Prognostics-Based Product Qualification

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Abstract—Qualification is the process of demonstrating that a product is capable of meeting or exceeding specified requirements. The specified requirements are expected to depend on the final product and its specific life cycle application conditions.

In this paper, a prognostics-based qualification is proposed, which is more efficient and cost effective than the traditional qualification process. The approach does not require a product to fail in the test, because in addition to detecting failure, the health of the product is monitored, including degraded health and intermittent product disruptions. The results are a significant decrease in qualification time and much improved understanding of the product's reliability.[1 2]

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1. INTRODUCTION

Product qualification aims to evaluate the performance of products under specified operating and environmental conditions within a specified period of time [1]. Improper qualification tests can cause many product problems: for example, the recall of Ford ignition modules, GM windshield wiper electronics, Sony batteries, Microsoft X-Box consoles, HP laptop computers, and Nvidia graphics chips [2].

Normally qualification tests are not conducted under the normal application conditions, but at accelerated levels of stresses to accelerate potential failure mechanisms. This traditional qualification method has numerous bottlenecks.

First, most qualification tests follow certain standards [1]; however, these standards do not reflect either the conditions of use or the duration of use.

Second, in some conditions there is no margin to perform an accelerated test since the real application conditions are at the limits of the failure mechanisms (normally the overstress and wear-out mechanism transition area acts as a margin). This is especially the case for the automotive and oil drilling industries, since their environments are already at accelerated conditions.

Third, traditional qualification tests take too much time and slow down the schedule, while time-to-profit is the driving force of a company's success. Therefore, a solution other than the traditional qualification method is needed.

A new qualification test based on Prognostics and Health Management (PHM) is presented in this paper. PHM is a method that permits the assessment of the reliability of a product (or system) under its actual application conditions [3]. It includes the physics-of-failure (PoF) approach, the data-trending approach, and a combination of both approaches (fusion approach). This new method considers the product life cycle loading, multi-components' interactions, and performance degradation trending. Therefore it provides the capability for better product qualification tests.

2. PRODUCT QUALIFICATION

Product qualification can be used to baseline the design, materials, and processes that go into making a product. It can also be used to compare different designs to help make design decisions. Product qualification is used to meet the requirements of customers with consideration of the intended application conditions.

The PHM-based product qualification methodology is shown in Figure 1. The first step is to conduct Failure Mode, Mechanisms, and Effects Analysis (FMMEA). Identifying the critical failure mechanisms induced by life-cycle loads on a product provides options for the selection of qualification tests. Tests targeting the identified critical failure mechanisms should be selected as qualification tests. A cross-functional team (design, manufacturing, reliability, etc.) will allow for better identification of issues and criticality. Then accelerated testing is conducted. There are

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three approaches toward assessing product qualification during testing: the Physics-of-Failure (PoF) approach, the data-trending approach, and the fusion approach. Each approach will be discussed later in this paper.

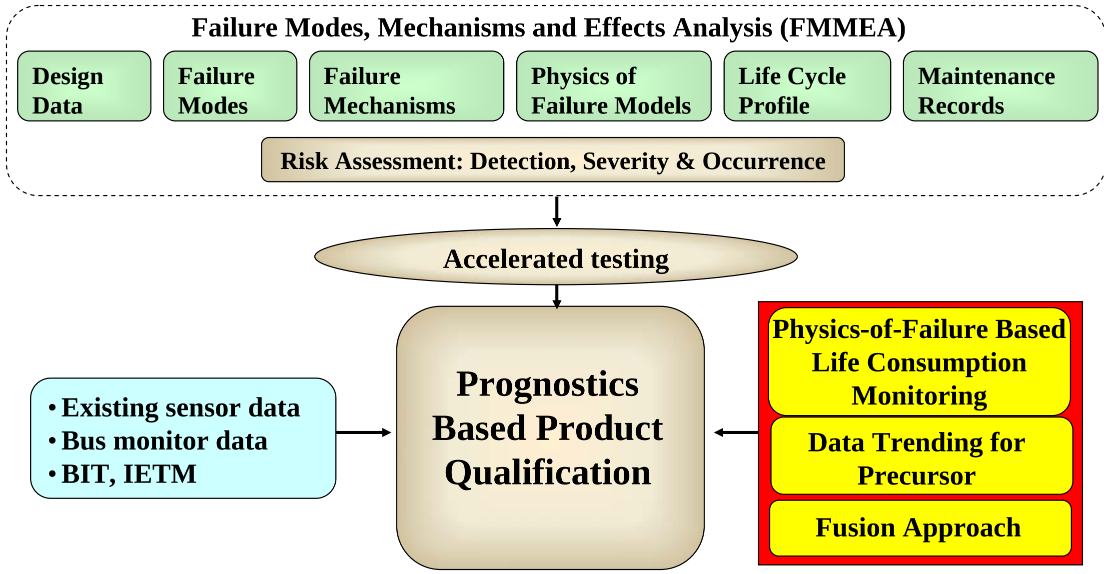

Figure 1. Prognostics-based qualification methodology.

2.1. Failure Modes, Mechanisms, and Effects Analysis (FMMEA)

FMMEA is a methodology used to identify critical failure mechanisms. FMMEA utilizes the basic steps in developing a traditional FMEA in combination with knowledge of the physics of failure [4]. It then uses a life cycle profile to identify active stresses and to select the potential failure mechanisms. Knowledge of load type, level, and frequency combined with the failure sites are used to prioritize failure mechanisms according to their severity and likelihood of occurrence. Figure 2 is a schematic diagram of FMMEA.

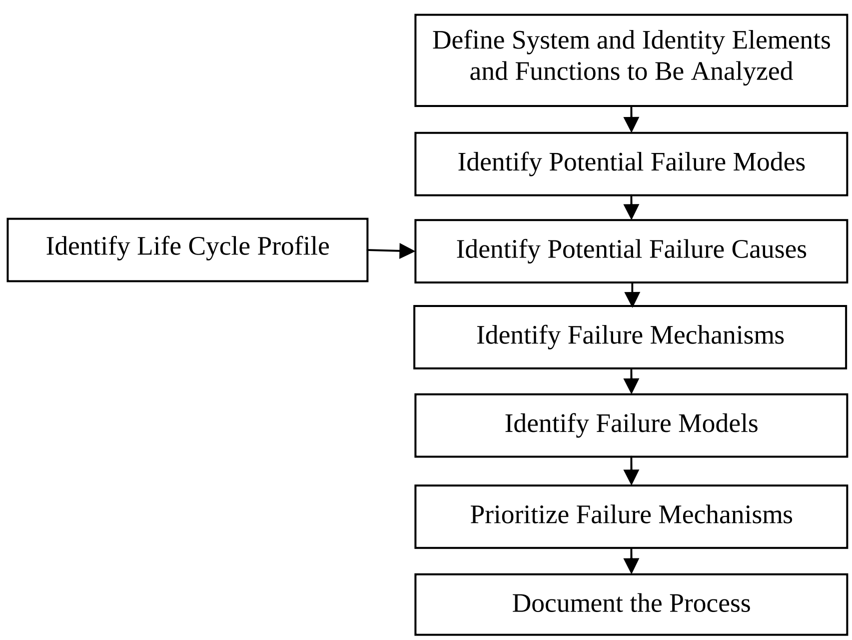

Figure 2. FMMEA methodology.

FMMEA is based on understanding the relationships between product requirements and the physical characteristics of a product (and their variations in the production process), the interactions of product materials with loads (stresses at application conditions), and their influence on the product's susceptibility to failure. Potential failure mechanisms are determined based on mechanisms corresponding to the material system, stresses, failure modes, and causes. FMMEA prioritizes the failure mechanisms based on their occurrence and severity in order to provide guidelines for determining the major operational stresses and environmental and operational parameters that must either be accounted for in the design or controlled. The high-priority failure mechanisms identified through the combination of occurrence and severity are the critical mechanisms. Critical failure mechanisms are the priority mechanisms considered in qualification tests. The failure sites, modes, and causes associated with the critical failure mechanisms will provide information used to select the qualification test conditions.

The basic categories of failures are overstress (i.e., based on stress strength interference) and wear-out (i.e., based on damage accumulation). They are often identified through a mode that goes beyond performance tolerance (e.g., excessive propagation delays). Overstress and wear-out failures generally result from irreversible material damage; however, some overstress failures can be caused by reversible material damage (e.g., elastic deformation).

Failure models are used as tools to assess failure propensity. In PoF models, the stresses and the various stress parameters and their relationships to materials, geometry, and product life are considered. Each potential failure mechanism is represented by one or more of the prevalent models.

A model should provide repeatable results, reflect the variables and interactions that are causing failures, and predict the behavior of the product over the entire domain of its operational environment. A PoF model allows for the development of accelerated testing and may help to reduce the number of test runs. Many PoF models, such as the Coffin-Manson model [5], and the Steinberg model [6], exist for predicting the behavior of components and products. Different models have different associated assumptions that limit their applications to specific ranges of conditions.

2.2. Accelerated Testing

After FMMEA assessment, accelerated testing is conducted, since a high level of stress can cause failures within a short period of time. Accelerated testing allows for reduced test times by providing test conditions that “speed up” the evolution of failures, thus saving the time-to-market of a product. Accelerated testing involves measuring the performance of the test product at loads or stresses that are more severe than would normally be encountered in order to enhance the damage accumulation rate within a reduced period of time. The goal of such testing is to accelerate the time-dependent failure mechanisms and the damage accumulation rate to reduce the time-to-failure. The failure mechanisms and modes in the accelerated environment must be the same as (or quantitatively correlated with) those observed under actual usage conditions, and it must be possible to quantitatively extrapolate from the accelerated environment to the usage environment with some reasonable degree of assurance.

There are two types of accelerated testing: qualitative accelerated testing and quantitative accelerated testing. In qualitative accelerated life testing, the engineer is mostly interested in identifying failures and failure modes without attempting to make any predictions as to the product’s life under normal usage conditions. In quantitative accelerated life testing, the engineer is interested in predicting the life of the product at normal use conditions from data obtained in an accelerated life test.

Accelerated testing should be targeted at the critical failure mechanisms that have been determined. Load parameters that directly cause time-dependent failure are selected as the acceleration parameters and are commonly called accelerated loads [7]. Common accelerated loads include thermal loads, such as temperature; chemical loads, such as corrosion; electrical loads, such as voltage; and mechanical loads, such as vibration. The accelerated test conditions may include a combination of these loads. Interpretation of the results for combined loads requires a quantitative understanding of their relative interactions and the contribution of each load to the overall damage.

Failure due to a particular mechanism can be induced by several acceleration parameters. For example, corrosion can be accelerated by both temperature and humidity, and creep can be accelerated by both mechanical stress and temperature. Furthermore, a single acceleration stress can induce failure by several wear-out mechanisms simultaneously. For example, temperature can accelerate wear-out damage accumulation not only by electromigration, but also by corrosion, creep, and so on.

Failure mechanisms that dominate under usual operating conditions may lose their dominance as the stress is elevated. Conversely, failure mechanisms that are dormant under normal use conditions may contribute to device failure under accelerated conditions. Thus, accelerated tests require careful planning in order to represent actual usage environments and operating conditions without introducing extraneous failure mechanisms or non-representative physical or material behavior. The degree of stress acceleration is usually controlled by an acceleration factor, defined as the ratio of the life under normal use conditions to that under the accelerated conditions. The acceleration factor should be tailored to the hardware in question and should be estimated from a functional relationship between the accelerated stress and reduced life in terms of all the hardware parameters.

Once the dominant failure mechanisms have been identified, it is necessary to select the appropriate accelerated loads; to determine the test procedures and the stress levels; to determine the test method, such as constant stress acceleration or step-stress acceleration; to perform the tests; and to interpret the test data, which includes extrapolating the accelerated test results to normal operating conditions [7] [8]. The test results provide qualitative failure information for improving the hardware through design or process changes.

2.2.1. Strength limits and margins

Strength limits are obtained by following the methodologies of the Highly Accelerated Life Test (HALT). The purpose of HALT is to expose design weaknesses by iteratively subjecting the product to increasingly higher levels of stress and then learning what aspects or components should be improved. HALT is the first physical test performed during the product qualification stage.

In product qualification, HALT can be used to identify the operational and destruct limits and margins, known as the “strength limits,” as shown in Figure 3. The limits include the upper and lower specification limits, the upper design margin, the upper operating limit, and the upper destruct limit. The specification limits are provided by the manufacturer to limit the usage conditions the customer might expose a product to. The design limits are the stress conditions at which the product is designed to survive. The operational limits of the product are reached when the product can no longer function at the accelerated conditions due to a recoverable failure. The stress value at which the product fails permanently and catastrophically is identified as the destruct limit. Generally, large margins are desired between the operational and destruct limits, and between the actual performance stresses and the specification limits of the product, to ensure higher inherent reliability.

Accurate mean strength limits and margins can be identified only if sufficient numbers of samples are tested to reveal complete distribution characteristics. The strength limits obtained from HALT can be used in planning the accelerated test and screening conditions. The destruct limits can be used as the baseline for highly accelerated stress screening tests (HASS) during production-level qualification. If the product demonstrates survivability well beyond its operational limits or the limits of screening equipment, then the search for destruct limits can be terminated.

For designs, the primary goal of HALT is to place as much margin as possible between the product’s specified or guaranteed operating limits and the operating limits observed during HALT. Studies have consistently shown that products with generous performance margins between the specifications and actual performance are inherently more reliable. The determined destruct limits are used to ensure that a sufficient margin exists between the operating and destruct limits in order to provide insight into how a product design process can be improved and to establish a baseline for a production-level HASS. For some products, the search for the destruct limits may be aborted when the product exhibits survivability well beyond the previously determined operating limits or survivability at the limits of the screening equipment.

Figure 3 indicates the margins for the acceleration tests. Generally, there are two ways of conducting accelerated tests. One is to increase the usage frequency, and the other is to increase the stress level. However, some industries (such as automotive and oil drilling) and the military do not have the margins to perform an accelerated test since the conditions are already at the limits of the failure mechanisms. In this case, the PoF approach for qualification tests would not be suitable. The data-trending and fusion approaches should be used and are discussed later in this paper.

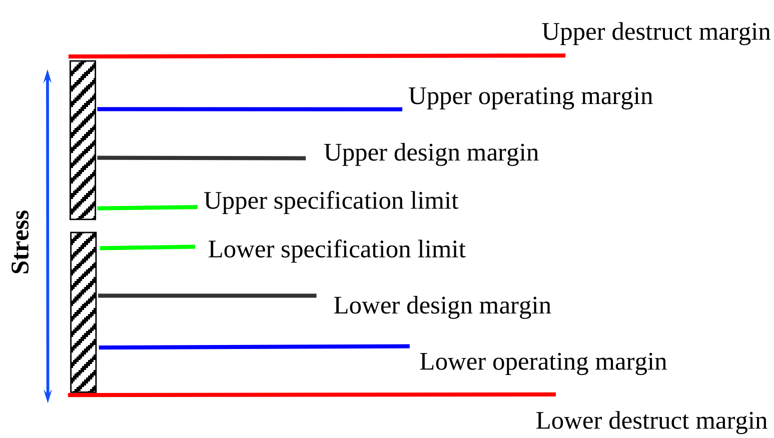

Figure 3. Stress limits and margins diagram.

2.2.2. Failure analysis and verification

Detailed failure analysis of failed samples is a crucial step in the qualification and validation process. Without such analyses and feedback to the design team for corrective action, the purpose of the qualification program would be defeated. In other words, it is not adequate simply to collect failure data. The key is to use the test results to provide insights into and, consequently, control over relevant failure mechanisms and to prevent them cost effectively. In addition, prognostics based qualification can predict some failure before failure actually happens. For example, even if a crack inside a solder joint in a piece of electronics has not fully propagated to cause product failure, it can still be detected using RF impedance analysis [9]. Failure analysis should be conducted to establish the relation between crack length and impedance change, and this relation can be used for prognostics purposes.

3. PROGNOSTICS APPROACH FOR QUALIFICATION ASSESSMENT

There are three prognostics approaches (shown in Figure 1): physics-of-failure (PoF), data-trending, and the fusion approach. The fusion approach benefits from the merits of both the PoF and data-trending approaches, and its procedure is shown in Figure 4. All three approaches will be discussed.

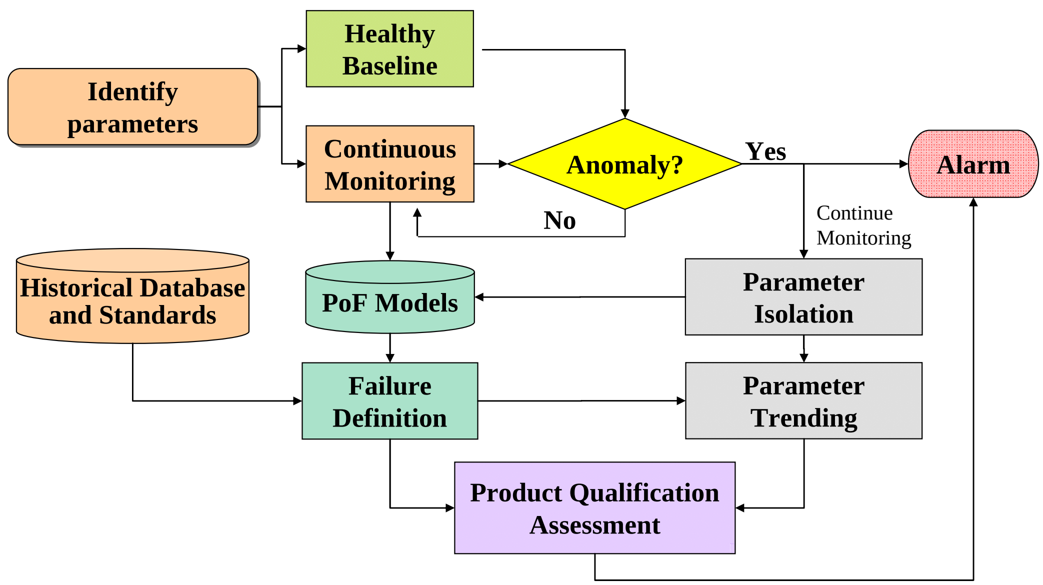

Figure 4. Fusion prognostics approach for product qualification.

3.1. PoF-based Qualification Assessment

In the product qualification process, physical tests are applied to the manufactured prototype to verify whether it meets its functionality and reliability requirements. A PoF-based methodology for product qualification was developed [10], and the flowchart is shown in Figure 5, which is part of Figure 4.

3.1.1. Product Configuration and Materials

One of the fundamental steps in product qualification is to characterize a product in terms of its configuration and materials. Information about the configuration and materials of the product provides engineers with the basic knowledge for qualification. Such information includes the architecture of the product, the materials used to manufacture the product, and the processes that the materials experienced during manufacturing.

A product consists of a number of components and subassemblies working together to deliver overall function. Each subassembly may consist of lower level assemblies that are also interconnected. The architecture of a product describes the physical and functional relations between the subassemblies. The hardware configuration of the product describes the design of the components and subassemblies and the product architecture. It may also include the effects of the manufacturing process on the final product in the form of tolerances on the dimensions and material properties.

The hardware of electronic equipment includes electronic parts, printed circuit boards, connectors, and enclosures. An electronic part may be a semiconductor chip and the package that provides power and ground inputs, signal communication paths to the outside, and protection from the environment. An electronic part may also be a passive component such as a resistor or capacitor. The part geometry and structure, the subcomponent geometry, and the connection methods, such as wirebonds or solder balls, should also be characterized. A printed circuit board description includes the materials; layer stacks; connections between layers; additions to the layers, such as heat spreaders; and elements like stiffeners.

Materials used to construct a product influence the level of stress on the product due to external and internal loads and the process of damage accumulation [11] [12]. To the extent that materials influence stress and damage, their physical properties should be characterized [13] [14]. For example, a failure in a solder joint may be driven by stress arising from repeated temperature excursions. In this situation, the coefficient of thermal expansion of a material is needed to determine the cyclic stress state. In another situation, a failure may occur due to a reduction in the contact force between connector elements. This situation may require the elastic modulus of the connector elements, loading elements, and their housings to determine the contact force and its degradation pattern. Properties for common materials used in electronic products can be found in references [13] [14] [15].

Products are not normally produced by a single manufacturing process. They often require a sequence of different processes to achieve all the required attributes of the final product. The manufacturing process applies stresses on materials, may produce residual stress, and may even modify some of the properties of the materials. For example, a lead-free reflow profile can change the thermo-physical properties of a printed circuit board. The variations in geometry and material properties caused by different manufacturing processes need to be characterized.

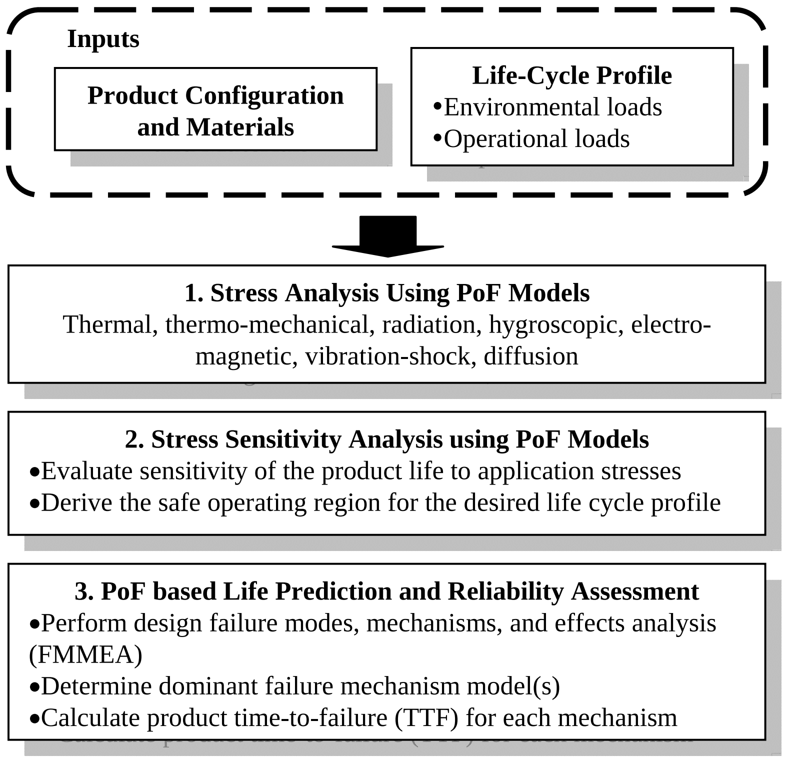

Figure 5. PoF-based product qualification.

3.1.2. Life cycle profile

The second step in product qualification is to understand the Life Cycle Profile (LCP) of products. The LCP is the basis for selecting product qualification test conditions, including types and severity levels. The major task in understanding the LCP is to characterize the loads applied onto a product during its life cycle. The environmental loading for a component should be considered to be from its surrounding environment as well as from within, but not from the system-level environment. For example, when a silicon chip is working, the temperature and humidity of its environment will affect its function and reliability, as does the heat generation within the chip.

An LCP is a time history of events and conditions associated with a product from the time of its release from manufacturing to its removal from service. The life cycle includes various phases that an item will encounter in its life, such as handling, shipping, and storage prior to use; mission profiles while in use; phases between missions, such as stand-by, storage, and transfer to and from repair sites and alternate locations; geographical locations of expected deployment and maintenance; and maintenance and repair procedures for the system and its components.

Loads applied during its life cycle drive the processes that lead to product degradation and failure. The life cycle of a product includes manufacturing and assembling, testing, reworking, storing, transporting and handling, operating (e.g., modes of operation, on-off cycles), and repairing. The life cycle loads include assembly- and installation-related loads, environmental loads, and operational loads. These loads can be thermal [16], mechanical, chemical, physical, or operational. Various combinations and levels of these loads can influence the reliability of a product. The extent and rate of product degradation depend upon the nature, magnitude, and duration of exposure to such loads.

Since a product may experience numerous loads, it is necessary to identify the ones most critical to its function and reliability. Some of the loads will play major roles in activating and accelerating the failure of a product, while others can be ignored. For example, low levels of radiation can often be ignored for ground-based electronic products, since this rarely causes dysfunction in or damage to products. Whether the loads can or cannot be ignored depends on the critical failure mechanisms that are identified in the analysis, which considers the life cycle conditions.

Normally, the LCP for a product is difficult to obtain. Even the product manufacturer will not know exactly how the customer will use their product. One contribution from prognostics and health management is that it really monitors the life cycle loading of a product. It can be used to improve the design of future products and verify the qualification tests. If the tests have not covered all of the usage loading levels, more tests should be perhaps performed. If the tests have exceeded the values for the customers' loading levels and time, some tests may be reduced to save costs.

3.1.3. Reliability Assessment

Reliability assessment is performed based on the accelerated test data and the PoF models. The reliability of the product is determined in terms of time-to-failure at the identified failure sites for a specific failure mechanism due to a specific load condition. With the failure sites, stress inputs, and failure models, the reliability of a product is estimated and reported in terms of time-to-failure of the identified failure sites. Most failure models define time-to-failure under a specific loading condition. In the qualification test, the reliability of products is defined in order to meet the specified reliability requirements under qualification test conditions.

For most products, the life cycle profile consists of multiple loading conditions. As a result, methods for evaluating time-to-failure over multiple loading conditions must be derived. One approach is to cast the time-to-failure for a specific failure mechanism in terms of the ratio of exposure time to the stress condition over time-to-failure for the stress condition. This ratio is often referred to as the damage ratio. If the exposure time is equivalent to the time-to-failure, then the ratio would equal 1. If one assumes that damage accumulates in a linear fashion, the damage ratios for the same failure site and mechanism can be added over multiple defined stress conditions. It is then assumed that once the accumulated damage ratio equals 1, failure at the site would occur. For the same site and the same failure mechanism and for fixed-duration load events, a specific damage ratio can be determined. For example, dropping a handheld device from a certain height may result in a loss of 10% of the life of a solder interconnect. In this case, each drop will result in an increment of 0.1 damage ratio for the solder interconnect. For repetitive events, a damage rate may be established by the use of the appropriate failure models to estimate the number of events required to produce failure. The damage rate is then defined as 1 over the estimated number of survivable events. For example, if a failure model estimates that a solder interconnect can survive 2000 temperature cycles, then the damage rate per cycle is 0.0005.

In general, time-to-failure data is obtained as a distribution for each failure site and failure mechanism. This distribution on time-to-failure is achieved by considering the input parameters to the failure models as distributions. In reality, all dimensional and material properties are distributed around a nominal value as a result of variations in manufacturing. The same is true for the environmental loads. The PoF-based reliability assessment allows for utilization of these natural variations in the reliability assessment. With the time-to-failure distribution for each site known, reliability can be evaluated in different metrics, such as hazard rate, warranty return rate, or mean time-to-failure.

In addition to evaluating time-to-failure, the use of failure models allows for the examination of time-to-failure sensitivity to material, geometry, and life cycle profile. By considering the impact of the identified material and product geometries and loading conditions, the most influential parameters can be identified. This information can be used to improve design through closer attention to critical design parameters.

One example of the use of the PoF approach is to calculate the acceleration factor. By comparing the environment loads in the application condition and accelerated condition, it is possible to obtain the acceleration factor. For example, suppose there is a product that is designed to be used for 3 years. From previous experiments and PoF models, we know that if the product can pass 100 temperature cycles under accelerated testing conditions without failure, it will remain useable for 5 years under the application conditions. Then we only need to conduct 60 temperature cycles in the qualification test and do not need to wait until 100 temperature cycles are completed.

3.2. Data-Trending-Based Qualification Assessment

In some cases, it is either difficult or impractical to use the PoF-based approach for prediction purposes. Data-trending approaches to PHM can be used for qualification by monitoring system operating and environmental data (e.g., power, current, voltage, temperature, humidity, vibration, and acoustic signal). The measured input/output data is the major source of data for understanding system degradation behavior. The approach is shown in Figure 6 [17]. It starts with functional evaluation of the system under consideration. After a feasibility study, data acquisition techniques are investigated to gather system performance information in real time. A number of features are looked upon to represent system behavior by sensor information. During this process, data cleaning and data normalization are performed on raw data to reduce the associated noise and remove the scaling effects. Data features are used to establish the healthy state of the system. These features are also used to identify performance deviation resulting from the presence of a fault. The threshold limits on these features are set to define system failure. The trending of features provides fault or damage progression over time. This information is used to perform system prognostics and qualification assessment.

One example of the data-trending approach is shown in research work on the failure prognostics of capacitors. In this particular study [18], 96 capacitors underwent Temperature, Humidity, and Bias (THB) tests. Five out of eight failed capacitors showed advanced warning of failure through the trending of the capacitance, dissipation factor, insulation resistance, and their correlations. This indicates that it is not necessary to run an experiment until a product fails. When an anomaly is detected, it is possible to estimate the time-to-failure of the product, which can save time and cost.

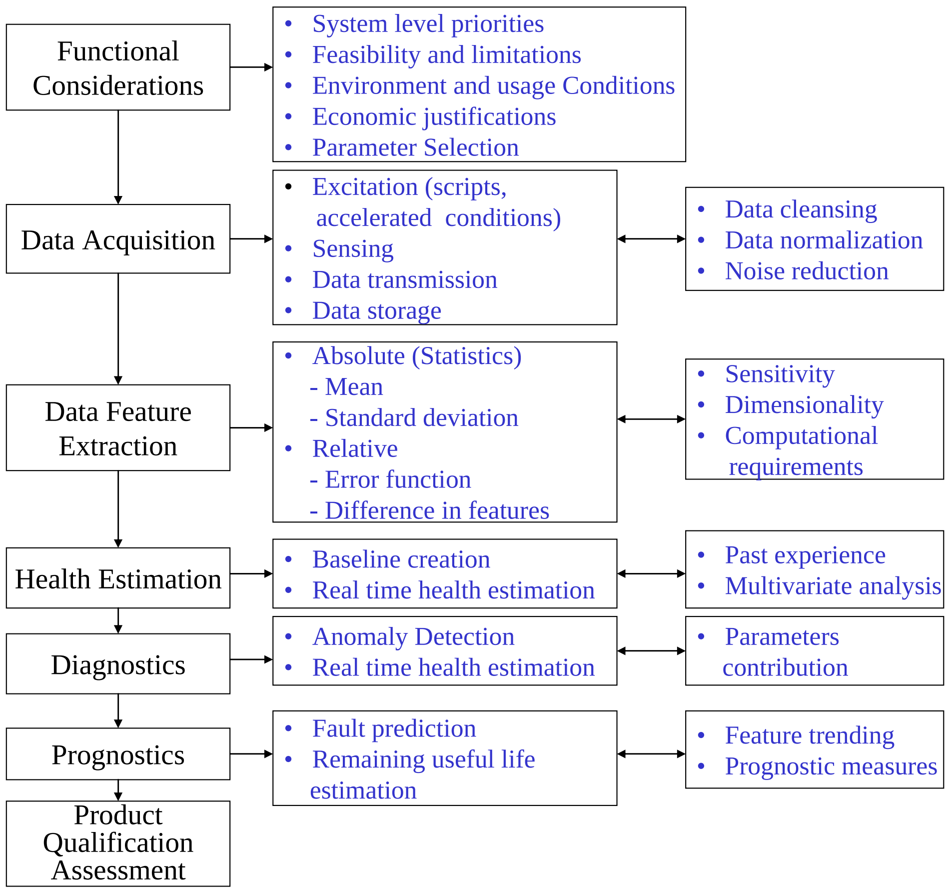

Figure 6. Data-trending-based product qualification.

3.3. Fusion Approach for Qualification Assessment

A fusion approach (PoF + data trending) can enhance the pure PoF and data-trending approaches. The fusion approach benefits from the merits of both the PoF and data-trending approaches. The advantage of the PoF method is its ability to isolate the root cause and the failure mechanisms that contribute to system failure. The advantage of a data-driven approach is that it addresses the complexity and the density of systems by utilizing system operating data.

The fusion prognostics approach is summarized in Figure 4. The first step in the process is to determine the set of parameters that can be continuously monitored. The identification of the parameters for monitoring can be aided by a process such as failure modes, mechanisms, and effects analysis (FMMEA), but in general it can consist of any available data, including operational and environmental loads, as well as performance parameters.

In the fusion approach, the continuously monitored data is compared with a healthy baseline to check for anomalies. A healthy baseline is a collection of parameter data that best represents the possible variations of the normal operation of a system. The healthy baseline is developed using data collected from various combinations of operating states and loading conditions when the system is known to be functioning normally, but is sometimes based additionally on specifications and standards. The parameters that contribute significantly to the observed anomaly are isolated. These parameters help to determine the PoF models most relevant to system degradation and that provide information such as the failure thresholds for system parameters, the failure modes, and the stages of degradation and labels of healthy and unhealthy conditions.

Appropriate PoF models are selected based on real-time anomaly detection and critical parameter isolation. The relevant PoF models are used to determine failure definitions. Accepted standards can also be used to aid in the determination of the failure definitions. Reliability assessment is estimated using the selected PoF model.

For performance parameters, statistical features and empirical relationships can also be established. The data-driven approach focuses on obtaining primary patterns or relationships, such as the correlation, covariance, residual, and inference patterns between system and component variables and operating and environmental loads. Failure precursor techniques are used to extract the features and track their deviation from the normal operating condition. This is especially useful for early detection of failures, where very distinct distribution patterns have been attributed to a specific failure. This also saves a lot qualification time.

One example of the fusion approach is tracking the crack length of a product under vibration fatigue. It is not necessary to run tests until the product fails. From the trending of crack growth along with the increase in vibration cycles, it is possible to predict the time-to-failure (the crack length reaches the failure definition) of the product under accelerated testing conditions. After that, failure models can be used to predict the time-to-failure in real usage condition loadings. This information can be compared with the product specifications to verify whether the product meets the qualification requirements. In this case, it is not necessary to perform the accelerated tests until the product fails, and a lot of time is saved.

4. Case Study: Accelerated Temperature Cycling Tests for BGA Components

This section provides a case study of the prognostics-based qualification approach. The approach has been applied to an accelerated temperature cycling test conducted on Ball Grid Array (BGA) components (as shown in Figure 7).

Test boards populated with 8 BGAs (256 I/Os) were subjected to thermal cycling. The temperature cycling was performed from -40°C to 185°C with dwell times of 15 min at both extremes. The ramp rate was chosen to be 3.5°C/min. Each BGA was provided with a separate daisy chain to permit continuous monitoring of resistance. The temperature and resistance of each BGA was recorded once every minute. The time to failure was 992 cycles from the data-logger recording as determined by referring to the IPC-SM785 standard [19]. This is the traditional way to conduct qualification tests.

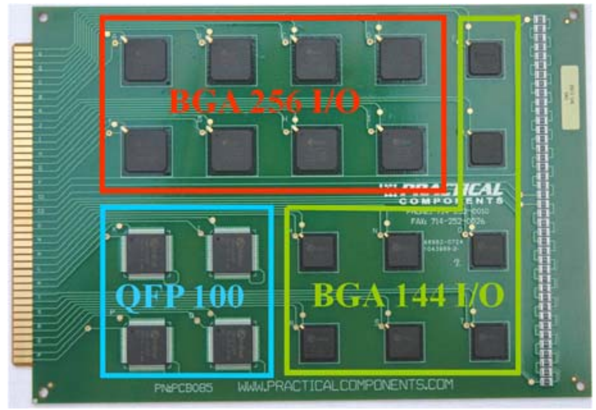

Figure 7. Qualification test board.

With the prognostics approach, the temperature and resistance data from each BGA was used for multivariate state estimation technique analysis and followed by the sequential probability ratio test. The anomaly was detected at the 583rd cycle (as shown in Figure 8). Then, by using the thermal fatigue PoF model, the cycles-to-failure was predicted to be 1038 cycles. That means it was not necessary to wait until failure occurred (992 cycles), and we could save more than 400 cycles in qualification testing.

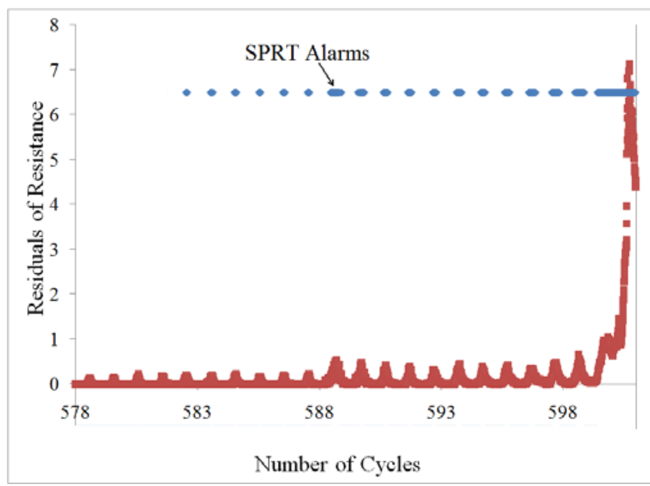

Figure 8. SPRT alarms for anomaly detection.

5. Conclusions

The qualification process is used to verify whether a product meets or exceeds the reliability and quality requirements of the intended application. Prognostics-based qualification can be used in product qualification tests. It can significantly reduce test time and save test cost because it is not necessary to run the experiment up to product failure. It can better incorporate combinations of loads and load profiles of the target applications, because in-situ monitoring provides the real life cycle load profiles for the lab qualification test. It can pick up various anomalies because it is sensitive to correlated parameter changes (parameter interactions). It can be incorporated into products for other prognostics and health management purposes, such as advance warning for field product failure and remaining life calculation.

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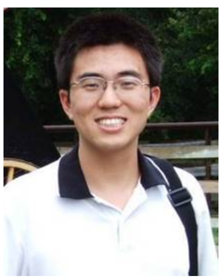

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