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A Methodology for Assessing the Remaining Life of Electronic Products

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Abstract: Remaining life assessment is an estimate of the reliability of a product in its life cycle application environment based on health monitoring and prognostics analyses. This paper reviews remaining life assessment methodologies that are currently employed for engineering products, and discusses their potential applicability to electronic systems. Based on this review, a generic 'Health Status Assessment' methodology for assessing the remaining life of electronic products is derived. The methodology is applied to an electronic circuit board used in a space application.

Key Words: *Health and usage monitoring, remaining life, life cycle, prognostics health management, FEMA, FEMMA, stress and damage modeling, electronics reliability*

1. Introduction

The reliability of an electronic product is defined as its ability to perform its intended functions for a specific period of time, in its life cycle application environment. Electronic products can experience a range of load conditions during their lifetime, from manufacturing, assembly, testing, storage, handling, transportation, to operation. Depending on the application and environment in which the product is used, the loads can vary from benign to destructive. Over time, such loads can cause accumulated damage to the printed circuit board, electronic components and component-to-board interconnects, and affect the reliability of the product [1].

Traditional electronics reliability prediction methods utilize field data, test data, stress and damage models, and reliability handbooks. These methods generally do not accurately account for the life cycle environment of electronic products [2]. This arises from either fundamental flaws in the reliability assessment methodologies used [3], or uncertainties in the product life cycle [4]. These limitations can be overcome through the use of health monitoring, which is a proactive approach of estimating the reliability of a product. Health monitoring is a process of observing and recording the extent of deviation or degradation from an expected normal operating condition [5]. Health monitoring techniques typically combine sensing, recording and interpretation of environmental, operational, usage and performance-related parameters indicative of the products health [2]. Applications of health monitoring are typically classified as diagnostics, prognostics and life consumption monitoring.

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Diagnostic systems monitor the current operating state of health of the product to identify the potential causes of failure [5], and can provide efficient fault detection and identification, thereby assisting in maintaining the effectiveness of the equipment through timely repair actions. Prognostic systems monitor the faults or precursors to failure, and predict the time to failure, or numbers of operational cycles to failure, induced by a monitored fault [5]. This approach provides real time reliability estimates for a product in its actual application conditions. Life consumption monitoring is a health monitoring method, which quantifies product degradation in terms of the amount of its life consumed [6]. The life consumption monitoring process involves the continuous or periodic collection, and interpretation of, the product's life cycle environment. The remaining life estimate of the product is an output of the life consumption monitoring method.

Estimating the remaining life of electronic products that has been already deployed in the field presents a unique challenge. For such products, the life cycle data available is not the data obtained by a pre-planned monitoring process, but through a routine general data collection event such as maintenance activities. In most such cases, actual life cycle environmental data may not have been monitored. A remaining life assessment estimates the ability of the electronic products to meet the required performance specifications in its life cycle application environment for the remaining service life of the product [7]. Only a limited number of studies [7], [8], [9] have been published on remaining life assessment methodologies for electronic products. These studies have estimated the remaining life of electronic hardware based on virtual assessment, physical analyses and testing techniques. However, no rationale or guidelines were provided for the selection of the techniques used and their applicability. This paper addresses this weakness by presenting a methodology for conducting remaining life assessment of electronic hardware already deployed in the field. Before developing such a methodology, remaining life assessment strategies applied to other engineering hardware are examined.

Remaining life studies for engineering products, excluding electronic assemblies, have focused on mechanical products and civil structures. Mechanical products include heavy equipments like gas and steam turbines, boilers, refinery heater tubes, industrial furnaces, pressure vessels, pressure vessel nozzles, components of petrochemical plants, liquid natural gas (LNG) plants, fossil power plants, power plants and ship turbines generators. The civil structures include reinforced concrete structures and bridges. Table 1 summarizes the techniques used by such studies to assess the remaining life of mechanical products and civil structures.

Remaining life assessment techniques used for civil structures and mechanical products can be categorized into three main groups: physical analysis (non-destructive and destructive), damage modeling (analytical and finite element), and testing. Most of these studies have employed a combination of the three techniques to determine the remaining life of a product. Many of the techniques used in the above studies could be applicable to electronic products deployed in the field. Some of these techniques are applicable (e.g., destructive testing of sample) only in cases where additional equivalent samples are available for possible destructive testing. Some are applicable (e.g., sample extraction) only on large mechanical systems where small samples harvested for testing does not impair the structural integrity of the system. These techniques were taken into consideration in this paper to develop a generic methodology for remaining life assessment of electronic products. The proposed methodology is described in the following section, and applied to the remaining life assessment of an electronic circuit board.

Table 1: Methodologies Applied to Estimate Remaining Life of Engineering Products

Product	**Analysis Approach**
Civil Structures	
Reinforced concrete bridge [10]	A non-destructive chemical diffusivity evaluation in reinforced concrete structures was conducted, and the result was used to analytically estimate remaining life.
Reinforced concrete structures [11]	An accelerated corrosion test was conducted on a reinforced concrete structure. The result was compared to empirical data to estimate remaining life.
Reinforced concrete structures [14]	A damage modeling technique was used to assess the degradation of a reinforced concrete structure. This data was analyzed to provide an initial estimate of the remaining life. A mathematical technique was employed to refine the estimate.
Reinforced concrete structures [15], [16]	Analytical calculations based on available data were used to estimate the remaining life of a bridge.
Mechanical Products	
Turbine rotors [17], [18], [19]	An ultrasonic detection technique was employed to examine the cracks in turbine rotors. Based on the ultrasonic test data, stress and fracture analysis of the cracks were conducted to estimate the time to failure.
Refinery heater tubes [20], Steam turbine components [21]	Creep properties of the product were obtained from nondestructive testing, and were utilized to calculate an acceleration rate of degradation. This estimate was compared to an empirical database to predict remaining life.
Furnace heater tubes [22]	Ultrasonic wall thickness examination of furnace heater tubes was conducted and the result was used to analytically estimate the remaining life.
Turbine rotor [23], Fossil fuel power plant components [24], Industrial furnace tubes [25], Petrochemical plant components [26], Power plant components [27]	Samples were extracted from the product and subjected to a variety of tests including creep, impact and hardness tests. The results were compared to virgin material properties to estimate the extent of degradation and thereby predict remaining life.
Boiler heater tubes [28]	Non-destructive and destructive testing was conducted on boiler re-heater tubes to assess damage and estimate remaining life. A virtual assessment was also conducted to estimate remaining life, and compared to the results of non-destructive testing.
Pressure vessel nozzle [29], Furnace tubes [30], High pressure rotor [13], [31], Super heater tubes [32]	A sample of the product was tested by subjecting it to cyclic stresses. Using characteristic curves of the virgin material and comparing the cracks that developed the remaining life was estimated.
Pressure vessels [33], Gas turbine [34]	A general approach for remaining life assessment of the product was developed, with emphasis on quantifying the system parameters and modeling the damage as a function of those parameters.
Service turbine generator of a ship [35], Power plant components [36]	A finite element modeling and assessment method of estimating the remaining life was used.
Pressure vessels[12], [37]	Non-destructive examination of the product was conducted and used to develop a finite element model for evaluation. The model predictions were compared to a predetermined failure criterion to estimate the remaining life.
Components of a liquefied natural gas (LNG) plant [38], Super-heater outlet header [39]	The damage to the components of the product was modeled using finite element analysis, from which remaining life was estimated.
Pressure vessels [33], Gas turbine [34]	A general approach for remaining life assessment of the product was developed, with emphasis on quantifying the system parameters and modeling the damage as a function of those parameters.

2. Health Status Assessment Methodology

The process of determining the remaining life of a product already deployed in the field is analogous to determining the status of the product's health at that given moment. Hence the methodology proposed here is termed as 'Health Status Assessment Methodology'. This methodology is depicted in Figure 1, with each step detailed in the following sections.

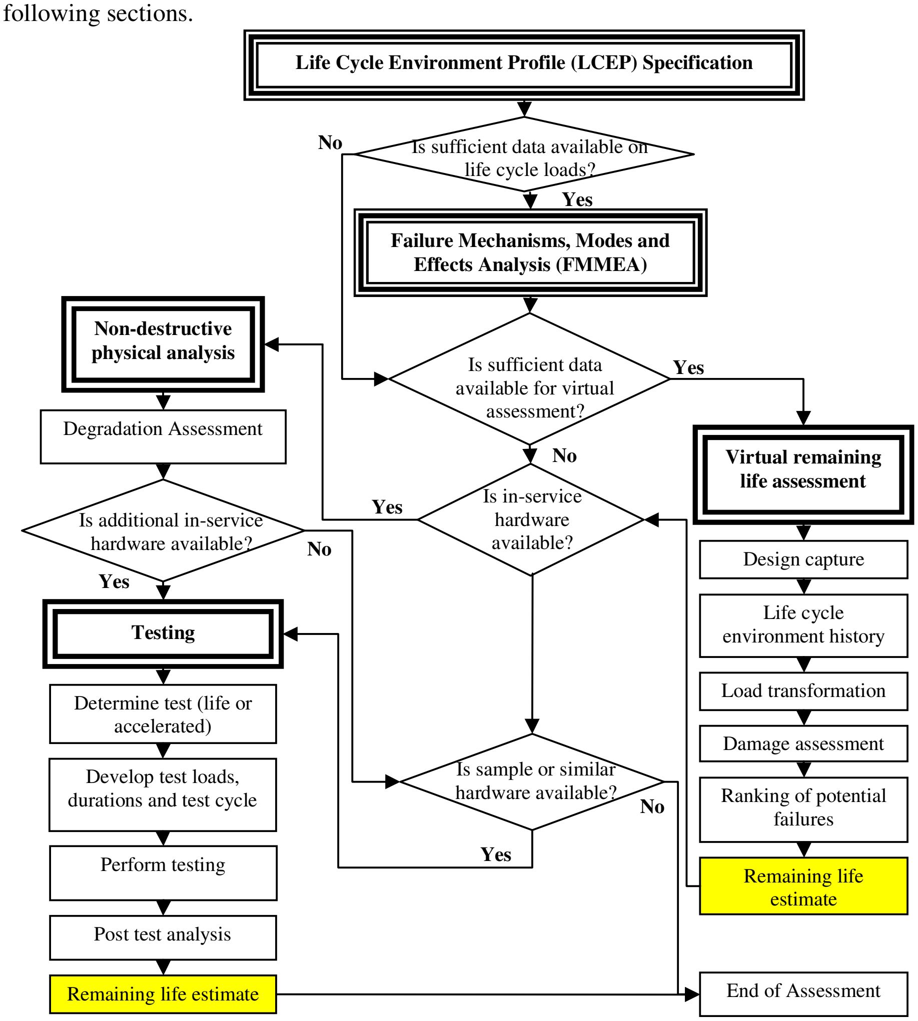

Fig. 1: Health Status Assessment Methodology

2.1. Step 1: Life Cycle Environment Profile

For electronic products having no in built monitoring system, or for which there has been no predetermined data collection, the first step towards assessing remaining life is to generate the life cycle environment profile (LCEP) of the product. LCEP involves the identification and quantification of the different operating and non operating load conditions of the products. The data to be collected involve the physical data, functional data and the life cycle environment data. Physical data includes geometrical information about the printed circuit board (length, width, thickness, number of layers, percent metallization, layer material etc.) and the architecture of the components mounted on the board (part types, dimensions, mounting styles, material, lead material, position of the component on the board etc.). The functional data includes the duty cycles, power cycles, and duration of operation. The life cycle environment data includes the life cycle loads, life cycle phases, operating conditions, and areas of application. A complete and accurate collection of data is vital to the accuracy of remaining life estimation.

It is important to assess the sufficiency of the data generated to move to step 2. If the life cycle data is limited, it will not be possible to proceed with step 2. In such a case the availability of sufficient data for a virtual assessment would help continue the remaining life assessment process as shown in Figure 1.

2.2. Step 2: Failure Mechanisms, Modes and Effects Analysis

If sufficient data has been generated in the LCEP analysis, step 1, then failure mechanisms, modes and effects analysis (FMMEA) for the products can be conducted. FMMEA is an extension of the traditional failure mechanisms and effects analysis (FMEA), and is described in [40]. This methodology involves identifying the failure mechanisms and models for all potential failure modes, and prioritizing them according to their potential damage impact. The prioritization process utilizes information related to the application conditions, duration of application, active stresses and potential failure mechanisms. The first step in FMMEA is to define the products and the components on the products. This is followed by identifying the potential failure modes and causes, the associated applicable failure mechanisms and appropriate failure models. The identified failure mechanisms are ranked according to their impact on the product's reliability in its life cycle environment conditions.

As indicated in Figure 1, if there is sufficient data about the material properties and geometry of the board and components, the analysis process progresses to a virtual remaining life assessment. However, if the data is insufficient for virtual remaining life assessment, a non-destructive physical analysis of an in-service products is performed to estimate remaining life. If no in-service product is available, a sample or similar product can be tested to estimate the remaining life of the products under assessment.

2.3. Step 3: Virtual Remaining Life Assessment

The virtual remaining life assessment is based on a physics-of-failure stress and damage accumulation analysis. This analysis involves using the material properties, geometry and measured life cycle loads of the product, to assess the dominant failure mechanisms. Based on a load-stress simulation, the physics-of-failure damage models give an estimation of the accumulated damage for the product in its life cycle environment. The virtual remaining life process consists of the following steps: design capture, life cycle loading history characterization, load transformation, damage assessment, and ranking of potential failures for remaining life estimation [41].

Design capture involves identifying the components on the board, recording their dimensions and position on the board, the board dimensions, and material properties of the board, component and interconnects. This data is prescribed into the physics-of-failure based software. Materials include substrate, encapsulants, underfills, leads and platings, solder~~s~~, conductive adhesives, socket materials, and the makeup of the printed wiring board (e.g., resin system, plating, embedded passives).

Characterization of the life cycle load history involves identifying and recording significant life cycle loads and simplifying them for assessment. Examples of environmental loads required for life cycle loading characterization include temperature extremes and mean temperature, frequency of the temperature cycles, vibration, shock and electrical loads. The magnitude of these loads should be accompanied with details of their rate of change and duration of exposure to these loads.

The life cycle loads' profiles are converted into a form that can be used as input to the software program for modeling. The load transformation process utilizes the characterized loading conditions to estimate the effect of these loads on the circuit card. The software takes the environment and architecture input and produces the stress fields (e.g., temperature, displacement, and curvature). Thermal stresses are usually associated with mechanical (structural) failures (e.g., ductile rupture, brittle fracture, creep, stress relaxation, thermal shock, stress, and corrosion).

The damage assessment is conducted using a failure model incorporating both a stress model and a damage model. Stress models correlate the environmental and operational loads, package architecture, and material properties to stress, strain and energy distributions within the components and the solder joint interconnects. The damage models are used to determine the number of cycles to failure. In the damage assessment step, the damage for each part is defined in terms of damage ratio (DR), which is the ratio of the number of cycles applied to the number of cycles (or other equivalent units) it can survive.

The ranking of potential failures involves ranking the components in decreasing order of damage ratios. Once the failure potentials are ranked, the remaining life of the component for which the damage ratio is highest is estimated. The remaining life is given by subtracting the damage ratio from the damage criterion (equal to 1) and dividing that value by the damage ratio per future life cycle. The remaining life of the electronic product is equal to the remaining life of the component with the highest damage ratio.

If an in-service product is available for assessment, the remaining life assessment process moves on to the fourth step of non-destructive physical analysis. If no in-service product is available, then the availability of a similar circuit card that has been in use or a sample circuit card with similar construction but not used in the field, should be determined. As shown in Figure 1, if samples or similar circuit cards are not available, the remaining life estimate obtained from the virtual remaining life assessment is the best possible estimate.

2.4. Step 4: Non-Destructive Physical Analysis

Non-destructive physical analysis of the product involves the assessment of degradation of the printed circuit board, the components on the board, the solder joint interconnects and the metal traces on the board. Non-destructive analysis uses techniques such as optical inspection, ultrasonic testing, and dye penetration test, to identify and investigate signs of degradation. Optical inspection of the components and solder joint interconnections reveals visible signs of damage. Cracks and voids affect the reliability of the component, which in turn affects the remaining life of the electronic circuit board. The components are inspected to determine the possible presence of visible physical damage to the components. The circuit board and the metal traces on the board are also inspected for any visible damage. Characterization of small solder samples taken from the solder joint interconnections, and comparison of the results to virgin solder properties will indicate the amount of degradation at the solder joints. The degradation can be expressed in terms of percentage of characteristic or virgin properties or in terms of damage ratio. From the estimated amount of degradation, the remaining life of the product can be predicted.

After non-destructive physical analysis, if additional in-service product is available for evaluation, the remaining life assessment process moves to the fifth and final step, namely testing. In case additional in-service product is not available, a similar circuit card that has been in use or a sample circuit card with similar construction but not used in the field, can be tested. As illustrated in Figure 1, if neither a similar circuit card or sample circuit card is available, the remaining life assessment is terminated.

2.5. Step 5: Testing

The fifth and final step in the remaining life assessment process is physical testing. The objective of the testing is to subject the electronic product to continuous cycles of life cycle environment load until a failure occurs. The test plan involves selection of the test type, development of the test loads, test durations, test cycles, actual testing and post test analysis [42].

Testing can be of two types: accelerated testing and life testing. Determination of the type of testing depends on the usage conditions of the products, at what stage in the designed life is the assessment being conducted and the practical feasibility of conducting the test activity. If an accelerated testing has to be conducted, the proper acceleration factors for the test loads should be estimated so as to correlate the testing results to the expected results under normal conditions. For a life test the test loads should be representative of the actual loading conditions. Testing may require design and manufacture of a test fixture that approximately recreates the mounting conditions of the electronic products in the actual life cycle environment.

The test loads, test cycles and test durations are then determined. The test loads are designed on the basis of the life cycle loads identified in the FMMEA. The load sequencing should consider the application of the load in the actual life cycle environment. The duration of application of the test load should be estimated from the actual duration of the load in the life cycle environment. In some instances, time compression may be necessary in order to reduce the total testing time.

Actual testing involves affixing the electronic products in the test fixture, setting up the monitoring products and subjecting the assembly to the test loads, in the determined sequence, for the determined duration, in a particular axis. The criteria for stopping the life test have to be defined before the beginning of the testing. Functional and physical monitoring should be continuously conducted during the testing. If the products fails during testing, the cycle before the cycle in which it failed is considered an estimate of the life of the products. For a life test, the total number of such cycles is the life of the products, while for an accelerated test, the life is estimated using the acceleration factors.

Post test analysis of the results of the testing is conducted to adjust the remaining life prediction. The testing procedure and results are analyzed for correctness and compliance with expected norms. If there are any variations, these are analyzed using analytical or numerical techniques, and the results of the analysis are factored into the remaining life prediction.

In case remaining life estimates from virtual remaining life assessment, as well as non-destructive analysis and testing are available, the result of the testing process should be used for future course of action. The virtual remaining life assessment will provide accurate estimates only for the failure mechanisms that have been modeled. Non-destructive physical analysis will provide an estimate of the amount of degradation in a component or at a particular site. The amount and rate of future damage may vary depending on the future operating conditions. Testing usually provides the best remaining life estimate since the products is actually subjected to its life cycle loads till a failure occurs. This result can be used as the basis for future operation and maintenance strategy for an electronic products unit similar to the products under review.

3. Application of the Health Status Assessment Methodology to an Electronic Circuit Board

The health status assessment methodology was utilized to assess the remaining life of an electronic circuit board that is part of the integrated electronic assembly (IEA) of one of the space shuttle's solid rocket boosters (SRB). The board is a single sided FR4-based printed circuit card, incorporating resistors, capacitors, diodes, transistors, transformer assemblies, connector, and optocouplers. All but four transistors and two transformers are insertion mount components. The four transistors are mounted on the aluminum brackets that are part of the aluminum wedge frame riveted to the board. The two transformers are affixed to the center of the board with screws. The C-shaped aluminum frame on the board is used to slide the board into the birtcher guides in the IEA box. Figure 2 shows the printed circuit board and the aluminum frame riveted to it.

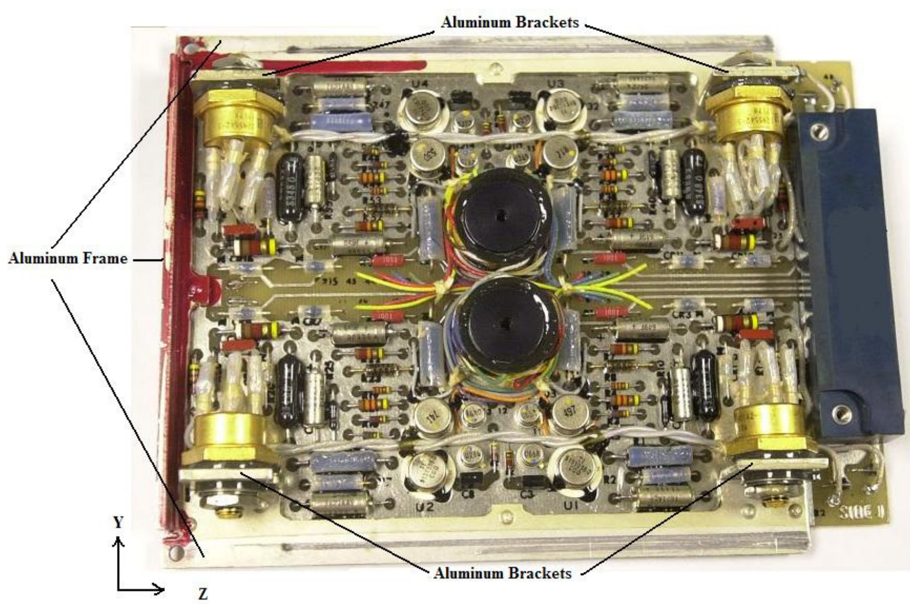

Fig. 2: Circuit Card.

The board life history consists of one flight prior to installation of vibration isolators, seven flights after installation of vibration isolators, fifteen exposures to acceptance level vibration tests, and twenty-seven exposures to acceptance temperature cycle tests. The detailed random vibration, shock and temperature cycling load data for each life cycle condition were provided by NASA. In addition to the actual circuit card, a sample engineering card, which was physically and functionally identical to the actual card, was available for assessment.

Employing the health status assessment methodology presented in this paper, the life cycle environment profile (LCEP) was generated by gathering the geometry and material details, life history and life load information of the board. A FMMEA indicated that the effect of random vibrations, shock and temperature cycling on the component-to-board solder joint interconnects was a potential reliability concern. The FMMEA also identified the effect of out-of-plane shock load on the components and 90° bend of aluminum bracket structure on the board as a potential concern.

Based on this FMMEA and available data, a virtual remaining life assessment using CalcePWA software was conducted with focus on the component-to-board solder joint interconnects. Using the stress and damage models for thermal and vibration fatigue, the damage caused by each type of life cycle load condition was calculated. This analysis indicated that the effect of the life cycle loading conditions on solder joint interconnect reliability was not as severe as anticipated. It was estimated that the circuit card could survive forty additional launch missions before any failure would occur.

Analytical and finite element methods were used to determine the effect of the shock loads experienced during the board life on the aluminum brackets. It was found that the aluminum brackets of the circuit card had lost significant life, and that damage accumulation occurred at the bend of the bracket due to shock loading. Since each launch mission, including the vibration acceptance test, lasted for only eight minutes, it was decided to conduct a life test to verify the results of the virtual remaining life assessment. It was determined from the virtual assessment that the random vibrations during preflight acceptance test and during the actual flight and the shock on water impact were the most damaging loading conditions that the circuit card had experienced. Therefore, the life test conducted involved simulating the vibration and shock loads representative of the actual operating conditions of the circuit card. During vibration testing in the out of plane axis of the board, an aluminum bracket used to mount a transistor failed (see Figure 3). The life testing added to the damage already accumulated in the bracket bend prior to this test, and caused the bracket to fail. The full details of the LCEP, FMMEA and life testing analyses are given in [43].

Fracture

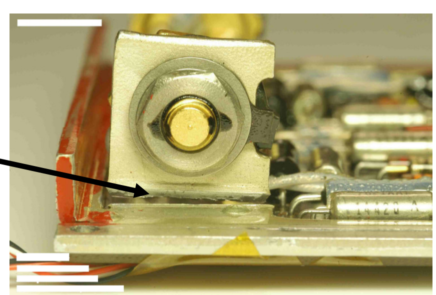

Fig. 3: Failed Aluminum Bracket.

From the health status assessment, it was found that the critical failure site was not the solder joint interconnect, as initially anticipated, but the aluminum brackets supporting the transistors. The concerns over the solder joint interconnects were cleared by the virtual assessment predictions. In addition, the life test proved that the shock in the out of plane axis of the board would cause lasting damage to the aluminum bracket. In conclusion, the health status assessment methodology implemented for assessing the remaining life of the circuit card identified and experimentally isolated the critical failure on the circuit card. Such analysis could be applied to other electronic hardware that are already deployed in the field.

4. Conclusions

To date, remaining life assessment methodologies for non-electronic engineering products already deployed in the field have combined physical analysis (non-destructive and destructive), damage modeling (analytical and finite element), and testing. In this paper, a health status assessment methodology was proposed for assessing the remaining life of electronic products already deployed in the field. The methodology utilizes life cycle environment specification (LCEP), failure mechanisms, modes and effects analysis (FMMEA), non-destructive physical analysis, virtual remaining life assessment, and testing, to estimate remaining life. The methodology was successfully applied to an electronic circuit board used in a space application.

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