Utilization Life of Electronic Systems - Aging Avionics Usable Life and Wear-Out Issues

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ABSTRACT

How a system ages is central to the assessment of the effective utilization life of the system. Utilization life represents more than estimating the remaining life in an aged system, it is determining how to optimally plan a system’s future management and future use to minimize the life cycle cost incurred. The consideration of utilization life of a system includes the physics of aging, damage accumulation techniques, mitigation of aging, qualified use of aged parts for spare replenishment, prognostics, and quantification of cost avoidance.

Any approach to evaluating utilization life depends on a making an effective evaluation of the reliability, durability and safety of the system. Traditional Mean Time Between Failure (MTBF) metrics that assume a constant failure rate are likely to be less useful in the evaluation and practical implementation of utilization life concepts than Failure Free Operating Period (FFOP). Consideration of the durability related issues of aging hardware and usable life for determining the best time to retire an avionics unit is a key factor in providing uninterrupted, reliable, and safe performance of avionics products.

INTRODUCTION

Conventional reliability engineering of electronic systems is focused on determining and insuring a product’s ability to survive and operate to specification for a required length of time under a specific set of environmental stresses. For aircraft, this includes a certified inherent level of safety. For avionics products the differences between reliability, durability, service life, usable life and safety are blurred.

For mechanical systems like bearings, engines, and tires, wear and aging are very well understood because these products are regularly used by consumers until they are no longer usable and inherent safety can be restored by replacements. Alternatively, the commercial electronic systems market drive is toward satisfying the warranty period and making sure that the product is obsolete long before wear-out becomes dominant. As a result, the phenomenon of aging and wear-out is much more poorly understood for electrical systems than mechanical systems.

Unlike consumer products, military and avionics systems are expected to last long periods of time and incur significant expenditures for sustainment. Military and avionics electronic systems suffer from the effects of aging. The specific mechanisms that occur with aging are often non-intuitive, and can lead to unexpected system operation. A classic example is an electrolytic capacitor, one of the few parts generally recognized as having some finite lifespan. Virtually all wet electrolyte capacitors show dramatically decreased capacitance with life, regardless of all other factors. In addition, they will often show increased leakage, especially when operated at elevated temperatures. These changes cause large reductions in filtering capability and shifts in offset/bias voltage in many circuits. But they rarely appear as a solid failure. Worse, this type of problem may go completely undetected during even stringent bench tests; especially in power supply circuits, because the box is not truly functionally tested. Solid tantalum capacitors exhibit other odd properties, especially with regard to voltage and leakage. They tend to become
stabilized to the applied voltage (which is zero in storage). These capacitors then exhibit failure of the dielectric when a higher voltage is applied. This is one reason why the excessive voltage "over-rating" of these parts has little effect on long-term reliability.

Aging is not confined to the physics and engineering of wear-out. It is also a logistical phenomenon. On the system LRU (line replaceable unit) level, USAir made a landmark discovery some years ago that "bad or problem boxes" eventually and inevitably gravitate to the spares pool over time. This makes effective field maintenance impossible and erodes confidence in the support system. The process occurs because many small, essentially undetectable problems accumulate as systems age, eventually leading the unit to be sent in for repair. These factors may not produce solid detectable faults, especially with ATE (automatic test equipment) testing. This causes the box to be marked "no fault found," and returned to the loaner pool, where it simply fails again when put into service, and returns for more "service" and heads back to the loaner pool, [1].

With the emphasis in military and avionics systems design shifting from the design and development of new systems to the sustainment 1 of existing systems. Sustainment costs for many military and avionics products now easily exceeds the cost of their development and original manufacturing. Sustainment is made more difficult by a combination of electronic parts obsolescence, the harsh environmental conditions associated with field use, strict qualification and certification requirements, and the long field lives expected from the system.

As a result of these pressures, there is a great interest in developing and applying an understanding of electronic system aging to the optimization of the system sustainment, i.e., the minimization of life cycle cost. In other words, how do we accurately predict, and using that prediction, maximize the utilization life of an electronic system subject to aging?

UNDERSTANDING UTILIZATION LIFE

Successful treatment of the utilization life of electronic systems involves a combination of the following six critical areas:

1) Physics of aging – development of a physical understanding of how electronic materials, technologies, and systems age. Understanding aging in electronics involves two different targets:
   a. Development of physics of failure models for aging related failure mechanisms in order to enable damage accumulation.
   b. Development of methods for estimating the environmental aging (damage) present in existing parts and systems without the benefit of knowing the part or system's environmental stress history, i.e., non-destructive methods of measuring the damage accumulated in existing systems and parts.

2) Life consumption monitoring – with an understanding of how systems age (damage accumulated), develop methodologies for monitoring and archiving the environmental stresses that a system is subjected to and use that information to enable a prediction of life consumed.

3) Mitigation of aging (life extension) – development of methodologies for extending the life of systems in a controlled and predictable manner through modification of the environmental stresses seen in the system (e.g., cooling).

4) Prognostics – if the life consumption of assets can be determined, this information could be used to select which assets have the highest probability of success on future missions. This area involves four key elements:
   a. Using life consumption monitoring results in conjunction with expected future environmental stresses to determine life expectation (i.e., life consumption modeling).
   b. Estimating the probability of mission success for a future environmental stress profile from the life consumption model.
   c. Determining optimum asset-specific maintenance schedules.
   d. Determining how parts can be traded between systems to optimize utilization.

5) Management of aging hardware – develop methods of qualifying salvaged subsystems and parts for use in sustaining operational systems (i.e., part obsolescence mitigation). Determine the logistics of documenting and managing aged no-fault-found systems.

6) Business plan – Determine how aging asset management approaches can be "sold" to customers and develop necessary ROI justifications for the cost of managing aging assets.

FAILURES IN AVIONICS

Failure mechanisms for electronics (and specifically avionics) are broadly grouped into overstress mechanisms and wear-out mechanisms. Overstress failures are catastrophic sudden failures due to a single occurrence of a stress event that exceeds the intrinsic strength of a material. Examples of overstress failures include buckling of materials, electrical failures resulting from electrostatic discharge. Accumulation of incremental damage leads to failure when the accumulated damage exceeds the material endurance limit, and is termed a wear-out failure. Examples of wear-out failures are fatigue damage due to

1 Sustainment includes retaining the ability to continue manufacturing the old system and the ability to maintain the systems that are fielded.
thermomechanical stresses, corrosion due to contaminants and moisture cycling.

- Mechanical failures result from elastic and plastic deformation, buckling, brittle and ductile fracture, fatigue crack initiation and propagation, creep and creep rupture.

- Thermal failures result from exceeding the critical temperatures of a component such as glass-transition temperature, melting point, or flash point.

- Electrical failures include those due to electrostatic discharge, dielectric breakdown, junction breakdown, surface breakdown, surface and bulk trapping, hot electron injection.

- Radiation failures may be caused by radioactive contaminants and secondary cosmic rays.

- Chemical failures result from chemical environments which act as catalysts to corrosion, oxidation, or ionic surface dendritic growth.

What are the issues and factors that define the remaining usable life of that generation of hardware? A typical older product designed would have an estimated MTBF random failure rate and in most cases a service life requirement in operating hours or calendar years. So for our case, wear-out is the issue and service life a reasonable metric. With out primary focus on durability, the reliability bathtub curve can be used to illustrate usable life, Figure 1.

Reliability is intimately related to product failure. Failure is defined as loss of product functionality. In order to quantify reliability, we must determine how the population of products will fail over time. This can be done by simulation, accelerated testing, or historical data. Examining failures of products, we generally observe that they can be grouped into the early, useful, and late stages of a product's life.

Failures in the early life stage, often referred to as infant mortality, are generally related to defects that escape the manufacturing process. The number of failures related to manufacture problems generally decrease as the defective parts fail leaving a group of defect free products. Thus, the early stage failure rate decreases with age. During the useful life, failures may occur due to freak accidents and mishandling that subject the product to unexpected stress conditions. The failure rate over the useful life is generally assumed to be very low and constant. As the product approaches the wear-out stage, the product degrades due to repetitive or sustained stress conditions. The failure rate during the wearout stage increases dramatically as more and more products fail due to wearout failures. When plotting the failure rate over time as depicted in the figure above, these stages form the so-called "bathtub" curve.

The period of useful life can vary significantly and the period when the failure rate is increasing can be difficult to pinpoint. Hardware in this phase of life may have intermittent and differing causes of failure, which are hard to isolate in that wear-out mechanisms can be complex and interactive with multiple symptoms. This condition can account for some avionics units sometimes called "a rogue unit". Finally, considering the issues of aging hardware and usable life, determining when to retire an avionics unit from service is a key factor if we are to provide un-interrupted reliable, safe performance of our avionics products.

THE FOLLY OF CONSTANT FAILURE RATE [2]

From an electronic viewpoint, we tend to see components, especially solid-state devices and passive parts, as essentially having unlimited life. We assume they will never fail except through overstress or physical damage. Most statistical models assign some weighting to temperature, cycle life and other factors, and then pick some defensible “failure rate” to arrive at an assessment of component life. These models assume a constant failure rate and perform poorly when predicting the life of systems in actual service because of the multiplicity of environmental stresses that work in concert to bring about part failures. Also contributing to the poor predictive capability of these models is the fact that stress management during handling and assembly is not always practiced in a consistent manner. A more useful and correct orientation is to understand how the parts, this includes the interfaces, the printed wiring card and all other items included in the assembly, will fail and then determine how one can prevent that from happening prematurely or in a dangerous manner, and establish what can be considered to be a useful working lifespan. The prevailing state of mind of the owners/users of avionics is that if the unit is operational the plane continues to fly. When the unit becomes non-operational (to the degree that the plane can not fly or applicable safety concerns deem that it may not be flown), the unit is replaced and sent for repairs. In the

![Bathtub curve](image-url)
repair process actions are taken to return the unit to operation as quickly and inexpensively as possible. Unless a part in the unit is non-reparable, little concern is paid to whether the unit is likely to fail again within a short period of time. As aircraft age, the average age of aircraft is increasing and therefore all the systems are aging too, repair is becoming more frequent and more expensive to perform.

A cost avoidance argument associated with assessing and tracking utilization life has historically been a tough sell – it goes against the prevailing pressures of aircraft owners/operators to show a profit on a quarterly basis. The tools and methods for assessing available life are now becoming available. Using a combination of damage accumulation based on understanding the reliability mechanisms associated with aging of electronics, methods for accumulating damage and interpreting it, and finally the ability to translate the knowledge gained into a more optimal life management plan (both tactical – what should be done now, and strategic – how can the life cycle costs be planned optimally many years in the future). The ultimate outcome is the reduction of unscheduled removals and reductions in sustainment costs. This essentially allows for the introduction of scheduled replacement into the process of supporting avionics.

**FAILURE FREE OPERATING PERIOD (FFOP)**

The most common procurement specification related to electronic system reliability, based on the assumption of a constant failure rate, is Mean Time Between Failures (MTBF) or Mean Cycles Between Failures (MCBF). The assumption of a constant failure-rate implies that random failures and faults are inevitable or even acceptable. In reality most electronic assemblies have a minimum life that depends on the operating environment and the mechanical features of the product such as material properties and dimensions of the components. A more useful measure of reliability is Failure Free Operating Period (FFOP). FFOP is defined as a period of time (or appropriate units) during which no failures, resulting in a loss of system functionality occur. The FFOP approach is anticipatory by nature, i.e., it is based on the identification and control of the causes of unreliability with the aim of improving equipment reliability in service and facilitating the calculation and management of utilization life.

The use of FFOP permits life cycle cost to be reduced by more effective scheduling of maintenance activities and the reduction of the logistics footprint by reduction of spares provisioning in the supply chain. If a 3-parameter Weibull distribution is used to represent the distribution of times-to-failure it is possible to determine decreasing, constant or increasing failure rates depending on the failure data. The location parameter in the 3-parameter Weibull is a representation of the FFOP, Figure 2.

**Figure 2.** The distribution of time to failure, $t_f$ represents the FFOP.

FFOP is subject to variations arising from variation of the operating environment, the physical dimensions of parts, solder joints etc., and material properties. The ability to establish a reliable and accurate $t_f$ will improve dramatically and become a key element of how we maintain and dispatch our aircraft.

**SAFETY IMPLICATIONS**

The original certification and the inherent safety level of an aircraft will degrade over time and is generally kept at an acceptable level by existing maintenance practices. The typical replacement-of-failed-component(s) approach to most avionics does not restore the original reliability of the entire unit or box, only the replaced device. This factor along with a significant increase in avionics usage in aircraft designs will also increase the implications of wear out or the usable life of avionics products, see Figure 3.

**Figure 3.** System safety versus time.

This is best typified in a fault tree analysis. Any element no longer at its original level of inherent reliability, i.e., increasing probability of failure, will degrade the overall system's level of safety.

**CONCLUSION**

Aging avionics and industry practices demand a fresh look at product life and risk. New knowledge and new
tools will enable us to maintain and restore the inherent safety in our fleets in this new era.

REFERENCES


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