

# **Environmentally Assisted Cracking:**

**PREDICTIVE METHODS FOR  
RISK ASSESSMENT AND  
EVALUATION OF MATERIALS,  
EQUIPMENT, AND STRUCTURES**

**RUSSELL D. KANE, EDITOR**

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***Environmentally Assisted Cracking:  
Predictive Methods for Risk  
Assessment and Evaluation of  
Materials, Equipment, and  
Structures***

*Russell D. Kane, editor*

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# Foreword

This publication, *Environmentally Assisted Cracking: Predictive Methods for Risk Assessment and Evaluation of Materials, Equipment, and Structures*, contains papers presented at the symposium of the same name held in Orlando, Florida, on 13–15 November 2000. ASTM Committee G01 on Corrosion of Metals and the G01.06 subcommittee on Environmentally Assisted Cracking in cooperation with NACE International, The Materials Properties Council (MPC), Inc., The Materials Technology Institute of the Chemical Process Industries (CPI), European Structural Integrity Society (ESIS), and The Electric Power Research Institute (EPRI) sponsored the symposium. The symposium chairman was Russell D. Kane, *InterCorr* International, Inc.

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# Overview

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For over 40 years ASTM Committee G01 on Corrosion of Metals has been a leading resource on the influence of corrosion on metals and engineering alloys. In keeping with this tradition, its subcommittee G01.06 on Environmentally Assisted Cracking-(EAC) sponsored a major international symposium entitled “**Environmentally Assisted Cracking: Predictive Methods for Risk Assessment and Evaluation of Materials, Equipment, and Structures**” held November 13–15, 2000 in Orlando, Florida. This symposium was a major technical event with participation from major industrial corporations and research, government and academic organizations from around the world. Organizations co-sponsoring the symposium included:

- NACE International
- The Materials Properties Council, Inc.
- The Materials Technology Institute of the Chemical Process Industries
- European Structural Integrity Society
- The Electric Power Research Institute

Several of these co-sponsor organizations assisted by organizing featured sessions, which focused on specific topics of interest.

## Background

In recent years, there has been an increased interest in prevention of stress corrosion cracking failures based on assessment of materials compatibility and prediction of operational risk. This has resulted in:

- Improved mechanistic understandings of EAC (i.e. stress corrosion cracking, hydrogen embrittlement cracking, liquid metal embrittlement, corrosion fatigue).
- Development of better predictive models for crack initiation and growth and analytical methods for assessment of the impact of corrosion induced damage on structural integrity.
- Generation of material data bases under simulated service conditions to identify and assess critical parameters
- Development of new methods for electrochemical monitoring and interpretation of data.
- Enhanced non-destructive inspection capabilities with increased reliability for detection of AEC-induced damage

The goal of this international symposium was to address two important areas of EAC investigation:

1. recent developments in the generation of relevant materials properties data based on laboratory tests, and
2. methodologies for evaluation and assessment of environmental assisted cracking in equipment and structures exposed to corrosive environments.

The symposium also was developed with the aim of highlighting a broad range of industrial and civil applications including marine, aerospace, chemical, petroleum, electric power, consumer prod-

## X ENVIRONMENTALLY ASSISTED CRACKING

ucts, and public infrastructure. Additionally, it provided a global forum through which a sharing of state-of-the-art ideas and concepts could be transformed into cost-effective solutions. The papers in the symposium included topics related to:

- Uses of electrochemical, surface analysis, slow strain rate, and fracture mechanics techniques.
- Correlation between laboratory and in-service cracking resistance
- State-of the art developments in fitness-for-service and risk assessment methodologies
- Monitoring of equipment and structure for environmentally assisted cracking

The theme for the symposium was developed to be of high interest to those involved in materials engineering, corrosion science, as well as many specialists involved in maintaining and monitoring the ongoing reliability of plant equipment, structures, and end-user products. One of the greatest features of the technical program was the combined focus on both theoretical and applied topics in the same forum. A specific effort was made to make sure that the keynote and plenary program included the foremost scientists in corrosion and material science. Their mission was to present the forefront of modern day thinking as it relates to mechanistic and predictive models for understanding EAC and materials performance. These presentations were followed by those from academics, researchers, and industrial practitioners illustrating new and more quantitative methodologies for the assessment of materials, equipment, and structures. This publication will serve as a fine reference for specialists and general practitioners alike that want to utilize the most current methodologies for prediction and assessment of materials performance and system reliability with respect to damage caused by EAC.

### **Keynote and Plenary Session**

The symposium was started with an extensive keynote and plenary program entitled “**EAC Models—Theory to Practice**” that ran most of the first day of the symposium. The theme of the symposium was illustrated in the first presentation by Prof. Robert Wei entitled, “Material Aging and Reliability of Engineered Systems.” His paper focused on a supreme challenge faced by both researchers and engineers when addressing “real” systems. These challenges include the addressing of the changing properties of materials as the materials age in service, and the even more demanding aspects of assessing system integrity in the face of these changing properties and changing usage. Following the keynote presentation, A. Turnbull, J. Scully, P. Sofronis and R. Gangloff reviewed the state-of-the-art methodologies for dealing with hydrogen transport, strain rate and crack morphology in current day EAC models. The plenary program was completed with presentations by R. Staehle and D. Macdonald. These presentations address a major industrial challenge: Implementation of these models on a broad scale for management of practical industrial problems that have very large economic consequences. Examples are given for electric power systems, which can also be extended to many other plant and field scenarios, as well.

### **Featured Co-Sponsor Session Papers**

Three featured sessions were organized by symposium co-sponsors. These included sessions by the Electric Power Research Institute (EPRI), NACE International and European Structural Integrity Society (ESIS). These papers primarily address practical industry problems associated with EAC and the use of fitness-for-purpose and risk-based inspection (RBI) methodologies to better manage plant assets for long term service.

- **EPRI Session—Prediction of IASCC Performance in Reactor Cooling Water Systems.** Three papers were included in this session. Kaji et al. discussed a 14 year data analysis effort including information on irradiation assisted stress corrosion cracking (IASCC). This study assessed the role of alloy composition, dissolved oxygen in the cooling water, and neutron flux as major variable in IASCC performance of stainless steels. Scott et al. also focused on IASCC but through a statistical analysis of plant observations of baffle/former bolts in French reactors. The data served as the basis for decision making concerning inspection frequency, possible replacement of cracked bolts and selection of alternative alloys. Yonezawa et al. emphasized the understanding of alloying and segregation in the prediction of IASCC performance. Alternative materials were investigated with controlled alloying and metallurgical processing to enhance IASCC resistance.
- **NACE Session—Understanding and Predicting EAC Performance in Industrial Applications.** Four papers were included in this session. Sridhar et al. focused on predicting stress corrosion cracking (SCC) performance of gas transmission lines and included information on SCC occurring in both alkaline and near-neutral conditions. The use of thermodynamic models to relate SCC tendencies and water composition in crevices was examined. Jones addressed the basis of laboratory testing to assess field SCC performance and identifies some of the present day limitations in merely conducting routine SCC tests, and the need for lab-field correlations to assist in predicting service performance. Pan et al. examined the role of chlorides in hot aqueous solutions and the relationship between SCC and the pitting potential in AISI 316L stainless steels. Rebak presented a summary of SCC performance in chemical process environments containing chloride and HF based on laboratory testing and failure analysis.
- **ESIS Session—EAC Testing and In-Service Experiences.** Two papers were presented in this session. Koers et al. related experiences in petroleum applications using fitness-for-purpose methodologies and the requirements for fracture data involving the influence of hydrogen and loading rate on pressure vessel steels. Dietzel describes an intensive effort to standardize rising load/rising displacement fracture tests using precracked specimens. This technique has great potential for accelerated testing.

### **Research Session: Mechanistic Studies for Understanding and Control of EAC**

Following the featured co-sponsor sessions, a session containing the results of somewhat more fundamental studies was held. These investigations utilized new analysis techniques and approaches to reveal various aspects of EAC in engineering alloys. Seven papers were presented. Toribio and Kharin examined the role of cyclic preloading on hydrogen assisted cracking of carbon steel. de Curiere et al. also relates the effects of cyclic pre-straining through corrosion/ plasticity interactions at the crack tip, but this time involving SCC of stainless steel. Numerical modeling of localized stresses and hydrogen diffusion was used show that residual stress distributions as affected by preloading cycles influenced hydrogen accumulation at fractures sites. Brongers et al. described a method for in-situ atomic force microscopy study for use in locating initiation sites for EAC. Chou et al. used Raman spectroscopy to investigate surface films on stainless steels in acidic and chloride-containing media, and their relationship to EAC susceptibility. Ellis et al. proposed a more systematic nomenclature (taxonomy) to reduce confusion when referring to the various forms of EAC. Lee et al. described a study of near threshold fatigue crack growth in an aluminum alloy in air, vacuum and a NaCl solution. Raicheff and Maldonado used SEM, X-ray and Mossbauer analysis techniques to examine the surface films and their relationship to SCC of steel in phosphate solution. Modeling was used to establish crack propagation rates and conditions favorable for SCC.

### **Industrial Session: Engineering Applications for New Experimental and Analytical Methods**

A total of four papers were presented which look at a wide range of practical plant and field problems and approaches used to assess the extent of the problem and prescribe solutions. Dean et al. utilized a cyclic slow strain rate technique for laboratory simulation of an EAC situation in a hot steam hydrocarbon reformer. Data was developed that assisted in the evaluation of conditions particularly conducive to in-service cracking, and for evaluation of alternative materials of construction. Toribio and Ovejero examined the EAC of cold drawing steel used in prestressed concrete structures. Resistance to cracking in  $\text{Ca}(\text{OH})_2$  solution increased with the amount of cold drawing based on time to failure alone; however, based on fracture load, an optimum (intermediate) amount of drawing was observed. Andersen described premature EAC failures in copper alloy valves in a major city water supply system, and efforts to simulate the failures in the laboratory. Alternative materials were identified through laboratory testing which yielded greater resistance to EAC and increased system reliability. Zheng et al. focused on external SCC in pipeline steels in near neutral pH solutions. Laboratory tests were used to examine the role of mean stress and cyclic stress on susceptibility to cracking. Full-scale pipe tests also showed the beneficial effect of hydrostatic pressure and resultant compressive residual stress on resistance to cracking.

### **Acknowledgements**

As symposium chairman, I hope that this STP benefits both researchers and engineers, alike. The authors of the papers contained herein have worked diligently, and in some cases, dedicated their careers to advancing corrosion science, solving important and challenging problems, increasing the reliability of operating equipment, and minimizing economy losses and loss of life resulting from EAC failures. I would like to thank them for their contributions to this volume and personally acknowledge their personal and professional efforts in this regard. Additionally, I wish to gratefully thank the ASTM staff that has worked so hard to make this publication a reality.

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