Challenges in the Qualification of Electronic Components and Systems

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***Abstract*—Qualification, which is the process of demonstrating that a product is capable of meeting specified requirements, is a costly and lengthy part of the product development process. This paper discusses the challenges that companies face when qualifying their products in an environment of abbreviated product development cycles, changing environmental regulations, which require the use of new materials or processes, and a complex and diffuse supply chain. A more comprehensive approach to product qualification involving the use of physics-of-failure principles, prognostics and health management techniques, and qualification at every stage of product development that builds on earlier work and industry standards is presented here.**

***Index Terms*—Qualification of electronic systems, physics of failure, prognostics and health management.**

I. Introduction

COMPANIES around the world are in a competitive struggle to make new and exciting products with higher performance capabilities at affordable costs. They often struggle with the conundrum of trying to ensure product reliability while offering competitive pricing and reducing time to market. Navigating from product conceptualization to delivery is made all the more difficult by the challenges of working with a diffuse and complex global supply chain and by social responsibilities and environmental regulations that often compel the use of novel technologies and materials. Qualifying a product or "demonstrating that it can reliably operate under use conditions [1]" can be a difficult and challenging task. However, when not properly conducted, products may fail in the field, resulting in high warranty costs, product recalls, and loss of reputation for the companies involved.

Qualification includes all activities that are intended to ensure that a product that meets the nominal design and manufacturing specifications will meet or exceed the reliability targets [2]. Its purpose is to define an acceptable range of variability for product parameters affected by design and manufacturing, such as geometry and material properties. Quality conformance, which includes process control and quality assurance activities, ensures that lot-to-lot variation is within specified tolerances. Units that fall outside this range are termed "defects," because they have the potential to make a product fail to meet its specified requirements.

Qualification needs to begin before a product is manufactured. Delaying qualification activities until after production can involve cost penalties due to low yields, higher rework costs, costly redesign, and delayed shipment [2]. It is more efficient to proactively design reliability into the product than to retroactively test for it. Accordingly, qualification should be conducted in the product development cycle during the design phase using simulation tools, during the development phase using prototype testing, and also during the early production phase. Requalification should be performed after any "significant" design or manufacturing changes to an existing product [2]. Significant changes, per JEDEC JESD 46 [3], are "changes that result in impact to form, fit, function, or reliability of a product." Changes in die structure, packaging materials, or the wafer fab process are examples of significant changes that warrant requalification at the component level.

Qualification processes have changed over the years, as the electronic supply chain has become complex, lengthy, and dispersed, with suppliers often located on different continents. The transition away from a process in which production and qualification were done in-house to a manufacturing system that relies on a complex and segmented supply chain has meant that original equipment manufacturers (OEMs) have less control of the overall qualification process. Traditional high-reliability industries such as aerospace, defense, and medicine are under pressure to use commercial off-the-shelf parts. Fig. 1 illustrates the complexity of the electronic supply chain, using the computer industry as an example. A single component manufacturer may supply parts to different OEMs, each with different product configurations and operating conditions, spanning a wide range of market segments. As a result, knowledge of qualification requirements and operating conditions may not flow from one tier of the supply chain to the next. The end use conditions of a component or subsystem are often unknown to the component manufacturer or may differ based on the final product configuration. As a result, it may not be possible or economically feasible for the manufacturer to qualify the same component for different use conditions.

A manufacturer may successfully qualify a stand-alone component, but as more components and subsystems are integrated to form the final product, the reliability of an individual component may decrease due to operating stresses induced by the surrounding components, the system design, or the assembly

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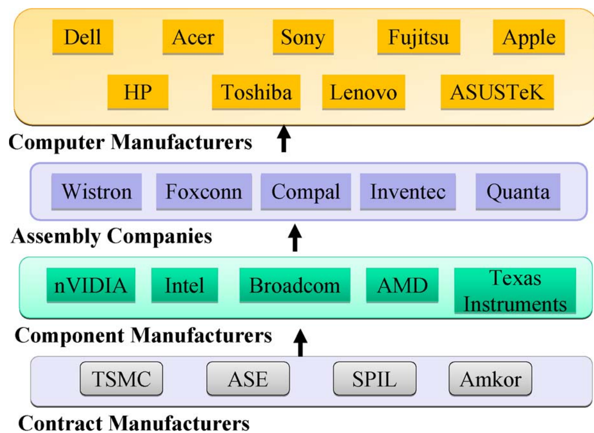

Fig. 1. Illustration of the complexity of the computer supply chain.

process. This can result, for instance, because a component is mounted close to high-powered components or because of poor system thermal design. Both these scenarios can cause a component to experience higher temperatures, making it susceptible to premature failure from temperature-related failure mechanisms. Component–component and component–system interactions may not always be captured during qualification testing, unless the component is verified in a system that is representative of the final product configuration. Unanticipated use conditions that arise as a result of these interactions can create an environment in which the component is likely to prematurely fail.

Environmental regulations that ban the use of certain materials have resulted in the use of novel materials or processes whose reliability risks are not yet fully understood. Using these novel materials or processes without appropriate testing can lead to product failures. For instance, Sumitomo Bakelite introduced mold compounds with red phosphorous flame retardant in the 1990s as an environmentally friendly alternative to bromide and antimony oxide flame retardants. However, these compounds were found to cause current leakage and resistive shorts between adjacent leads inside leaded components, with occurrences ranging from six months to many years, depending on the usage environments. Hundreds of millions of dollars were lost in field returns of final products and, in 2002, the company discontinued its inorganic red phosphorous-based mold compounds [4]. Another example is from companies that are exempt from the Restriction of Hazardous Substances (RoHS) and Waste Electrical and Electronic regulations, which effectively ban the use of lead. As a result of the nonavailability of tin–lead parts, these companies are forced into using lead-free parts in existing tin–lead assembly processes. The mixing of different solder materials can introduce new reliability concerns and increase the risk of failure, unless adequate testing is conducted [5].

Qualifying an electronic component or subsystem amid the complexity of an extended supply chain, where use conditions are often not known, can be a challenging task. Rapidly changing environmental regulations, which require novel materials and processes that present new failure mechanisms, and technology advances due to market demands can pose further qualification challenges. For reasons largely attributable to the increasingly diffuse supply chain for electronic products and the ever-abbreviated product development cycle, many manufacturers have become content to qualify their products using established standards (for example, JEDEC or MIL-STD) without focusing on how the testing relates to actual use conditions. Despite the qualifiers and disclaimers in many standards, many companies use these without understanding how the testing relates to the final application.

In a standards-based testing approach, the only claim that can be made is that a component has passed a specified test. Passing the test, however, does not imply that the component will actually satisfy the life requirement in the final product under actual use conditions. Unfortunately, this “common language” approach to product qualification, which standards-based testing provides, increasingly fails to achieve the real goals of the qualification process. The result is that current qualification testing is often not suited to a specific application and leads either to a waste of resources due to “over-qualification,” with good products being rejected, or to field failures because products are shipped that passed tests that were not stringent enough to meet life requirements.

Costly field failures highlight the need to adopt a more comprehensive qualification process utilizing a variety of tools and techniques. These include the following: 1) physics-of-failure (PoF) principles that allow tests to be focused on use conditions and relevant failure mechanisms for a specific application; 2) prognostics and health management (PHM) techniques that allow life-cycle conditions to be determined, intermittent failures to be detected, and provide early warning of impending failures; and 3) qualification through every stage of product development and manufacture, in order to proactively incorporate reliability into the product, rather than test for, after the fact. This paper presents a unified approach to qualification that builds on the PoF and PHM approaches already discussed in earlier work and literature in order to identify qualification methods that are suited to a specific application and most likely to prevent field failures through early detection.

II. Repercussions of Unidentified Failures

Failure to qualify a product adequately or appropriately can result in costly field failures, exorbitant warranty costs, and loss of reputation and revenue for both the OEM and the contract manufacturers involved. There are numerous examples of field failures in electronics that proved to be extremely costly for the companies involved. Between 1983 and 1995, twenty-two million Ford vehicles were affected by defective ignition modules that could cause the vehicle to stall at any time on the highway [7]. The ignition modules were found to intermittently fail when hot and function again when the engine cooled, without leaving any physical evidence of the failure. Ford projected warranty returns of 10 per 100 modules (10%) before five years or 50 000 miles (5/50) based on its earlier ignition system. Actual field returns were 40% on average, and as high as 99% in some cases, with many modules exhibiting trouble not identified. Ford settled the ignition lawsuit in a deal that is estimated to have cost ~2.7 billion, by agreeing to pay for repairs in vehicles with the flawed ignition modules [7], [8].

Another good example is the 2006 recall of over 9.6 million Sony batteries used in computers due to the risk of overheating and fire in what was then the largest computer-related recall ever [9]. Laptop manufacturers Dell, Apple, Toshiba, and Lenovo issued battery recalls individually before Sony issued a worldwide recall. Sony explained that "the recall arises because, on rare occasions, microscopic metal particles in the recalled battery cells may come into contact with other parts of the battery cell, leading to a short circuit within the cell. Typically, a battery pack will simply power off when a cell short circuit occurs. However, under certain rare conditions, an internal short circuit may lead to cell overheating and potentially flames" [10].

Another example involved numerous laptops using NVIDIA graphics processing units (GPUs) and media and communication processors (MCPs) with problems such as overheating, blue screens, and display problems in HP, Dell, Sony, Toshiba, Apple, and Samsung computers [11], [12]. According to NVIDIA, the contributing factors were a "weak material set of die/package combination, system thermal management designs, and customer use patterns" [11], [12]. As of May 2010, NVIDIA reported that its GPU problems had cost it close to $\sim$400 million [13]. Class action lawsuits were filed against several of the computer companies for selling defective laptops. Purchasers of NVIDIA stock sued NVIDIA's president and chief financial officer, claiming that NVIDIA concealed the GPU and MCP problems for months [14]. NVIDIA was also directly sued by consumers for selling defective products [15]. The lawsuit was settled after NVIDIA agreed to pay for the replacement of chips, the replacement of computers, or the value of the computers [14].

Another example concerns the recall of apnea monitors made by Electronic Monitors Inc. following the 1994 death of a patient [16], [17]. An apnea monitor is a medical device intended to sound an alarm if the user ceases to breathe; it is frequently used to monitor infants' breathing to avoid sudden infant death syndrome or to monitor persons recovering from anesthesia. The apnea monitor's failure was traced to zinc whiskers in a rotary switch component used in the monitor made by Electro Switch Corp. Litigation followed the patient's death, with the monitor company suing the switch manufacturer and the switch manufacturer seeking recovery from the zinc electroplaters. The switch manufacturer, which had reliably produced switches for decades with the same zinc electroplating process, was originally unaware that a zinc whisker problem existed. The problem resulted because the switch had mostly been used and tested in high-voltage applications, where the zinc whiskers would form a short but would then simply burn. The zinc whisker development and subsequent burning, which produced no qualification test failures, happened both in normal application and during the testing conducted by the switch manufacturer. The problem, however, manifested itself as intermittent failures under low-voltage use conditions in the apnea monitor. The switch manufacturer was originally not aware of the low-voltage application conditions of the apnea monitor. Accordingly, the manufacturer was not in a position to conduct qualification testing with those conditions in mind. The apnea monitor company went out of business following the device failure.

Toyota initiated two related recalls between October 2009 and February 2010 to address unintended acceleration problems in several Lexus and Toyota models [18]. While Toyota attributed the unintended acceleration problems to floor mat entrapment and sticky gas pedals, the National Highway Traffic Safety Administration launched an investigation to determine whether electronics were to blame for the failures. While NASA's January 2011 report [19] did not find proof that electronics were responsible for the unintended acceleration problems, the report shed light on a different problem—tin whiskers due to the use of tin plating and lead-free solders. The study found tin whiskers through destructive physical analysis in a failed pedal that could lead a jumpy response. Electromagnetic interference (EMI) testing conducted by the NASA team was not found to cause unintended acceleration but in some cases caused the engine to slow and/or stall. While safety features in the Toyota system design prevented the electronic errors from causing unintended acceleration, both tin whiskers and EMI can be of intermittent nature, which can lead to field failures with a no-fault-found (NFF) situation, unless uncovered during qualification testing.

Ineffective qualification processes can easily result in large numbers of defective products entering the stream of commerce. A defect or reliability problem in one level of the supply chain can manifest itself at other levels and affect members in the supply chain whose products incorporate or interact with the defective component. The resulting costs for litigation, recalls, warranty service, and redesign, not to mention loss of reputation and market share, are staggering.

III. Problem(s)

Many companies perceive standards-based testing to be a means of quickly and cheaply qualifying products. Standards-based qualification practices in use today were developed at a time when the supply chain was not as diffuse and product development cycles were not as abbreviated. New technologies (for example, sub-micron, RoHS compliant and halogen-free) have evolved over the years in response to market demands and environmental regulations, but standards have not kept pace with the changes.

Standards-based testing involves assessing the capability of a product to pass a specified set of test procedures and thereby demonstrate reliability under environmental conditions that are expected during the life of the product [20]. With this approach, the evaluation is qualitative, since the relation between the applied test and application conditions is usually not established [1], [20]. Existing component qualification standards may be broadly classified as qualification test procedures and test plans, which contain a suite of tests. Qualification test procedures define individual test methods that describe how to conduct a specific test and include the JESD 22 series [21] and MIL STD 883 [22]. These test procedures are analogous to a cooking recipe, with step-by-step details on how to conduct a test. Qualification test plans, such as JEDEC JESD 47 [23], MIL-STD 883, and AEC Q100 [24], specify a combination of tests as part of a qualification regimen. These are more like a menu planner, putting together a combination of tests to create

a full qualification test plan. These qualification methodologies do not consider the failure mechanisms and acceleration factors for the specific application; rather, they rely on historical precedence in trying to ensure that products that pass certain standards-based tests will perform with adequate reliability in field applications [20].

Standards-based testing may be appropriate for known materials, processes, and end use environments. Problems however arise when the end use application is different from what the product was originally qualified for, or when materials, processes, and technologies change. While standards-based testing methodologies (e.g., JESD 47 and AEC Q100) explicitly state in their scope that qualification plans should be chosen only after considering any potential new failure mechanisms, process and technology changes, the disclaimers in many cases are not read or simply overlooked.

While a standards-based approach may have worked in the past with mature technologies, the lack of historical experience creates risks as new products and technologies evolve and as companies use new materials and processes in an effort to comply with evolving environmental regulations (or create the perception of being more environmentally friendly). Moreover, system manufacturers have in recent times been aggressively working toward energy savings. One way to achieve energy efficiency is by throttling system fans so that they run as little as possible. Consequently, components operate at higher temperatures, sometimes close to specification limits. While these components may have satisfied field requirements by passing certain standardized tests in the past, this may not hold true under the more severe field operating conditions imposed by energy-efficient system thermal designs.

Passing a standards-based test does not imply that the product will meet its reliability life requirements under actual use conditions, unless a relation has been established between the field use and test conditions. In some cases, the standards-based test is not stringent enough to meet field reliability requirements, and passing the test may create a false sense of security, while subsequently leading to field failures ("consumer's risk") [26]. In other cases, standards-based tests are too lengthy and can lead to a waste of resources, by rejecting good products that could have otherwise been shipped ("supplier's risk") [25]. The apnea monitor case [16] demonstrates how testing that is not suited to a specific application can miss key problems.

A manufacturer may successfully qualify a stand-alone component, but as more components are integrated to build the final product, the reliability of an individual component can decrease due to its interaction with other components or with the overall system design. The operational stresses on a component are often dictated by the surrounding components and the system design. For example, the NVIDIA GPU problems were created in part by unanticipated thermal issues resulting from the thermal design of some laptops. Component–component or component–system interactions may cause failures at some higher level that was not evaluated in qualification testing. Further, more severe operating load profiles imposed by the system design or by surrounding components may not be anticipated, and this can result in premature failure.

Intermittent behavior, which is the loss of function for a specified time and a subsequent recovery, may not always manifest itself during qualification testing [6]. Some of the worst field failures in electronics have been due to intermittent behavior. If not caught during qualification, intermittent failures often lead to problems such as NFF or retest OK (RTOK), as seen in the Ford ignition module failures. If the companies reporting these field failures conducted qualification testing, which we assume, then why were the failure modes not detected during the testing? Qualification testing that does not monitor performance parameters *in-situ* may fail to detect intermittent behavior and thereby create the false impression that a product is reliable because it passed a particular set of tests. If tests are conducted by monitoring parameters offline—that is, by periodically removing samples from the test chamber to conduct measurements, rather than measuring *in-situ*, intermittent faults that tend to recover without leaving any physical evidence of failure can go undetected. This is illustrated by the Ford ignition module case, where intermittent failures occurred under a stress condition (high temperature) but recovered when the stress was removed. While *in-situ* monitoring of performance parameters is more likely to uncover intermittent failures, it must be noted that success of identifying intermittants during testing is governed by a number of factors, such as the sampling rate (frequency) and the selection of parameters to monitor.

IV. A More Comprehensive Qualification Approach

The proposed solution involves a multipronged approach: 1) use of PoF principles in order to select optimum accelerated tests suited for a specific application; 2) use of PHM techniques in order to detect intermittent failures, determine life-cycle conditions, and provide early warning of failure; and 3) qualification at every stage of the product development cycle starting at the design stage, to proactively build reliability into the product.

A. PoF Testing

This section reiterates the PoF approach that has been discussed in literature and in earlier JEDEC [23], [26] and SEMATECH publications [20], [27], notably JESD 94 and JESD 47. PoF-based qualification (also referred to as knowledge- or failure-mechanism-based qualification) involves stressing and testing devices to precipitate failures that are subsequently analyzed [1]. This approach, which considers qualification as an integral part of design and development, involves identifying root causes of failure and developing qualification tests that focus on those particular issues [1], [20]. The PoF approach requires knowledge of the field use conditions, the expected failure modes and mechanisms, and the failure models for the specific mechanisms. Based on the usage environment, the critical failure mechanisms for the specific product configuration are identified. Appropriate failure models for the identified mechanisms are then applied in order to obtain time-to-failure data. Acceleration factors derived from the failure models provide a quantitative relationship between the field use and the qualification test conditions. By using these acceleration transforms, qualification test conditions can be selected so that

TABLE I
ILLUSTRATION OF DIFFERENCES IN APPLICATION CONDITIONS [JESD 94]

Application	Field lifetime (years)	Environmental and power cycles	Operational temperature range
High end server	11	4/year	14 to 55 °C
Avionic electronics in cockpit	23	2.5/day	0 to 50 °C
Automotive under-the-hood	15	5/day	-40 to 150 °C

passing the test indicates that the product will meet the required life in the field.

Standards-based testing without knowledge of use conditions and the expected failure mechanisms can lead to tests that are too severe and lengthy or not severe enough. Consider the example cited from JEDEC JESD 94 [26] of a temperature cycling test from -65 °C to 150 °C for 500 cycles. If the acceleration factor (defined as the time to failure at use conditions divided by the time to failure at test conditions) were 20, then passing the above test for 500 cycles would imply that the product can survive 10 000 cycles or 13.7 years, based on two cycles per day. If, on the other hand, the acceleration factor were 80, then passing this test would imply that the product could survive 54.8 years, which is well beyond the life requirement of any consumer product [20]. Therefore, by using a PoF-based approach, wherein a quantitative relation exists between the field use and qualification test conditions, testing can be optimized to ensure that it is not too lengthy or severe, resulting in a waste of resources, but stringent enough to ensure product reliability in the field.

As another example, consider the different use conditions (for illustration purposes only) cited from JEDEC JESD 94 [26] for a high-end server application, an avionic electronics application, and an automotive under-the-hood application (see Table I). A temperature cycling test from 0 °C to 100 °C for 2300 cycles is suggested to verify solder joint integrity, per JESD 47. For the high-end server application using a modified Coffin–Manson equation with $\Delta T_{\text{field}} = 41$ °C (see Table I) and $\Delta T_{\text{test}} = 100$ °C, an acceleration factor of 4.27 was obtained, as cited in JESD 94. Using a life requirement of 44 cycles (life requirement of 11 years $\times$ 4 cycles/year, from Table I), the number of test cycles required to verify solder joint integrity at the end of life = life requirement under use conditions/ acceleration factor, that is, $44/4.27 = 10$ cycles. Therefore, a temperature cycling test from 0 °C to 100 °C for 2300 cycles would be excessive for demonstrating solder joint integrity in this example. For the avionic electronics application illustrated in Table I, the life requirement is 21 000 cycles (23 years $\times$ 365.25 days/year $\times$ 2.5 cycles/day). Based on an acceleration factor of 3.08, the number of test cycles required to demonstrate that the product will meet its reliability life requirements is 6819, indicating that 2300 cycles of a temperature cycling test from 0 °C to 100 °C is not adequate. Next, consider the automotive under-the-hood application in Table I. The operational temperature range is wider than the temperature cycling test range, leading to an acceleration factor of 0.09. A temperature cycling test from 0 °C to 100 °C would not be severe enough to qualify as an accelerated test. Qualification testing can therefore predict whether a product will satisfy end-of-life requirements only if the use conditions and the relation between use and test conditions are known.

A common difficulty encountered in implementing a PoF-based approach is a lack of knowledge of the applicable use conditions and failure mechanisms/models. Failure mechanisms and models for electronic components have been widely documented in the literature, which can be consulted for details [2], [30]–[37]. If unknown failure mechanisms are identified, appropriate acceleration models need to be developed. The JEDEC standard JESD 91A [36] describes a method for developing acceleration models for electronic component failure mechanisms. Application-specific qualification systems are prescribed in JEDEC JESD 94 [26], JEP 148 [1], and in SEMATECH documents [20], [27]–[29]. These systems use test methods documented in the JESD 22 series or other JEDEC standards. Although standards-based testing as it is currently used has its flaws, many standards provide a baseline for qualification testing and detailed test procedures. Others, such as stress-test-driven test plans, specify what combination of tests needs to be used for a specific package type (for example, hermetic versus nonhermetic). By considering the use conditions and failure mechanisms for a specific application, stress-test qualification systems can be modified to use only those tests and test conditions that ensure that the product will meet its life requirement. When appropriately modified for a specific application, standards can still be useful tools for estimating the reliability of a product rather than simply standing as a "seal of approval" that a specific test was passed.

Information on use conditions can be obtained from customer requirements, from general knowledge of typical use, or from operational requirements of the product market segment [26]. While the SEMATECH guidelines [20] indicate that qualification must take into account the most severe use conditions that are likely to be encountered, overdesigning products to survive lengthy qualification tests can be needless and expensive. The use of PHM techniques can allow the life-cycle conditions to be determined *in-situ*, allowing a more meaningful reliability assessment through use of optimum test conditions.

B. PHM for Improved Qualification

PHM permits the evaluation of a product's reliability in its actual life-cycle conditions. PHM can be used to assess degradation (product health), determine the advent of failure, estimate the remaining useful life (RUL), and mitigate system risks.

1) Life-Cycle Monitoring for a More Accurate Reliability Assessment: Reliability predictions based on the expected life-cycle environment of electronic equipment, without knowledge of actual use conditions, can be inaccurate. Fig. 2(a) and (b) show the risk in extrapolating accelerated test data based on anticipated load profiles without actual knowledge of the life-cycle conditions. Fig. 2(b) indicates failure earlier than anticipated due to high-severity usage.

Knowledge of the life-cycle loads in field applications can help in designing qualification tests that pertain to the type of exposure the product experiences. Erroneous reliability predictions can be avoided by *in-situ* monitoring of the life-cycle loads.

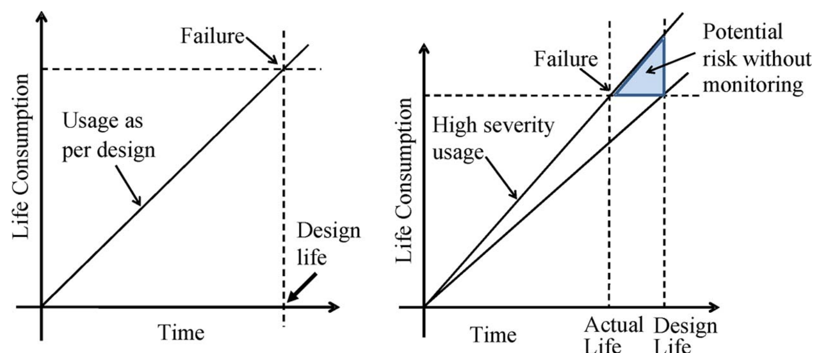

Fig. 2. (a) Life consumption when use conditions are per design. (b) Life consumption under severe use conditions leading to premature failure.

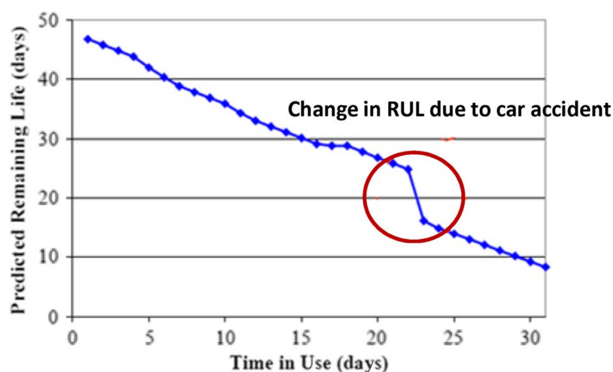

Fig. 3. Remaining life versus time; change in RUL as a result of unanticipated life-cycle conditions is reflected.

Several studies have characterized the environments of electronic products under actual use conditions. Searls *et al.* [37] undertook *in-situ* temperature measurements in both notebook and desktop computers used in different parts of the world and found that notebooks experienced more severe temperature cycling, both in magnitude and frequency, than desktops. The usage profiles were also found to be significantly different, with a greater percentage of "on" time for desktops. For similar components in laptops and desktops, the RUL for the laptop components should reflect the more severe life-cycle conditions experienced. Not accounting for these differences in use conditions can lead to overdesign and overqualification in some cases, or to earlier failures than anticipated. The NVIDIA GPU failures discussed earlier were mostly reported in laptops rather than desktops and may reflect the more severe life-cycle environments in laptop use.

Mishra *et al.* [38] and Ramakrishnan and Pecht [39] monitored the temperature, humidity, vibration, and shock loads experienced by electronic boards operated in automotive under-the-hood environments. Fig. 3 shows the change in the RUL estimate of the test system due to an unexpected life-cycle event, namely, a car accident. The damage due to the accident was calculated based on the monitoring of life-cycle conditions. This example demonstrates how life-cycle monitoring can detect unexpected loads that can lead to a decrease in the time to failure that may not have been otherwise anticipated.

The importance of understanding the actual life-cycle conditions has led some manufacturers to implement *in-situ* monitoring of their fielded products. For example, Toshiba has implemented condition monitoring in some of its fielded notebook computers. Toshiba's preinstalled software monitors key parameters including CPU temperature, system cooling, battery life, and hard drive shocks that were identified through analysis of product failures [40]. The software allows users to view the monitored parameters continuously and alerts them when a potential problem is detected. While this information is used primarily for preventive maintenance purposes, it can provide an understanding of the life-cycle loads during the actual use of the components in notebook computers. This information can then be used to obtain better reliability estimates of the internal components.

2) Fusion Prognostics Approach: Traditionally, PHM has been implemented using approaches that are either model-based or data-driven. The fusion prognostics approach combines elements of the model-based and data-driven approaches in order to provide the ability to detect intermittent faults, estimate RUL, detect anomalous behavior of the system, and allow effects of component interactions to be determined, while providing a physical understanding of failures [44].

The model-based approaches to PHM use mathematical representations to incorporate a physical understanding of the system. Prognosis of RUL is carried out based on knowledge of the processes that cause degradation and lead to failure of the system. The advantage of the model-based approach is the ability to predict RUL based on a physical understanding of the underlying processes. The limitations of this approach are the inability to capture intermittent behavior and the need for detailed knowledge of the system's geometry, material properties, and life-cycle conditions. Failure models are not suitable for detecting intermittent faults because sudden changes in system parameters that characterize such faults are not accounted for in the models.

The data-driven approaches use statistical pattern recognition and machine learning to detect changes in parameter data, thereby enabling diagnostic and prognostic measures to be calculated [44]. Data-driven techniques "learn" from the data and provide valuable decision-making information. This attribute makes it possible to detect sudden changes in system parameters, allowing for detection and analysis of intermittent faults. Data-driven approaches depend on historical (training) system data to determine correlations, establish patterns, and evaluate data trends leading to failure.

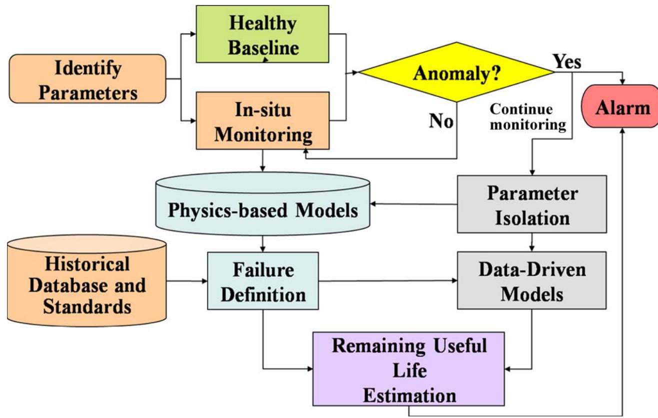

Fig. 4. Fusion prognostics approach.

The data-driven approach can be applied to complex systems, such as computer servers and notebooks where a large number of parameters are monitored [41], [42]. This approach can be used to model the correlation between parameters and interactions between subsystems, as well as the effects of environmental parameters, using *in-situ* data from the system. For instance, Kumar *et al.* implemented a prognostic approach for fault isolation in notebook computers [41], [42]. Various parameters, including CPU temperature, video card temperature, CPU usage, fan speed, and motherboard temperature, were monitored, and a baseline was created from an initial healthy state. Anomalies were then detected by comparing against this baseline. Field-returned laptops were tested against the baseline, and both anomalies and the parameters contributing to the anomalies were identified. A fault was deliberately introduced by creating a gap between the CPU and the heat pipe in order to simulate a problem with the thermal interface material. The CPU temperature was identified as an indicator of the fault [43]. In addition, the authors analyzed data from a field-returned computer and found that the fan speed was the faulty parameter [43]. While in this example it is not known whether the fault would have progressed into a failure, the authors have demonstrated that an anomaly could be detected through a Mahalanobis-distance-based data-driven approach, along with the contributing parameters. While every fault does not necessarily progress into a failure, diagnosing faults early can provide forewarning in cases where the fault has the potential to progress into a failure.

The selection of parameters to monitor in the fusion prognostics approach (see Fig. 4) is critical for the detection of intermittent failures and is aided by a failure modes, mechanisms, and effects analysis (FMMEA) and virtual qualification. FMMEA uses knowledge of expected life-cycle conditions to identify active stresses and to select potential failure mechanisms. Knowledge of load type, level, and frequency, combined with the failure sites, is used to prioritize failure mechanisms according to their severity and likelihood of occurrence [44]. Virtual qualification is the application of simulation software in order to determine the probability that the product will meet its life requirement goals [45]. Using inputs of product configuration, material properties, and expected life-cycle loads, times to failure are calculated for the identified failure mechanisms.

Information from the FMMEA and virtual simulations may be used to determine the environmental and product parameters to be monitored *in-situ* when the product is subjected to accelerated testing. Identification of the parameters can be supplemented with expert knowledge and maintenance records for similar products. Once the qualification tests targeting the identified failure mechanisms and the parameters to be monitored *in-situ* are chosen, the products are subjected to the selected accelerated tests. The next step is to assess the health of the product as it undergoes a qualification test. One way to detect anomalies, and thereby determine the health of the system, is to compare the monitored data in real time against a healthy baseline. A baseline is developed using data collected from various combinations of operating modes and loading conditions when the product is known to normally function [41], [42].

After an anomaly is identified, the parameters that significantly contribute to the anomaly are isolated (see Fig. 4), using techniques such as principal component analysis, least squares estimation, and maximum-likelihood estimation. Physics-based models, which use the isolated parameters as the primary inputs, are selected and used to calculate the RUL based on the environmental and parameter data, material properties, and product specifications. Failure definitions and thresholds are obtained from standards and from established failure criteria for a product. Using the failure thresholds, methods such as time series analysis or particle filtering techniques can be applied to predict the critical parameter values over time. The time until the parameter crosses the failure threshold is estimated as the time to failure of the product. Therefore, an estimate of RUL based on a combination of information from anomaly detection, parameter isolation, physics-based models, and data-driven techniques can be calculated. Alarms can be set off to announce that failure is impending based on the value of the reported RUL.

A PHM-enhanced qualification process allows the "health" of a product to be monitored rather than simply identifying the failure. As previously mentioned, testing for failure without monitoring performance parameters can miss uncovering intermittent behavior. A fusion prognostics approach can effectively capture anomalous behavior and intermittent faults, thereby allowing root-cause analysis of NFF errors.

C. *Qualification at Every Stage of Product Development*

In accordance with PoF principles, qualification should be an integral part of product design and development. Qualification should begin at the design stage through the use of analytical tools and simulation. Subsequent steps should involve an evaluation of the wafer fab process, package level reliability in both free standing and assembled states, as well as board and interconnect integrity before final product qualification. Fig. 5 illustrates the stages in an ideal qualification process.

The use of virtual qualification in the design and development phases can help determine the probability that a product will meet its life requirement goals [45]. Limited prototype testing may be done at this stage to validate the virtual qualification results. Significant savings in time and money can be achieved

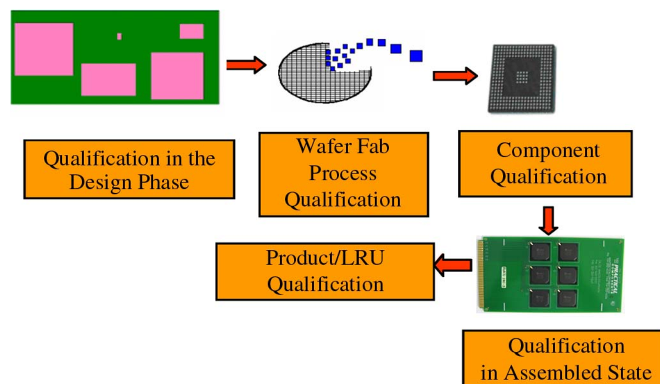

Fig. 5. Qualification at every stage of product development, LRU=line replaceable unit.

by using virtual qualification coupled with limited prototype testing, since this allows design parameters to be optimized.

The next stage of qualification should involve qualification of the wafer foundry process that produces the silicon [46]. The applicable JEDEC standard calls for two levels of wafer foundry qualification [47]. The first stage is a pure process qualification using specially designed test structures. In the second stage, a relevant functional technology qualification vehicle is used to evaluate the long-term failure rate of the process [47].

After the dies are assembled into packages, the overall component reliability should be assessed by subjecting the packages to various component qualification tests [21]–[24]. Qualification of free-standing components does not evaluate the effects of assembly processes, special attachments such as heat sinks, or component interactions [48]. For instance, an assembled component may be more prone to delamination than a free-standing component due to contaminants introduced during the assembly process. Therefore, once the components are assembled, the PCB assemblies need to be qualified to verify the reliability of assembled components and interconnections, as well as to identify any board-level issues. Product-level qualification should be subsequently conducted to ensure system reliability and to check for component interactions. For instance, in the NVIDIA example, the thermal design of some laptops was believed to precipitate failures in the GPU chip. The incremental qualification approach proposed here would have been able to capture component failures that resulted from interactions with the system design. While many commonly used test methods proposed here are standards based, as pointed out earlier, these can be appropriately modified by considering the use conditions and failure mechanisms for a specific end use application.

While qualification tries to ensure that a product with nominal design and manufacturing specifications will meet or exceed reliability targets, quality conformance is needed to ensure that lot-to-lot variation during manufacturing is within an acceptable tolerance range already established during qualification. Quality conformance is therefore required during the manufacture of qualified products and includes screening products through use of a stress or non-stress test, in order to weed out products that are defective [2].

V. Discussion and Conclusion

It can be difficult or expensive for component manufacturers to qualify their components to the specifications and use conditions of each product manufacturer to whom they sell. When it is possible and warranted, component manufacturers should qualify to a product manufacturer's specifications. When a component manufacturer cannot qualify to the product manufacturer's application, the latter will have to take the responsibility to ensure that the components utilized work reliably under the unique use conditions of the end product.

Consider a component manufacturer producing a commodity item such as common resistors, which the company may supply to both a toy manufacturer with a large market volume and to a medical device company that will use the same resistor in high-reliability applications such as implantable defibrillators. The market volumes in the latter case may be so small that the resistor manufacturer has little incentive to conduct more stringent qualification tests and also risks little if it loses sales in the high-reliability but relatively small medical device market. In such a scenario, the product manufacturer may try to work with the contract/component manufacturers in order to ensure that the components reliably work in their applications. In some cases, the product manufacturers may need to conduct additional testing on their own. Medical electronics manufacturers, for instance, must often "requalify" components because they find the qualification practices of the contract manufacturer to be insufficient. In other cases, contract manufacturers offer different grades of components, and the additional cost of qualifying to a more stringent specification may be passed on to the product manufacturer.

There have been also high-profile product failures where the contract manufacturer has suffered damage to its reputation and market share because of recalls by the product manufacturer. Toyota's January 2010 recall involved unintended acceleration due to sticky gas pedals. An Indiana-based company, called CTS, supplied the gas pedal assemblies to the Toyota vehicles that were involved in the particular recall [49]. This little-known company came to be associated with problematic gas pedals, and within days, a Chinese company suspended production of a commercial van because it used CTS pedal assemblies [49]. Even though CTS supplies its products to diverse markets, with the automobile sector accounting for 30% of its overall market and Toyota only 3%, the Toyota recalls brought CTS much unwanted and negative attention.

The NVIDIA case discussed earlier further illustrates how contract manufacturers can suffer severe damage to their reputations and market share due to component failures. Thus, the component manufacturer is often faced with a difficult business decision. Should it become more proactive in the qualification process to ensure a greater level of reliability of its component in a particular application in order to avoid potential damage to its reputation in the event the product fails? Or, should it focus attention on reducing costs (and thereby growing its market share and profits) by utilizing a standardized qualification process that is not adapted to the unique applications into which its component may be placed?

The increased cost associated with unique product qualification, on the one hand, must be balanced against the damage potential that follows from the use of a standards-based qualification model on the other. The damage potential from epidemic failures and subsequent litigation is likely to be higher for those in the supply chain who are closest to the consumer. For instance, computer manufacturers such as Dell, HP, and Apple were subject to litigation from consumers in the NVIDIA GPU case. NVIDIA itself was subject to claims by both consumers and computer manufacturers for supplying faulty GPUs. The further removed supply chain members are from the consumer, the less likely they are to face litigation from consumers or their own customers for product failures. Unfortunately, the incentive to change and improve current qualification processes subsides as the supply chain moves away from the consumer; this leaves the product manufacturers to bear the risks associated with current qualification practices.

In conclusion, companies around the world today face several challenges related to product qualification. These include shorter development cycles, a drive to reduce costs, and a more diffuse and complex supply chain over which they have less control. As a result, they often turn to standards-based testing as a means of quickly and cheaply qualifying their products. However, use of standards without understanding how the tests relate to the end use application can lead to testing that is too severe, with good parts being rejected. In other cases, testing is not stringent enough, leading to poor quality products being shipped, with subsequent field failures. Failures due to unexpected use environments, component interactions, and intermittent faults are not effectively captured using current qualification practices. Interactions between components or with the system in the final product configuration can lead to severe operational stresses, as shown in the NVIDIA case. A further problem often encountered in field failures is "NFF" or "RTOK" due to intermittent behavior, as demonstrated in the Ford ignition module case.

A more comprehensive qualification process involving the use of PoF principles, PHM techniques, and qualification at every stage of product development, starting at the design stage, will lead to increased product reliability and to a reduction in the massive waste of time and resources that field failures create.

By using PoF principles, tests can be focused on the relevant use conditions and failure mechanisms for a specific application. The apnea monitor failure, for instance, could have been avoided by tailoring the qualification testing to the specific application. By applying failure models for the identified mechanisms, test conditions can be selected so that passing a test will ensure that the product performs with adequate reliability in the field.

Use of PHM techniques enables life-cycle conditions to be determined, intermittent failures to be detected, and also provides early warning of failure. Anomalous behavior and the environmental/performance parameters that contribute to the anomaly can be identified, thereby allowing intermittent faults, which are characterized by sudden changes in system parameters, to be detected during qualification testing. Identification of anomalies before they progress into failures can provide forewarning of impending failure and allow a root-cause analysis.

Component interactions can be effectively addressed by using "incremental" qualification, that is, qualification at every stage of product development. The effects of operational stresses that arise from surrounding components, system design, or the assembly process can be captured through such an incremental qualification process. Ultimately, a more comprehensive qualification process will yield a better product through true reliability assessment rather than the currently employed narrow process of qualification through simply passing a specified set of standard tests.

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