

The Systems Engineering Relationship between Qualification, Environmental Stress Screening and Reliability

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ABSTRACT

The Systems Engineering Relationship between Qualification, Environmental Stress Screening (ESS), and Reliability is often poorly understood: as a consequence resources are expended on efforts that degrade inherent hardware reliability and vitiate reliability predictions. This article expatiates on the Systems Engineering relationship between Qualification and ESS, and how their proper application enhances inherent reliability and supports credible reliability predictions. Examples of how their uninformed application degrades inherent hardware reliability and vitiates reliability predictions, and how program/equipment managers can avoid this, are presented.

INTRODUCTION

There is a problem with the reliability of recently fielded systems: Department of Defense (DoD) concerns have been widely reported.

Emerging data shows that a significant number of U.S. Army systems are failing to demonstrate established reliability requirements during operational testing and many of these are falling well short of their established requirement. . . . Enclosure 1 outlines the process for establishing and reporting the new reliability threshold, as well as a mechanism for detecting and reporting threshold breaches. The routine use of this process and the implementation of reliability best practices (Enclosure 2) will help the Army achieve its reliability requirements.¹

Ensure programs are formulated to execute a viable systems engineering strategy from the beginning, including a RAM growth program, as an integral part of design and development.²

I share your concerns regarding the recent downward trend of reliability, availability, and maintainability (RAM) test results, and agree with your assessment that RAM considerations must be strengthened as our weapons systems move through the development and production phases and into operational service.³

This is not, as discussed below, a commercial-off-the-shelf (COTS) vs. "custom or military specification design" issue: the focus of the above references is on Program Management and System Engineering processes and best practices.

This focus on processes and practices is a positive development; however it is essential that we get the "content" right. Two areas where there seems to be widespread failure to do so are the definition of durability environments, and the application of ESS: showing why this is so requires some review of fatigue engineering principles, the "bathtub curve," and the limitations of our reliability prediction methods.

FATIGUE ENGINEERING PRINCIPLES

Materials will fatigue^{4, 5, 6, 7} under the repeated application of stresses and strains that do not cause failure on the first application: imagine bending a paper clip back and forth. For "engineering materials" the stress level (SL) vs. cycles to failure typically plots as a straight line on a "log-log" scale: this is a power law

relationship (see ARP 5890⁸, Equation B-9). The “stress level” may be expressed as pounds per square inch, as strain (inch per inch), power spectral density (PSD) for random vibration, or as the magnitude of a temperature cycle, etc. The “cycles to failure” may be expressed as cycles or as time (assuming a consistent cyclic rate).

There is scatter in the data. The time or cycles to failure for a number of “identical” samples tested at the same stress level will form a Gaussian distribution. This scatter is due to the variety of defects in each sample: as a consequence larger samples, with a greater probability of containing a more severe defect, will fail sooner.

We use *Miner’s Rule*⁹ to determine fatigue damage accumulation and a Composite Damage Index (CDI) for items subjected to combinations of different stress levels.

CDI = the sum of n_x/N_x

n_x = number of applied stress cycles at stress level “x”

N_x = number of cycles to failure at stress level

“x”

Failure is expected to occur when the CDI is approximately equal to one.

THE BATHTUB CURVE

The bathtub curve¹⁰, describing failure rate as a function of time, is described in a number of sources and shown in Figure 1. This bathtub curve can be used to describe a range of phenomena including human death rates as a function of age, and electronic failure rates as a function of time.

The “Infant Mortality” portion of the curve is the initial section for which the failure (death) rate decreases with time (age). For military electronics this higher initial failure rate is purported to be due to latent manufacturing defects. Environmental Stress Screening (ESS), comprising random vibration and temperature cycling, is used to precipitate these defects as failures so that they can be repaired to produce items without “infant mortality defects.”

The “Constant Failure Rate” portion of the curve is the section after Infant Mortality defects have been eliminated, but before Wearout has begun to occur. Failures are “random.” This is the period for which Constant Failure Rate statistical prediction techniques (MIL-HDBK-217¹¹, VITA 51.1¹², etc.) have some validity.

The “Wearout” portion of the curve is the last section and has a Gaussian distribution that goes to zero when the last item in a set starting “population” has failed. Failures in this portion of the curve are due to fatigue, and follow the Gaussian distribution that was previously discussed for fatigue phenomena. Durability⁸ verification (analysis and/or test) during item Qualification, as shown

in Topic 2.2 “Bathtub Curve”¹⁰, is commonly used to demonstrate that wearout will not occur during the planned life of the item.

*Typically, reliability analysis is aimed at assessing the random failures that will occur in the equipment during its useful life. These failures are usually assumed to be repairable, and may be due to a variety of causes, such as defects in the equipment, improper use, damage due to unusual conditions, inadequate maintenance, etc. Durability analysis, on the other hand, assesses failures due to wearout of certain elements of the design.*⁸

LIMITATIONS OF THE RELIABILITY PREDICTION PROCESS

MIL-HDBK-217 (as do most similar analysis techniques) relies on a number of assumptions, two of which are germane here: 1) infant mortality failures have been eliminated by good process control, or screened out by an effective ESS program that consumes a relatively small tranche of “demonstrated life,” and 2) the period of performance, after ESS, is within the “demonstrated life” of the item, so that “wearout” failures will not occur: these analysis techniques “typically do not model wearout mechanisms”¹³.

Selection of the appropriate MIL-HDBK-217 “PiE-factor” will not remotely compensate for the failure to adequately specify durability environments. The “PiE-factor” ratios assume, as does everything in the MIL-HDBK-217 methodology, that durability has been demonstrated and that the item is in the “constant failure rate” portion of the bathtub curve: they do not account for limited life due to “wearout.”

DURABILITY ENVIRONMENTS

The salient contributors to equipment durability environments are vibration (high cycle fatigue) and temperature (low cycle fatigue). The deleterious effects of these environments are widely understood, and have been thoroughly investigated in a number of venues.

*AVIP also broadens the tools and focus of electronic packaging design to address the life cycle issues through fatigue analysis*¹⁴

*Complexities include 1) Surface Mount Technology, . . . Thermal cycling fatigue life of electronics was improved through 1) Coefficient of thermal expansion (CTE) matching, 2) Omega and other strain relieving lead wire designs for large devices, 3) Plated Thru hole improvements . . . The F-22 program’s typical durability life test requires from 500 to 1500 thermal cycles on one unit. . . . The design analysis included consideration of the damaging effects on electronics from thermal fatigue.*¹⁵

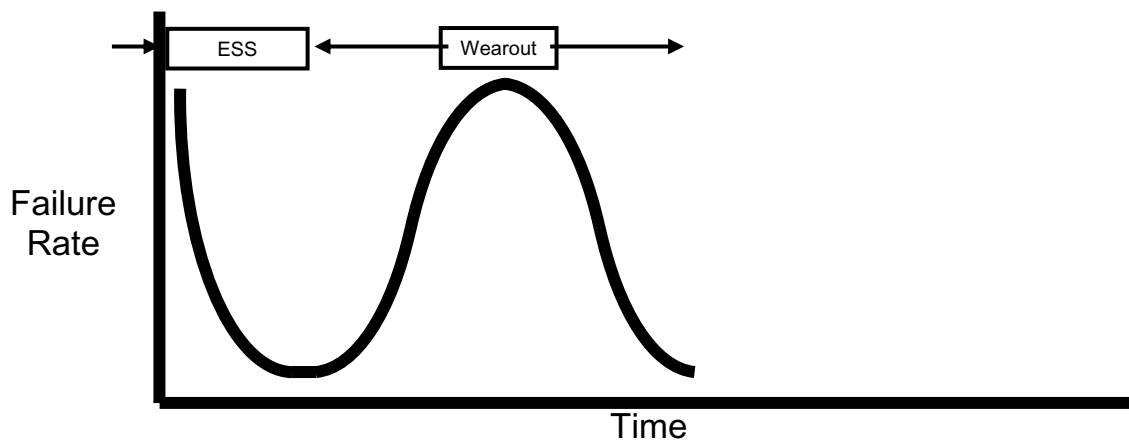
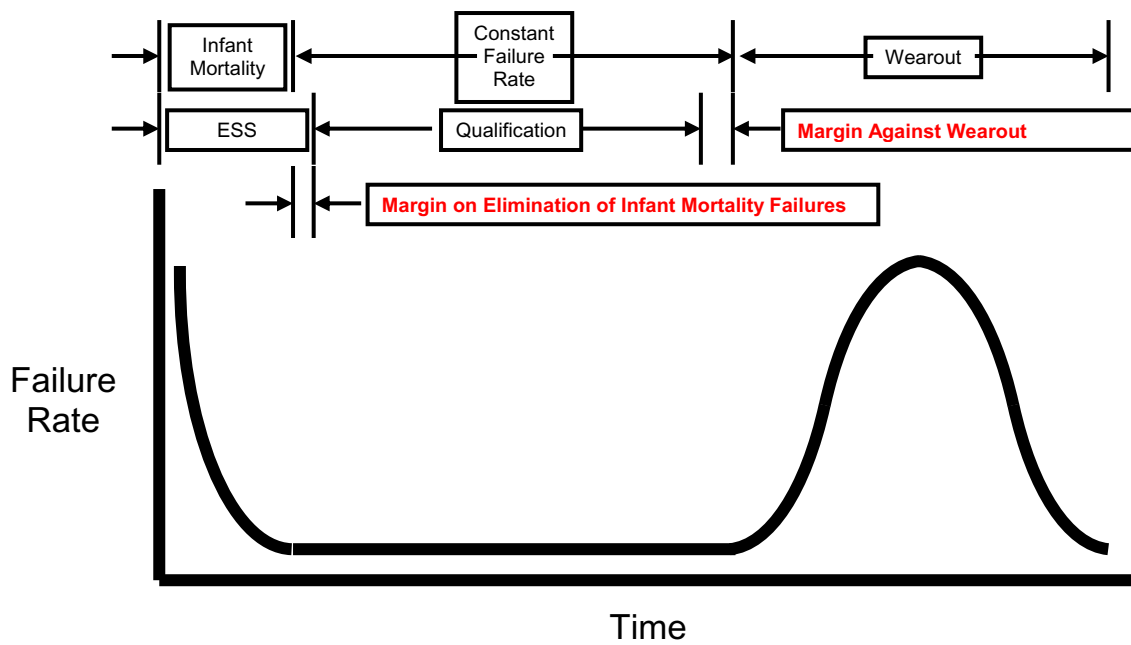


Table 1 -- Vibration Durability Life Consumed by ESS						
ESS			Durability			Percent of Demonstrated Life Consumed by ESS
Duration (Minutes)	PSD (g ² /Hz)	Duration x PSD ⁴	Duration (Minutes)	PSD (g ² /Hz)	Duration x PSD ⁴	
10	0.04	2.56E-05	300	0.002	4.8E-09	99.98%
				0.004	7.68E-08	99.70%
				0.008	1.2288E-06	95%
				0.016	1.96608E-05	57%
				0.032	0.000314573	8%
				0.040	0.000768	3%
				0.064	0.005033165	1%
				0.128	0.080530637	0.03%