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Reliability Simulations for Electronic Assemblies: Virtual Qualification, Reliability Assurance, Maintenance Scheduling and Obsolescence Mitigation

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ABSTRACT

Reliability Physics simulations for electronic assemblies has matured to become best practice during specification and design. However, the potential advantages of these simulations to programs and integrators are more far reaching. This paper will explore how the simulations can be used for virtual qualification, reliability assurance, maintenance scheduling and obsolescence management.

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1. INTRODUCTION

Reliability prediction has evolved from traditional actuarial models to design-specific model-based calculations. However, the activity remains limited to the design phase of hardware developers, while the broader lifecycle benefits associated with reliability physics are yet to be realized. The electronics content of systems continues to increase, even as the supply chain becomes deeper.

We are in an era of great potential to evolve a range of engineering practices by orders of magnitude:

- Championing org-wide reliability programs that provide for long term performance gains what the quality revolution did for early life failures
- Feedback loops across all stakeholders in the supply ecosystem
- Lifecycle predictions that evolve with mission requirements and user behavior
- Sustainment resiliency, demand-side obsolescence mitigation
- extending condition-based maintenance advances to electronics, with sustainment savings potentials nearing 70%

Organizations that make use of reliability-physics to inform decisions throughout the lifecycle can realize a significant market advantage.

Traditional reliability estimation practices such as MIL-HDBK-217 have been shown to have weaknesses that include the narrow application of broad data, disincentivize the use of new technologies, and a tendency to be manipulated to meet specified targets [1]. Since before the turn of the century, reliability practitioners were looking forward to reporting on the reliability of their product based on the suitability of the design for the intended application, moving away from the actuarial reliability. Graduate students engage in research to understand and model the underlying physics behind component and assembly failures, only to be frustrated by their inability to effectively apply them once employed by industry.

The advent of reliability physics-based simulation tools has begun to realize the dream of transferring Physics of Failure from theoretical understanding to practical application during product development. The last decade has shown an increasing adoption of model-based reliability predictions in the electronics industry. However, these advanced methods and the insight that they provide has been restricted, for the most part, to informing the recommended improvements and supporting design approval of reliability teams. This paper explores the utility of reliability physics analysis (RPA) in areas beyond the reliability team, empowering supply chain management, systems engineering, test plan development and sustainment activities.

2. STATE OF RELIABILITY PHYSICS ANALYSIS

RPA tools have evolved from calculation engines designed for specific failure mechanism assessment in-house use to commercial tools that take advantage of computing advances to automate analyses for entire designs over a range of mechanisms [2]. Reliability teams are now performing RPA to meet contractual requirements. The requirements themselves are evolving. Component management plan requirements such as SAE's EIA-STD-4899 include language that requires consideration of the operating, storage and environmental stresses [3]. Maturity and acceptance of RPA methods is further demonstrated by the development SAE J3168 to standardize Reliability Physics Analysis [4], and RPA simulation is being adopted as an acceptable means of satisfying reliability due-diligence.

However, challenges remain for the adoption of RPA throughout the business processes and supply chain. Tools exist to combine RPA predictions up to the board and box level, but systems engineers are challenged by time-dependent failure rates as they attempt integration into larger subsystems comprised of repairable and non-repairable assemblies. While time-dependent failure rates more accurately capture reliability and durability behavior over the life of the product, traditional systems engineering (SE) methods for reliability allocation, fault tree analyses (FTA) and Functional Safety Analysis expect constant values as reliability inputs, and non-constant values render these analyses far more resource intensive. This difficulty has, to this point, led to resistance from the SE community in adopting RPA during planning and integration.

It has become ever more difficult to attain target reliability metrics using actuarial handbook methods as the electronic content in systems increase, both in terms of component count per assembly and number of assemblies in a system. Furthermore, the pace of technology development has accelerated to the point where available, relevant field history can no longer be assured before capability drives adoption in aerospace, defense and high performance (ADHP) equipment.

The desire for more computationally challenging systems such as autonomous vehicles, directed energy applications and hypersonics has surpassed the ability of traditional parts count methods to provide reliability predictions that can be rolled up to the system level while still providing a reasonable system availability prediction. This increasing challenge is beginning to overcome their resistance to accepting RPA as an input and leading them to begin exploring ways to incorporate time-dependent reliability metrics into standard SE analyses.

3. LEVERAGING RPA FOR VIRTUAL QUALIFICATION

The groundwork for quality systems as we know them was laid in the 1930s when Walter Shewhart introduced statistical analysis and quality control [5], and later made practical for implementation through the works of Dr. Deming and Dr. Juran. Since then, we have come to expect that manufacturing suppliers be governed by a robust quality program that spans from upper management to the shop floor, minimizing process variation and maximizing yield.

Given the increase of electronics content in ADHP systems and the fact that 95% of lifecycle costs are locked by design release, a practical method for implementing a reliability physics approach to assess prospective PCBAs before design approval or COTS selection is needed. This would be a step towards a robust and comprehensive reliability program that does for long term performance what the quality revolution did for early life failures.

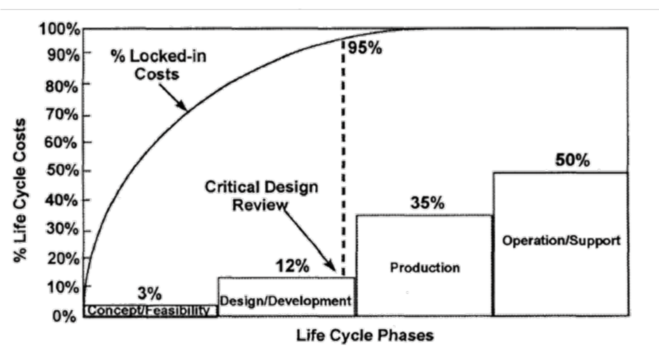

Figure 1: By the time the design is released for testing, 95% of the lifecycle costs are set. This has a direct relationship with reliability, as indicated by the percentage of cost associated with operation and support. If reliability issues are identified after design release, cost and timeline pressures discourage redesign and product improvement is restricted to 'band-aid' approaches that only impact the remaining 5% *[6]*.

3.1. Supplier Design Assurance

Given the complexity of the electronics supply chain and ADHP systems, the definition of COTS assemblies is ambiguous at best and often a subject of argument, as even suppliers that design for application can be extremely protective of design information. Design authority by the next highest level of the supply chain is therefore less of a yes/no and more of an analog spectrum.

Where a relationship exists between supplier and next-level integrator, specifying reliability physics simulation results as part of the deliverable requirements for design approval can empower customers with a quantitative understanding of design strengths and weaknesses. These simulation results also provide customer assurance that the product will perform as intended in the field over the intended lifetime, and that sufficient margin exists that qualification test failures are less likely to result in program delays. In cases where reliability design simulations are performed, cost savings per PCBA are reported to be between \$50k and \$150k, with time-to-market reduced by 3 to 10 weeks [6].

Where there is no relationship with the supplier, or where the supplier may be unwilling to provide a reliability physics-based analysis, modern RPA tools like Sherlock allow the customer or integrator to perform their own analysis using a physical sample as a template [8].

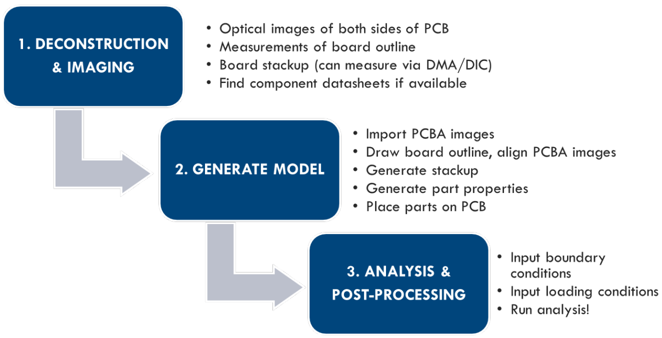

Figure 2: Basic process for modeling a COTS device without design files in Sherlock.

The accuracy of these models increases with the fidelity of information that the users provide. For example, interconnect reliability for integrated circuits is sensitive to the die size. X-ray or destructive physical analysis can provide more precise information to replace assumptions, improving the model. Additional levels of fidelity can be gained from an understanding of the thermo-mechanical properties of the laminate, which can be easily captured using methods like digital image correlation (DIC), and PCB stack-up can be captured with cross sectional analysis. The level of effort, cost and timeline, availability of samples and model fidelity can be balanced to appropriately meet the program needs.

3.2. Communication and Collaboration

Sharing information with suppliers and co-development has been strongly correlated to product performance [9]. Nowhere would this be more apparent than in the area of reliability and durability. When designing for reliability, suppliers struggle to glean actual operating conditions from customer requirements, while customers are challenged when trying to understand the actual impact of the operating conditions on the product's reliability performance.

Supplier designs can only consider the environments and use cases that are communicated by the customer. Often, reliability requirements are provided in the form of test standards ("The product must pass MIL-STD-810 Test Method XXXX") or provide a generic description of the intended use and lifetime ("The product must survive in an off-road ground vehicle cabin for 12 years").

In the first case, designers have a firm target, but no understanding of any nuance associated with the actual use environment, nor any understanding of how the test environment correlates with the use environment. Suppliers must assume that the test was selected for its relevance to the intended use, but it is not unknown for test target selection to simply be a function of what has been done on previous programs. Reliance on test conditions established and correlated to legacy systems may miss risks associated with evolving technology and integration environments.

In the case of the descriptive requirement, the supplier may understand the intended use, but is often left to assume and design for operating conditions that they may not be familiar with.

RPA methods standardize and simplify the communication of detailed and even complex use environment. Incorporating RPA-based stress descriptions into reliability requirements provides specificity while being flexible enough to describe any application environment. An internal process that requires RPA-based reliability requirements also incentivizes the customer to better characterize an understand the stresses they expect their suppliers' product to endure.

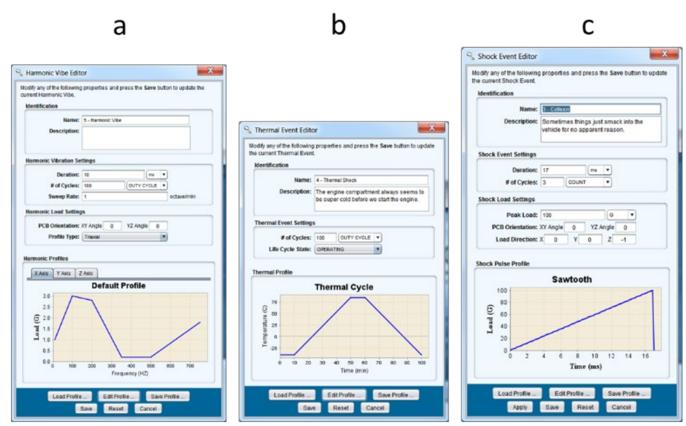

Figure 3: Example RPA-based environment stress profiles that capture levels, durations, number of cycles, and

frequency of exposure for harmonic vibration (a), temperature (b), and mechanical shock (c).

Communicating reliability assurance back up the supply chain can be just as challenging, given the highly competitive nature of many ADHP industries. Because reliability analyses performed during development involve design, many suppliers prefer simple go/no-go tests for reliability verification.

Suppliers may be performing RPA for their own risk mitigation but may keep the results for internal use only. A means to effectively transmit design reliability analysis without compromising IP would benefit integrators and program managers, especially those trying to meet JCIDS requirements when faced with supplier reluctance [10] [11].

Reduced order models and locked models are becoming more available from simulation providers [12] [13]. In the case of reliability, reduced order models generate response surfaces from multiple runs that explore key parametric variations as a function of external inputs. The trend toward reduced model creation is driven by practical what-if exploration and tradeoff analysis of system level models. However, these models also lend themselves to overcoming the trust barrier and enabling engineering collaboration.

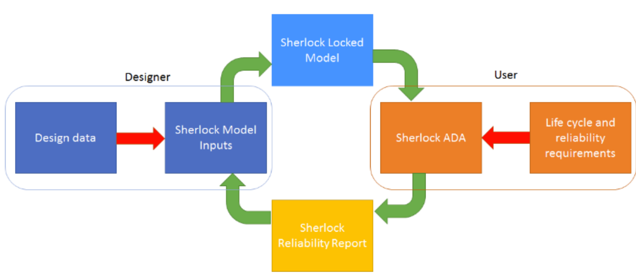

Figure 4: Locked models enabling communication between design and users, informing designers of their impact on reliability, while empowering users to affect reliability with configuration choices *[13]*.

Fatigue, damage and ultimate reliability is determined by a combination of design decisions and environmental stress. Access to a locked or reduced order model that predicts reliability allow integrators to better understand the impact of their system configuration on product reliability. When attempting to improve system availability, tradeoff analyses can be performed that balance mounting configurations, auxiliary cooling budgets and housing requirements with the cost of component modification or redesign. For example, it may be more cost effective to add isolators to the housing mounts than to either structurally reinforce or redesign the electronic components within the enclosure. Locked models allow for quantitative analysis providing system integrators with the data they need to understand their options and evaluate the impact on system reliability. When evaluated as part of the design review process, this virtual qualification can provide users with reliability assurance before costs and schedules are committed to prototyping.

4. Model Based Test Planning

Why do we test? This is a fundamental question that begs to be answered when creating a test plan. Often testing is performed merely to satisfy contract minimum performance criteria. A fixed amount of time or number of cycles under specified environmental stresses such as temperature, mechanical shock and vibration.

These conditions and durations are drawn from tables found in industry standards, most of which were established decades ago, when the scales, geometries, and processes for electronics design and assembly were far different from today's technology. While most component standards are periodically updated to provide guidance for newer technologies, assembly standards continue to fall back on previously specified conditions and durations.

As technology has advanced, the prevalent failure mechanisms and our understanding of them has evolved [14] [15]. Test conditions established to qualify assemblies manufactured predominantly with through-hole technology may not correlate to field conditions as well for surface mount technology or the high-density electronics and advanced packaging making their way through the supply chain today.

A more sophisticated approach to test plan development allows for testing that is more than simply meeting specification, it allows for a deeper understanding of the lifetime reliability of the design.

Applying package specific failure models to specific application environments to calculate the damage accumulated at the specified lifetime, we can then design test conditions that stress the relevant mechanisms. Furthermore, time to equivalent damage can be assessed quantitatively, optimizing test programs to provide reliability assurance without leveling onerous test requirements on the supplier.

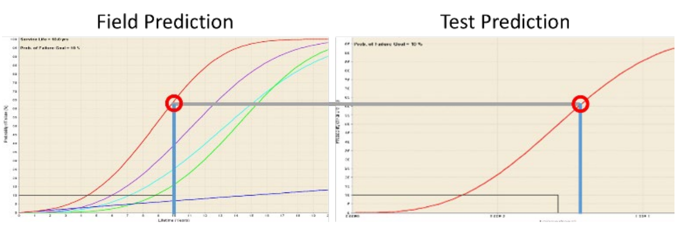

Figure 5: Visual representations of failure cumulative density function (CDF) curves expressed as unreliability over time and obtained from RPA processes can easily allow test engineers to understand test-to-field correlations for the specific technologies under test. The number of test cycles that induces a damage level equivalent to what the assembly sees in the field can become the new target test duration.

An optimization approach such as this has the obvious advantage of obtaining the maximum assurance while minimizing the cost and timeline impacts on the program.

5. Model Based Predictive Maintenance

Electronic assembly maintenance is currently a completely reactive evolution. Failed assemblies received at the depot for maintenance undergo fault isolation to a specific component, which is then replaced. When the assembly tests operational, it is assumed that the failure was in the part, and the assembly is returned to the field. The fallacy of this argument centers around the fact that as the component is replaced, so are the solder joints.

It has been reported that solder joints account for 70% of failure in electronic assemblies [16]. The ability to predict the order of failure, component by component, using RPA methods has the potential to empower electronic assembly repair to become proactive.

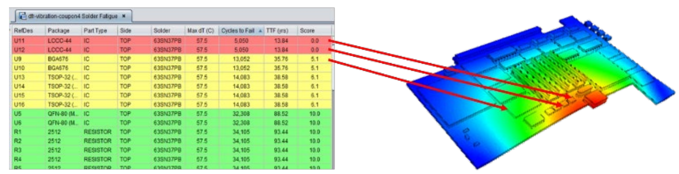

Figure 6: Reliability predictions can now be made at the component level, providing item managers and maintenance planners a deeper understanding of future repair requirements [17].

These potential failures can be then grouped by time to failure. When the assembly arrives at the depot for repair of the first failure, the solder joints of components predicted as subsequent failures can be reworked, resetting the damage accumulated to date, and avoiding future failures.

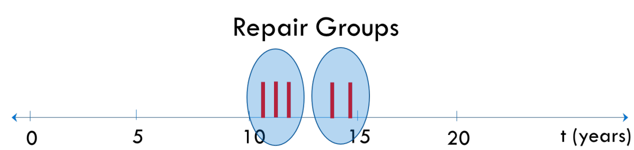

Figure 7: By grouping the predicted times to failure, what would be five independent repair activities may be reduced to two**.**

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Condition based maintenance has been widely implemented for rotating machinery and other devices where direct measurement of telltale parameters can be directly observed. Electronics degradation is often unobservable or too subtle to measure directly. Previous efforts to apply condition-based maintenance to electronics has been hampered by the assumption that stress history at the board level must be captured.

Each assembly will likely see varying duty cycles and relative stress levels. However, given valid representative environmental inputs to the RPA model, these variations will only result in a stretching in the time domain, having little to no impact on order of failure. This allows a more practical approach to predictive maintenance: Using the first failure in any repair group as the critical telltale parameter.

The impact on materiel availability, depot maintenance scheduling, item lifecycle cost and the extended useful life can be significant. Assuming that for every maintenance cycle where the traditional component replacement process is employed, three future-failing components are repaired, and assuming 70% of electronics failures are related to solder joints, this would result in a 52% reduction in repair activities, to include associated cost and down time.

6. RPA Impact on Obsolescence Management

The impacts on obsolescence management relate directly to the predictive maintenance process. Every piece part that is repaired in place is a component that is not replaced, a component that is not drawn down from inventory.

Solder joint failure tends to occur sooner in larger components, owing to the distance of the furthest joint from the typically central neutral point. These larger components tend to also be more complex and have shorter production lives. Repairing and extending the useful life of these components reduces inventory pressures by an amount corresponding to replacement avoidance (52%).

Life of Type buys made for assemblies whose useful lives are more often extended may no longer be adequate, forcing programs to procure obsolete components from alternative sources. The risks associated with procuring obsolete parts, and the costs associated with counterfeit avoidance can therefore be drastically reduced through the implementation of a model-based maintenance program.

The program and organizational cost savings associated with a cultural shift toward RPA based sustainment have not been studied but are expected to be significant.

7. Conclusion

The advances in model-based reliability physics analysis have been impactful during product development. However, these benefits have been limited to enabling reliability practitioners to easily obtain more quantitative data upon which to base their recommendations to the design team.

The science is mature, the tools are becoming more mainstream. The challenge is cultural, dependent on trust, standardized methods across the industry that ensure IP protection, and alignment of incentives for integrated reliability processes. The potential for organizational benefits derived from increased supply chain collaboration, reliability assurance, test plan validation, and sustainment stand to be far more transformational.

- Accelerated development with greater levels of collaboration and coordination.
- 52% decrease in unplanned electronics repair downtime
- Greatly increased systems availability
- Surge planning for repairable component staging
- 52% reduction in Obsolescence program costs and counterfeit risks.

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