CONF-960647--7

LA-UR-96-172

Title:

RISK ASSESSMENT AND LIFE PREDICTION OF
COMPLEX ENGINEERING SYSTEMS

RECEIVED

MAR 13 1996

OSTI

Author(s):

Michael D. Garcia, ESA-EA
Ravi Varma, MST-6
A. Sharif Heger, University of New Mexico

Submitted to:

International Conference on Probabilistic
Safety and Management, PSAM-III,
June 24-28, 1996, Crete, Greece

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Form No. 836 RS
ST 2629 10/91

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

NOTICE

Page(s) size did not permit electronic reproduction. Information may be purchased by the general public from the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161 (Area Code 703-487-4650). DOE and DOE contractors may purchase information by contacting DOE's Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831, Attn: Information Services (Area Code 423-576-8401).

Risk Assessment and Life Prediction of Complex Engineering Systems

Michael D. Garcia and Ravi Varma
Los Alamos National Laboratory
Los Alamos, New Mexico, U.S.A.

A. Sharif Heger
The University of New Mexico
Department of Chemical and Nuclear Engineering
Albuquerque, New Mexico, U.S.A.

Abstract

Many complex engineering systems will exceed their design life expectancy within the next 10 to 15 years. It is also expected that these systems must be maintained and operated beyond their design life. This paper presents a integrated approach for managing the risks associated with aging effects and predicting the residual-life expectancy these systems. The approach unifies risk assessment, enhanced surveillance and testing, and robust computational models to assess the risk, predict age, and develop a life-extension management procedure. It also relies on the state of the art in life-extension and risk assessment methods from the nuclear power industry. Borrowing from the developments in decision analysis, this approach should systematically identify the options available for managing the existing aging systems beyond their intended design life.

1 Introduction

This paper establishes specific technical issues and challenges to assess a complex system in terms of aging effects, life prediction, prediction of failure modes, and providing cost-effective retrofits for aging, complex engineering systems. In this paper we define complex in terms of the basic requirement to integrate the risk assessment to a fundamental understanding of the engineering materials used in the system as they deteriorate with age, material synergistic effects and compatibility issues, and the evaluation of the resulting change in total system reliability. Risk assessment involves identifying and characterizing most common materials failure modes of aging, in-service components. For example, corrosion with or without stresses may lead to "fracture" which constitute major materials failure modes. Radiation damage in materials (e.g., beryllium, polymers) that results in swelling and decreased tensile strength becomes prone to mechanical fracture. Hydriding of zirconium alloys, for example, will degrade the mechanical strength of the element, and this may lead to fracture.

Life prediction of aging, complex engineering systems will involve the development of robust computational models that utilize, a real-time experimental data base. While a physical foundation is essential to achieve generality and some measure of confidence in extrapolations, phenomenological constraints is equally crucial for achieving reliability and predictive value in descriptions of macroscopic behavior, despite the enormous complexity of underlying physics. There are lessons to be learned from the research programs [1, 2, 3] on structural aging and aging of nuclear power plants. Much of this work can provide a basis and relevant objectives for developing an integrated plan for life-prediction of aging complex systems. Other aging research programs such as those related to conventional weapons and aircraft must be researched for relevance.

In this approach, it is also critical that existing system surveillance units (if they exist) provide information and data to support computational model development and predict anticipated failure modes. For example, we need to detect and measure the initiation of material degradation which may involve corrosion, the progression stage which may involve microcracks developing during corrosion particularly in presence of stress, and the ultimate materials failure involving mechanical fracture of the metal/alloy specimen. Certainly measurement tools are needed; some of which may be readily available while others may have to be developed for the particular application. Additionally, surveillance must be enhanced to recover a refined set of data and information that directly supports the computational models, such as obtaining time-dependent material properties. Where there is no data, we must rely on accelerated-aging testing to simulate the aging process and extrapolate our models.

Of particular interest is the development of robust computational models to predict failures or sequences of failures (coupled failures) that have not been observed in existing surveillance or shelf life units, due to synergistic effects or existing units that are not old enough to have initiated or detectable failures. Common-mode failures are of particular interest since they may affect a significant number of common systems.

The four critical competency development areas are :

- 1) Probabilistic risk assessment (PRA) and reliability,
- 2) Enhanced surveillance - destructive and nondestructive evaluation (NDE),
- 3) Constitutive model development and aged material properties, and
- 4) Deterministic computational code modeling.

2 Critical Capabilities and Associated Technical Issues

2.1 Probabilistic Risk Assessment (PRA) and Reliability

It is important to organize and systematically evaluate system operation and system reliability. With PRA system models, failures can be analyzed in terms of how they might be initiated, how failures progress, how they might be mitigated, and how human actions might affect their progression. Failure modes for each complex system will differ because each system has different common materials (for example, different types of explosives, different special materials, different types of foams, etc.), different ages, different fabrication techniques, and different assembly procedures. Each complex system also has a unique set of mission environments that it must endure. The same components in the system also have different reliabilities due to statistical differences in the manner in which they are machined, formed, welded, etc. and they have different material properties. In view of these differences, it is appropriate to perform failure modes and effects analyses (FMEA) that identify the unique set of potential failure modes for each system.

Generally, failures are defined as an incident or condition and sequence of events that causes the complex system to operate unsafely, unreliably, and not cost-effectively. Failure modes that may be considered are fracture, stress corrosion, pitting, cracking, radiation induced embrittlement, radiation damage, hydriding, wear, etc. or a combination of any these failure modes. Scientific data accumulated from a comprehensive aging research program together with careful documentation of surveillance experience make this tool more effective as a practical tool for managing and assuring system safety and reliability, for example, in weighting the relative merits of inspection, surveillance, testing, and maintenance as measures to assure acceptable reliability. This can be accomplished with the general PRA framework.

2.2 Enhanced Surveillance - Destructive and Nondestructive Evaluation (NDE) Assessment

Current techniques in support of model development includes metallography, tensile tests, radiography, photography, physical inspection, surface characterization, weight testing, gas testing, chemistry, and acoustic resonance. In general, however, the emphasis associated with these tests was to ensure conformance to manufacturing specifications. The requirements from the aging and life prediction standpoint is to define an enhanced and robust set of surveillance techniques and corresponding data that directly supports the development of accurate failure and aging computational models.

2.2.1 Residual-Stress Measurements

A complementary area for model development is the characterization of residual stresses induced into as-built components resulting from welding, high-temperature forming, machining, or fabrication. Redistribution of these stresses in as-built configurations will occur due to cracking, volume expansion due to radioactive decay daughter-product production, or by other means. Residual

stresses can be measured using various methods, including X-ray, and strain gauge techniques. The enhancement of old techniques or the development of new techniques such as using neutron diffraction techniques should be explored and developed. Furthermore, improved fabrication techniques should be explored to relieve stresses (stress-improvement techniques) such as induction heating and mechanical techniques, especially since potentially different fabrication techniques may be implemented in the future.

2.2.2 Crack Detection Measurements

In general, conventional NDE methods fail to detect incipient damage which can lead to crack initiation, followed by failure. It is also unlikely these methods will determine the nature or location of these cracks or damage within the component or system. Several improved NDE techniques have been recently developed for estimating life consumption. These include strain monitoring techniques, microstructural techniques, hardness-based techniques, and ultrasonic testing. Acoustic Emission (AE) are result of stress waves in stressed materials due to microstructural events leading to cracks. An important feature of AE is that it is non-destructive and non-intrusive and that with suitable sensors, the entire device or component can be evaluated for flaw or cracks in one measurement session. Because of known stress-strain relationships, accurate measurement of residual stress levels in a structure can be made by measuring strain using highly sensitive resistance strain gauges. Fiber optic, heterodyne, dual probe interferometer for laser ultrasonic crack detection has been refined to an extent such as that flaws or crack depth of 100 micron sizes may now be measured.

2.3 Constitutive Model Development and Aged Material Properties

The purpose of this area is the development of constitutive material models for aging system materials. The development of this aged-material data base is a basic requirement for the development of robust, computational models. This will require the measurement of critical material properties as a function of time. The data base will be used to assist in the prediction of long-term deterioration of critical system components. The bulk macroscopic mechanical properties of interest are typically derived from stress-strain measurements such as the elastic modulus, yield stress, hardness, creep strength, and ultimate stress.

The difficulty associated with development and measurement of the degraded or aged material properties is the fact that it is difficult, if not impossible, to simulate the natural-aging processes that occur within nuclear materials. For example, it is well-known that radiation damage to organic materials may depend not only on the absorbed dose but also on the irradiation time and dose rate. Furthermore the presence of external gas species such as oxygen that may present for diffusion into the organics may strongly influence the amount of permanent damage to the

material. Other limitations are the fact that naturally-aged materials are not available for the ages of interest, such as ages greater than 20-years. Additionally, most of the data on relevant reactor material properties are at high dose-rates and high temperatures, that typically occur in nuclear reactors. Virtually all existing information on the aging effects of temperature and radiation on the properties of organic materials comes from artificial-age conditions.

2.4 Deterministic Computational Code Modeling

In general, the computational models (e.g. finite element models) must be developed in conjunction with the aged-material data base and constitutive models for predicting the residual-life of complex systems. Furthermore, the models must be verified against accurate experimental data or extrapolations that are theoretically sound. With aging systems there is greater emphasis on predicting the type of damage or state-of-stress that may develop in a system as it ages and the initial state of stress as it is delivered for operation. For example, these computational models will be used to simulate residual stresses present in the components due to welding or fabrication and then modeling and superimposing the mission environments. This level of damage or initial state-of-stress (such as residual stresses, cracking, corrosion, etc.) then serves as initial conditions for subsequent mission environment calculations and the assessment of how the system performs. These initial conditions vary depending upon the age of the system and system type.

Accurate computational modeling of welding must model the weld cooling rate, temperature gradient of the weld pool, turbulence, multiphase flow, surface tension flow, transient heat transfer, weld solidification microstructure, convection of nuclei and grains, and evaporation. Of particular interest is the requirement for stress-strain relationships that are a function of microstructure. Existing models also ignore high-temperature strain-rate dependence and creep. Refinement of the existing models are required to better understand the welding process and how it affects the residual-life of system components.

In some cases existing flaws or microcracks on a component or part (e.g., aircraft wing panels) under applied load or residual stress may suddenly and rapidly propagate. Crack-growth-rate characteristics for components are important in predicting residual-life of system components. Cracks of less than a critical-size will likely increase in size during mission environments. The key issues here are will these cracks be initiated, how they propagate if initiated, what are critical sizes, how fast these cracks grow in size in mission environments, and do the cracks affect system operation. The key concept of the model is the coupling between the internal and the external environments involving all the variables that have been observed to have a significant role in crack growth.

Corrosion is characterized by spatially separate anodic and cathodic areas and is accompanied by a flow of electric current for perceptible distances through the metal surfaces. The localized corrosion modes, namely pitting, crevice corrosion, and stress corrosion is more destructive than general corrosion (e.g., corrosion of a steel coupon in sea water, $\sim .13$ mm per year). Pitting corrosion is usually attended by the breakdown of passivating film on the metal surfaces. Such areas are adjacent to weld zones in a metallic structure. The use of empirical and deterministic models for calculating crack growth rates and for predicting damage functions for pitting corrosion in stainless steel-403 has been demonstrated to be very successful in their applications to nuclear power reactor plants, particularly for the heat transport circuits. For the first time the extent of surface damage by localized corrosion can be predicted.

3 Conclusion

This paper has established the framework, issues, limitations, tools, and competencies required to assess an aging, complex, engineering system in terms life prediction and assessment. It addresses the importance of :

- integrating the information derived from surveillance units with the system assessment or establishing an enhanced surveillance management program,
- integrating fundamental information on material behavior to the risk assessment,
- improving measurement techniques on surveillance systems and integrating this information, such as aged-material properties, to the deterministic computational models,
- performing refined calculations of the mission environments that incorporate defects, welding or fabrication residual stress effects, or aged-material properties, and

References

1. Morris, and Vora, Nuclear Plant Aging Research (NPAR) Program Plan, NUREG-1144 (Rev. 1), Division of Engineering Technology, Office of the Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC, July 1985
2. Edited by Sinnappan, Meligi, Narayanan, Bond, Power Plant Systems/Components Aging Management and Life Extension, 1991, PVP-Vol. 208, ISBN 0-7918-0802-5
3. Edited by Shah, Macdonald, Aging and Life Extension of Major Light Water Reactor Components, 1993, ISBN 0-444-89448-9