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Guide for Reliability Analysis Using the Physics-of-Failure Process

RATIONALE

To provide a guide to engineers involved in implementing a physics-of-failure approach for improving reliability.

This guidebook was developed under The Technical Cooperation Program (TTCP) Joint Systems and Analysis Group – 1 Action Area 2 – Physics-of-Failure

INTRODUCTION

The Physics-of-Failure (PoF) is a science-based approach to reliability that uses modeling and simulation to design-in reliability. This approach models the root causes of failures such as fatigue, fracture, wear, and corrosion. Computer-Aided Design (CAD) tools have been developed to address various loads, stresses, failure mechanisms and sites. PoF uses knowledge of basic failure processes to prevent failures through robust design and manufacturing practices, and aims to:

- Design-in reliability up front;
- Eliminate failures prior to testing;
- Increase fielded reliability;
- Promote rapid, cost effective deployment of Health and Usage Monitoring Systems (HUMS);
- Improve diagnostic and prognostic techniques and processes; and,
- Decrease operational and support costs.

This guide provides an overview, methodology and process to performing a PoF assessment.

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1. SCOPE

The Physics-of-Failure (PoF) is a science-based approach to reliability that uses modeling and simulation to design-in reliability. This approach models the root causes of failures such as fatigue, fracture, wear, and corrosion. Computer-Aided Design (CAD) tools have been developed to address various loads, stresses, failure mechanisms and sites. PoF uses knowledge of basic failure processes to prevent failures through robust design and manufacturing practices, and aims to:

- Design-in reliability up front;
- Eliminate failures prior to testing;
- Increase fielded reliability;
- Promote rapid, cost effective deployment of Health and Usage Monitoring Systems (HUMS);
- Improve diagnostic and prognostic techniques and processes; and,
- Decrease operational and support costs.

This guide provides a high level overview of the methodology, process and advantages to performing a PoF assessment.

2. REFERENCES

- [1] University of Maryland's Center for Advanced Life Cycle Engineering, <http://www.calce.umd.edu>, (2008)
- [2] IEEE Guide for Selecting and Using Reliability Predictions Based on IEEE 1413, IEEE Std. 1413.1, New York, 2003
- [3] Ministry of Defence Standard 00-40, Management Responsibilities and Requirements for Programmes and Plans, June 2003
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- [7] Dstl, Model of Integrated Logistics Operations, Hoehl L, April 2003
- [8] M. Pecht and A. Dasgupta, "Physics-of-Failure: An Approach to Reliable Product Development," *Journal of the Institute of Environmental Sciences*, Vol. 38, pp. 30-34, September/October 1995
- [9] M. Osterman and T. Stadterman, "Failure Assessment Software for Circuit Card Assemblies," Proceedings of the Annual Reliability and Maintainability Symposium, pp. 269-276, January 18-21, 1999

3. DRIVING FORCE AND MOTIVATION

The driving forces for this guidebook and associated national research programs are to improve the design, development and manufacturing practices to create robust products and facilitate a growth environment for HUMS and prognostic technology. These will return many benefits by:

- Increasing "design-in" reliability and eliminating failures prior to testing;
- Reducing maintenance costs by minimizing requirements for time directed maintenance as well as improve maintenance planning and logistics support;

- Reducing logistics footprint by decreased sparing and transportation requirements;
- Improving operational flexibility by accurate usage monitoring that will enable operators to make tactical, mission specific decisions with full knowledge of the remaining useful life of vital equipment.

The effort in this PoF study has been targeted at electronic circuit card analysis and mechanical land systems, such as trailers. However, the techniques and processes employed in this study, are applicable to the broader range of systems, including electronics systems, structural components and systems and weapons systems.

4. PoF PROCESS OVERVIEW

The PoF approach is founded on the fact that failure mechanisms are governed by fundamental mechanical, electrical, thermal, and chemical processes. By understanding the possible failure mechanisms, potential problems in new and existing technologies can be identified and solved before they occur.

A top level model of the PoF approach [8] is shown in Figure 1. A designer defines the product requirements, based on the customer's needs and the supplier's capabilities. These requirements can include the product's functional, physical, testability, maintainability, safety, and serviceability characteristics. At the same time, the service environment is identified, first broadly as aerospace, automotive, business office, storage, or the like, and then more specifically as a series of defined temperature, humidity, vibration, shock, or other conditions. The conditions are either measured, or specified by the customer. From this information, the designer can model the thermal, mechanical, electrical, and electrochemical stresses acting on the product.

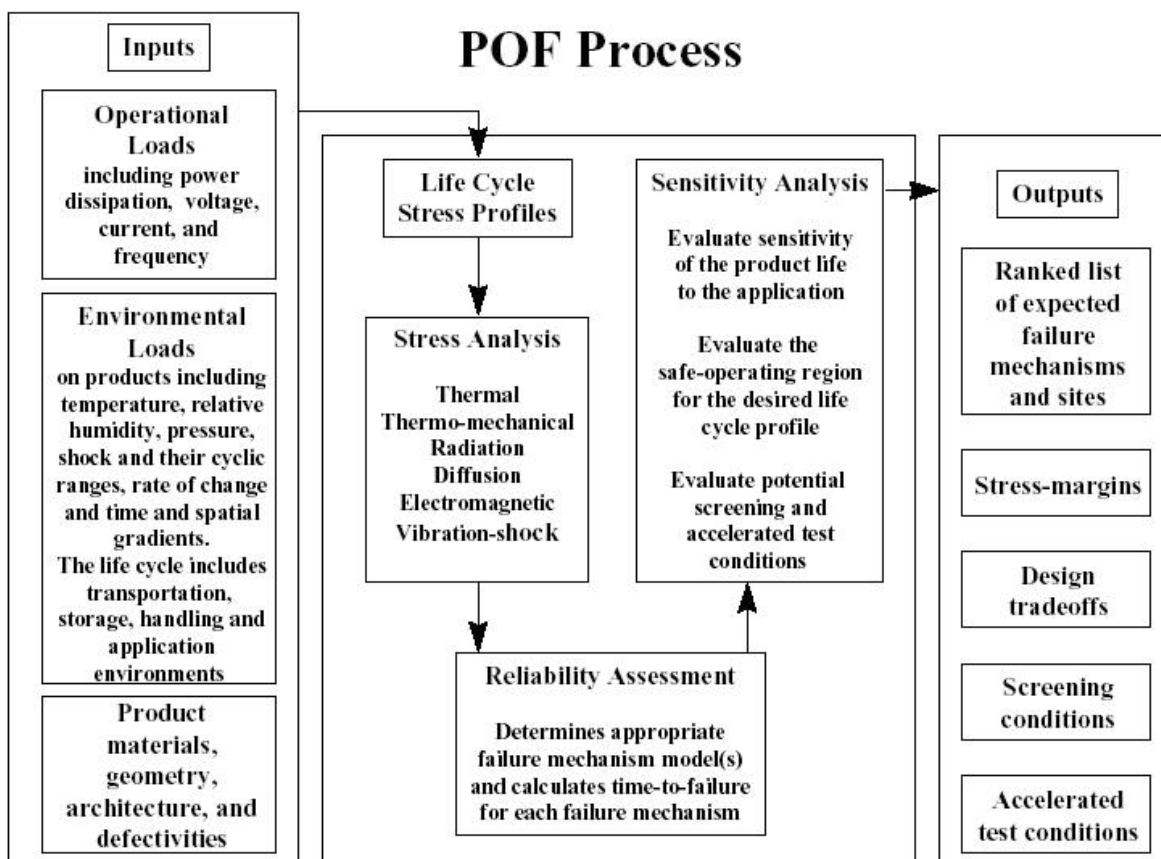


FIGURE 1 - A TOP LEVEL ILLUSTRATION OF THE PHYSICS OF FAILURE PROCESS (ADOPTED FROM [8])

Next, stress analysis is combined with knowledge about the stress response of the chosen materials and structures to identify where failure might occur (failure sites), what form it might take (failure modes), and how it might take place (failure mechanisms). Failure is generally caused by one of the four following types of stresses: mechanical, electrical, thermal, or chemical, and it generally results either from the application of a single overstress, or by the accumulation of damage over time from lower level stresses. Once the potential failure mechanisms have been identified, the specific failure mechanism model is employed.

The reliability assessment consists of calculating the time to failure for each potential failure mechanism, and then, using the principle that a chain is only as strong as its weakest link, choosing the dominant failure sites and mechanisms as those resulting in the least time to failure. The information from this assessment can be used to determine whether a product will survive for its intended application life, or it can be used to redesign a product for increased robustness against the dominant failure mechanisms. The PoF approach is also used to qualify design and manufacturing processes to ensure that the nominal design and manufacturing specifications meet or exceed reliability targets. Many examples of application of this methodology can be found at [1].

Appendix A of this guide gives a detailed description of how to perform an analysis along with the different levels of an analysis that can be performed.

4.1 Advantages of PoF

The use of the PoF process can lead to improvements in system reliability and availability, thereby substantially reducing operation and support cost. By improving reliability early in the design process, the reliability growth testing (i.e., test-fix-test cycle) can be greatly reduced and by identifying the key areas for reliability problems, testing can be focused into these areas.

4.1.1 Improvements in Reliability

One of the greatest benefits of PoF is the information provided concerning reliability throughout the expected life cycle of a system. This insight provides the ability to predict the reliability of the design before the system is built and to assess the reliability of commercial components. The bottom line is that by using the PoF process, an increase in system reliability is to be expected due to the understanding generated in the process. In this process, information is generated that aids in general understanding and system weaknesses are identified so that problem areas can be flagged and addressed directly.

A PoF analysis also provides a basis for performing environmental stress management. Stress management solutions can be evaluated in terms of their effectiveness in reducing damaging loads and increasing useful life. For example, the response of a circuit card assembly to various levels of vibration could be used to determine the amount of damping required to adequately protect that assembly.

In order to achieve the greatest positive impact on reliability, the PoF analysis should be performed in early design (the concept phase), then updated during detailed design and testing. It has been estimated that up to a 40% reduction in cost and weight can be achieved if reliability analysis is integrated into the design phase. Benefits of a PoF analysis include the following [9]:

- Identification of design flaws;
- Identification of weak or problem parts;
- Identification of destruction limits;
- Identification of wear-out limits; and,
- Estimation of failure free operating periods.

4.1.2 PoF Benefits to Testing

The enhanced understanding of the basic causes of failure, and failure mechanisms from a PoF assessment can be used by design engineers to reduce and focus reliability testing. For example, accelerated life tests which are conducted at higher than expected operating stress levels (in order to reduce the length of a test) can benefit from a PoF analysis by determining test conditions and how best to affix the sub-system or component as so to excite only the relevant failures. PoF can then be used to map the outcome of accelerated test conditions to actual use conditions. In addition, PoF can be used to identify failures that occur only as a result of the accelerated test conditions, as opposed to actual use conditions.

PoF is also key to electronic screening. Screens are used to remove items that fail earlier than expected due to manufacturing defects. Screening involves examining the items during or after manufacture to find types, locations, and severity of defects or flaws associated with the manufacturing process. Screens can be carried out by inspection alone or in conjunction with stress-based screening methods. To apply a stress screen, it is necessary to know what failures result from defects in the item and how the application of external loads can precipitate failure of flawed item. A manufacturing flaw may be represented by an inappropriate geometry and/or a changed material property. A PoF analysis is necessary to determine if a stress-based screen is viable.

4.1.3 Application to HUMS and Prognostic

PoF is central for applying stress-history based life consumption monitoring (LCM) or a prognostic capability. Early warning of impending failures becomes possible when usage monitoring systems combine with PoF (which provides the stress-life relationship) to create the LCM / prognostic potential. By understanding the type, location, and severity of failures in the product, stresses / loads may be monitored and remaining life estimated, in real time. In an alternative approach, devices such as calibrated fuses can be developed based on expected failures. Under field loading conditions, these devices would be designed to fail before the expected component or subsystem failure, thus becoming an integral part of an early warning system.

4.2 Potential Users of Guide

The PoF approach has been successfully used for many years in the design of buildings, bridges and generally one-off or small batch size engineering structures, where the product is expected to work first time.

However, the PoF approach is now being demanded by other industries. It is demanded by suppliers to measure how well they are doing and to determine what kind of reliability assurances they can give to a customer and by customers to determine that the suppliers know what they are doing and that they are likely to deliver what is desired. In addition, PoF is used by both groups to assess and minimize risks.

5. RELEVANT STANDARDS

The goal of this program is not to create new standards and definitions but to interface with existing commercial and military classifications and benchmarks. The practice of interfacing with existing standards ensures that the analysis of a system using PoF is a more efficient process. Hardware reliability, Land HUMS capability and Reliability and Maintainability are a few of the areas where standards could be utilized.

5.1 Electronic Equipment

There are several common reliability prediction standards and guides that have generally followed on from the US military MIL-HDBK-217, which is now by and large considered obsolete. Reliability prediction alternative approaches such as similarity analysis, stress and damage analysis, and the use of field and test data are now becoming common features of modern standards.

The Institute of Electrical and Electronics Engineers (IEEE) has issued Standard 1413.1 [2] as a guide which reviews the various reliability prediction methods such as MIL-HDBK-217-F, RAC's PRISM, and SAE's Reliability Prediction Method (for a full list see Appendix A.6). Progenies of these standards like FIDES, RIAC's 217-Plus also get similar assessment as the ones evaluated.