposed for assessing the potential impact of the environmental effects. Chapter 13 discusses more aspects of this.

In recent years the aviation industry has devoted much attention to introducing design and integrity practices into aircraft structural integrity programs. This is in part related to recognition of the significance of the problems of corrosion and corrosion fatigue as they relate to integrity after the Aloha Airlines Accident in 1988. The commercial and military aircraft fleet surveys subsequent to the event led to an understanding that these two degradation modes were much more serious than originally envisaged. Thus, all the structural integrity programs are being modified to deal with corrosion and corrosion fatigue along with fatigue, damage tolerance and residual strength issues.

The need to understand the potential for the occurrence of corrosion and corrosion fatigue on structural components is critical. Thus, to even begin the assessment of this potential the technical community needs to know the following:

- The chemical environment likely to be encountered on the structure of interest at the location of interest;
- The material from which the component is manufactured;
- The orientation of the critical forces (loads) applied externally and internally with respect to the critical directions in the material;
- The susceptibility of the material to occurrence of a given type of corrosion;
- The temperature of exposure of the component;
- The type of forces applied (i.e., sustained force {SCC} or cyclic force (constant force amplitude or variable force amplitude corrosion fatigue);
- The type of exposure to the chemical environment (i.e., constant, intermittent, concomitant with the forces (corrosion fatigue or stress corrosion cracking) or sequentially with force (corrosion/ fatigue or corrosion-fatigue);
- The rates of corrosive attack;
- The potential influence of the effects of corrosion on fatigue crack nucleation and propagation;
- The impact of any related corrosion degradation on residual strength;
- The type(s) of corrosion encountered;
- The means of inspecting for corrosion at the locations of interest;
- Models to assist and guide the estimation of lives and lives between inspection and maintenance intervals where corrosion fatigue will be a major failure consideration;
- The potential for Widespread Corrosion Damage (WCD) to occur; and
- The potential impact of corrosion on the occurrence of Widespread Fatigue Damage (WFD) and its impact on structural integrity.

9.5 CONCLUDING REMARKS

Based on today's understanding of both corrosion and corrosion fatigue the technical community can effectively deal with these issues in a component integrity and reliability program. Some companies and government agencies are deeply immersed in this at present.

Obviously the above list is formidable but the assessment of these items is possible to some degree to make the estimation or prediction of the effects of corrosion more accurate than they have been to date. To assist in making Prevention and Control and Prediction and Management of corrosion fatigue more realistic in the future engineers will have to be educated with respect to the phenomenon. In addition more models will need to be developed. The issue of modeling has not been addressed extensively in this chapter but other papers by Hoeppner, Bellinger, Mills, Liao et al. and others (see Chapters 13, 14, 17, 18 and 19 of this document for more detailed descriptions of modeling and quantitative treatment of environmental effects on fatigue crack propagation) have focused on this issue.

At present few U.S. or Canadian Universities **require** a basic undergraduate class in corrosion and related electrochemistry principles for most undergraduate engineering students. Most engineers get a two to three day exposure in their basic material science class that is often the only requirement beyond inorganic chemistry dealing with either corrosion or wear. Of course chemical engineers tend to study more chemistry but many also do not study either electrochemistry or corrosion as a basic requirement. Various technical bodies have attempted to rectify this situation but to date have been unsuccessful. A part of the education must deal with the issues that impact structural integrity to enhance quality and reliability of components critical to many areas of industry and government. To this end there is no doubt that engineers will have to learn much more about the physics of failure including as many aspects of corrosion and fatigue as possible. This, of course, must be coupled with the study of tribology and creep as well.

Corrosion fatigue is one of the major considerations now recognized as a major failure prevention issue on products. With energy issues becoming more and more important relative to the survival of the planet the issue of corrosion fatigue, along with other failure mechanisms, will become even more critical to the future integrity of products. The last 100 years or so have produced great strides in both understanding and designing for the anticipation and management of corrosion fatigue. The next 100 years will undoubtedly produce many more advances.

9.6 REFERENCES

[1] Roberge, P.R., "Handbook of Corrosion Engineering", McGraw Hill Book Co., New York, NY, USA, 1999.

[2] Roberge, P.R., "Corrosion Engineering: Principles and Practice", McGraw Hill Book Co., New York, NY, USA, 2008.

[3] Roberge, P.R., "Corrosion Inspection and Monitoring", Wiley-Interscience, John Wiley and Sons, Hoboken, NJ, USA, 2007.

[4] Fontana, M.G. and Greene, N.D., "Corrosion Engineering", McGraw Hill Book Co., New York, NY, USA, 1967, 1978, 1986.

[5] Hoeppner, D.W., "Cyclic Loading and Fatigue", Tribology Encyclopedia, in press, 2010.

[6] ATSM E 1823, Part 3, ASTM Standards, ASTM, New Conshohocken, PA, USA, Issued Yearly by ASTM.

[7] Hoeppner, D.W., "Corrosion Fatigue Considerations in Materials Selection and Engineering Design", Lead Paper, Corrosion Fatigue: Chemistry, Mechanics, and Microstructure, Editors; Devereux, O., McEvily, A.J., Staehle, R.W., Proceedings of the Conference held at the University of Connecticut, 14-18 June 1971, NACE-2, National Association of Corrosion Engineers, Houston, TX, USA, pp. 3-11, 1973.

[8] Hoeppner, D.W., "Estimation of Component Life by Application of Fatigue Crack Growth Knowledge", Fatigue, Creep of Pressure Vessels for Elevated Temperature Service, MPC 17, ASME, NY, USA, pp. 1-85, 1981.

[9] Haigh, B.P., "Experiments on the Fatigue of Brasses", Journal of the Institute of Metals, Vol. 18, pp. 55-86, 1917.

[10] McAdam, Jr., D.J., "Stress-Strain-Cycle Relationship and Corrosion-Fatigue of Metals", Proceedings of the ASTM, Vol. 26 (II), pp. 224-280, 1926.

[11] McAdam, Jr., D.J., "Corrosion-Fatigue of Non-Ferrous Metals", Proceedings of the ASTM, Vol. 27, No. 2, pp. 102-152, 1927.

[12] McAdam, Jr., D., "Stress-Strain-Cycle Relationship and Corrosion Fatigue of Metals", Proceedings of the ASTM, Vol. 26, No. 2, pp. 224-280, 1926.

[13] McAdam, Jr., D.J., "Corrosion Fatigue of Metals Under Cyclic Stress", Proceedings of the ASTM, Vol. 29, No. 2, pp. 250-313, 1929.

[14] Gough, H.J. and Sopwith, D.G., “Atmosphere Action as a Factor in Fatigue of Metals”, Institute of Metals Journal, Vol. 49, pp. 93-122, 1932.

[15] Gough, H.J. and Sopwith, D.G., “Some Further Experiments on Atmospheric Action in Fatigue”, Journal of the Institute of Metals, Vol. 56, pp. 55-89, 1935.

[16] Gough, H.J. and Sopwith, D.G., “Inert Environments as Fatigue Environments”, Journal of the Institute of Metals, Vol. 72, pp. 415-421, 1946.

[17] Gough, H.J. and Sopwith, D.G., “Some Further Experiments on Atmospheric Action in Fatigue”, Journal of the Institute of Metals, Vol. 56, pp. 55-89, 1935.

[18] “Effects of Environment and Complex Load History on Fatigue Life”, ASTM STP 462, Proceedings of the Symposium on Effects of Environment and Complex Load History on Fatigue Life held in Atlanta, GA, 29 September – 4 October, 1968, Edited by M. Rosenfeld, D.W. Hoeppner, and R.I. Stephens, ASTM, Philadelphia, PA, USA, 1970.

[19] “Corrosion Fatigue: Chemistry, Mechanics, and Microstructure”, Editors:, Devereux, O., McEvily, A.J., Staehle, R.W., Proceedings of the Conference held at the University of Connecticut, 14-18 June 1971, NACE-2, National Association of Corrosion Engineers, Houston, TX, USA, 1972.

[20] Duquette, D.J., “A Review of Aqueous Corrosion Fatigue”, in Corrosion Fatigue: Chemistry, Mechanics, and Microstructure, O.F. Devereux, A.J. McEvily and R.W. Staehle, Eds., NACE-2, pp. 12-24, 1972.

[21] Pettit, D., Ryder, J., Krupp, W. and Hoeppner, D., “Investigation of the Effects of Stress and Chemical Environments on the Prediction of Fracture in Aircraft Structural Materials”, AFML-TR-74-183, Lockheed California Company, December 1974.

[22] Hall, L.R., Finger, R.W. and Spurr, W.F., “Corrosion Fatigue Crack Growth in Aircraft Structural Materials”, AFML-TR-73-204, Boeing Company, September 1973.

[23] “Corrosion-Fatigue Technology”, ASTM STP 642, Proceedings of a Symposium held in Denver, CO, 14-19 November 1976, Edited by H.L. Craig, Jr., T.W. Crooker, and D.W. Hoeppner, ASTM, Philadelphia, PA, USA, 1978.

[24] “Aircraft Corrosion”, AGARD Conference Proceedings No. 315, Papers presented at the 52nd Meeting of the AGARD Structures and Materials Panel held in Cesme, Turkey, 5-10 April 1981, NATO-AGARD, 64 rue De Varenne, Paris, France, 1981.

[25] “Corrosion Fatigue”, AGARD Conference Proceedings No. 316, Papers presented at the 52nd Meeting of the AGARD Structures and Materials Panel Meeting held in Cesme, Turkey, 5-10 April 1981, NATO-AGARD, 64 rue De Varenne, Paris, France, 1981.

[26] “Corrosion Fatigue”, ASTM STP 801, Proceedings of the Symposium on Corrosion Fatigue: Mechanics, Metallurgy, Electrochemistry, and Engineering held in St. Louis, MO, 21-22 October 1981, Edited by T.W. Crooker, B.N. Leis, ASTM, Philadelphia, PA, USA, 1983.

[27] Campbell, G.S. and Lahey, R., Int. J. Fatigue, Vol. 6, No. 1, pp. 25-30, 1984.

[28] Metals Handbook, 9th Ed., Vol. 13, Corrosion, American Society for Metals, Metals Park, OH, USA, pp. 584-609, 1985.

[29] Wallace, W., Hoeppner, D.W. and Kandachar, P.V., "Aircraft Corrosion: Causes and Case Histories", AGARD Corrosion Handbook, Vol. 1, AGARD-AG-278-Vol. 1, 1985.

[30] Schütz, W., "Corrosion Fatigue-The Forgotten Factor in Assessing Durability", ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, Vol. 1, Edited by J.M. Grandage, G.S. Jost, Proceedings of the 18th Symposium on the International Committee on Aeronautical Fatigue, 3-5 May 1995, Melbourne, Victoria, Australia, EMAS, Warley, West Midlands, UK, pp. 1-52, 1995.

[31] Swift, S.J., "The Aero Commander Chronicle", ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, Vol. 1, Edited by J.M. Grandage, G.S. Jost, Proceedings of the 18th Symposium on the International Committee of Aeronautical Fatigue, 3-5 May 1995, Melbourne, Victoria, Australia, EMAS, Warley, West Midlands, UK, pp. 507-530, 1995.

[32] Hoeppner, D.W., Grimes, L., Hoeppner, A., Ledesma, J., Mills, T. and Shah, A., "Corrosion and Fretting as Critical Aviation Safety Issues", ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, Vol. 1, Edited by J.M. Grandage, G.S. Jost, Proceedings of the 18th Symposium on the International Committee of Aeronautical Fatigue, 3-5 May 1995, Melbourne, Victoria, Australia, EMAS, Warley, West Midlands, UK, pp. 87-106, 1995.

[33] Cole, G.K., Clark, G. and Sharp, P.K., "Implications of Corrosion with Respect to Aircraft Structural Integrity", DSTO –RR-0102, AMRL, Melbourne, Victoria, Australia, March 1997.

of Metal-Forming Processes Application and Characterisation of Hybrid Halide Perovskites Application of Atom Probe Tomography in Metallic Materials Application of Numerical Simulation in Welding Applications of CFD on Metallic Materials Arc-based Additive Manufacturing Arc-Sprayed Metallic Coatings Assessment of Multifunctional Nanostructured Coatings/Metal Interfaces in Extreme Environments Atomistic Modelling and Simulation of Structural and Phase Stability in Metals and Alloys Bainite. and Martensite Transformation in Steel Bainite and Martensite: Developments and Challenges Bearing Steels Environmental assisted cracking of metals is an important topic related to many industries in lives. Although the problem with this type of corrosion has been known for many years, the debate on the effects and possible remedies available under different environmental conditions is ongoing and topical.Â Quantification of the effects of crack tip plasticity on environmentally-assisted crack growth rates in LWR environments (T. Shoji, Z. Lu, H. Xue, K. Yoshimoto, M. Itow, J. Kuniya and K. Watanabe). The role of hydrogen and creep in intergranular stress corrosion cracking of Alloy 600 and Alloy 690 in PWR primary water environments - a review (F.H. Hua and R.B. Rebak).