Failure Mechanisms Based Prognostics

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***Abstract*—Prognostics methods are being developed to evaluate the reliability of a system in its actual life-cycle conditions, to estimate the times to failure and to mitigate system risks. A key requirement in any prognostics method is identification of the appropriate parameter(s), which, can be used to asses impending failure, if monitored. This paper presents a physics-of-failure based methodology, which uses failure modes, mechanisms and effects analysis (FMMEA) to enhance prognostics planning and implementation. Also presented are two ways of implementing the FMMEA based methodology.**

***Index Terms*—Failure mechanisms, legacy systems, precursors, remaining life, prognostics**

I. INTRODUCTION

The reliability of a product is defined as the ability of the product to perform its intended functions for a specific period of time, in its life cycle application conditions [1]. For some products, such as those used in aircraft systems, network servers, and medical products, degradation of performance can be catastrophic. For example in aircraft, flight critical components like actuators, pumps, valves and engine control electronics must function properly for safe flight [2]. It is therefore vital to know the health of such critical systems for safe and reliable operation.

Conducting regular maintenance of electronic products (systems and system-of-systems) can ensure their reliable operation and in many cases can extend the useful life of the products. Two common types of maintenance activities are corrective maintenance and preventive maintenance [3]. Corrective maintenance aims to repair or replace failed parts of a system, while preventive maintenance, conducted at pre-scheduled time intervals, seeks to repair or replace parts before a failure occurs. In the both cases the product is out of operation until the maintenance activity is complete. A continuous prognostics approach to determine the health of the product enables condition based maintenance, repair and replacement activities.

Prognostics and health management (PHM) is an approach that is used to evaluate the reliability of a system in its actual life-cycle conditions, to determine the initiation of failure, and to mitigate the system risks [4]. Prognostics of a system can yield an advance warning of impending failure in the system and thereby help taking appropriate corrective actions. It helps in preventing catastrophic failures and reduces unscheduled maintenance expenses. Prognostics have become the preferred approach to achieve efficient system-level maintenance and reduce the life cycle cost of the system [4]. The Unites States Department of Defense’ 5000.2 policy document on defense acquisition, states that program managers should utilize diagnostics and prognostics to optimize the operational readiness of defense-related systems [5].

Engineering hardware is typically a combination of sub-systems and parts. All of these sub-systems and parts can fail by various failure mechanisms in the product’s life-cycle environment. Many modern design and development practices include identification of possible failure mechanisms under application conditions. This paper presents of a physics-of-failure based methodology, which implicitly involves failure modes, mechanisms and effects analysis (FMMEA), to enhance the prognosis of a product. This methodology for prognostics can be applied to products in the design and development stage, products that have already been fielded, and for legacy systems.

II. APPROACHES TO PROGNOSTICS

The approaches adopted for conducting prognostics for a product are: (1) use of canaries to provide advance warning of failure, (2) monitoring the precursors to impending failure, and (3) modeling of life cycle environment stress to compute accumulated damage [4]. Monitoring of precursors and modeling of life cycle environment involves sensing parameters related to the product and environment and using predictive models to estimate the damage to the product.

A canary device behaves similar to the “canary bird” in a coal mine. Because the canary bird is more sensitive to hazardous gases than humans, death or sickening of the bird indicated impending hazardous environment for humans. Canary devices embedded in a product provide advance warning of failure due to specific wear-out failure mechanisms. Canaries are designed to fail due to the same failure mechanism as by which the product would fail if the product is subjected to extended life cycle loads. Under the same environmental and operational loading conditions the canary devices are designed to fail faster than the actual product. The prognostic distance, that is, the difference between the time to failure of the canary device and the

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expected time to failure of the product can be designed so as to enable appropriate maintenance and replacement activities. Fuses and circuit breakers which have been traditionally used for protection of structures and electrical power systems should not be confused with a canary. Fuses and circuit breakers are used in electronic products to sense excessive current drain and to disconnect power from the concerned part. Canaries on the other hand do not disengage the product, but rather indicate that the beginning of anomalous condition for the product.

The precursor monitoring approach to prognostics involves continuously measuring the change of a selected parameter, which can be associated with a particular type of failure. The use of precursor reasoning and trending techniques is quite common in the diagnostics of mechanical systems. A failure precursor is an event or series of events that is indicative of an impending failure. The failure is predicted by correlating the change in the monitored precursor parameter and the effect of such a change to the operation of product. Usually parameters that are critical for safety of the product and users and are essential for reliable operation of the product are monitored. Knowledge of the critical parameters established by past experience, field failure data and data from qualification testing assists in the selection of a parameter to be monitored [4]. The correlation between the precursor parameter and the impending failure is determined by measuring the parameter under a known usage condition or an accelerated test condition. Based on the data a model is developed which will provide a trend for the event and the expected failure. For products with multiple usage conditions the precursor parameter must be selected such that a change in combined loading is accounted for in the reasoning model. For example the solder joints of components on an electronic circuit board used under temperature cycling and vibration conditions will fail earlier than when the circuit board is subjected to only temperature cycling or vibration. In such a situation the reasoning model should account for the combined effect of temperature cycling and vibration on the monitored parameter.

The life-cycle environment of a product consists of manufacturing, transportation, storage, handling, operating and non-operating conditions. Life cycle load can be mechanical, thermal, chemical, or electrical in nature. Physical degradation of a product and reduction in its service life is brought about by the individual or combinatorial effect of the life-cycle loads [4]. The amount of product degradation depends upon the magnitude and duration of exposure to the life cycle loads. In situ measurement of the life cycle loads helps in determining the frequency and severity with which the loads are applied on a product. These load profiles are the inputs for damage models which can estimate the degradation of the product due to exposures a particular load. In situ measurement of loads combined with physics-based stress and damage models for assessing the life consumed can provide a good estimate of the state of the product. Based on this estimate corrective action can be taken at an appropriate prognostic distance. In cases where in situ measurement of data is not possible, data collected at regular intervals can be used as inputs for the stress and damage models to estimate the degradation. This approach towards prognostics is preferred when monitoring precursors is difficult.

III. FAILURE MECHANISMS AND APPROACHES TO PROGNOSTICS

In the previous section the general approaches used to conduct prognostics were discussed including use of canaries, precursor monitoring and modeling of life cycle environment stress upon a product. In order to implement the above mentioned approaches to prognostics, it is very essential to understand what is causing damage to the product and how do the damages manifest in the product. In other words what are the failure mechanisms and failure modes for that product? The argument for the need of understanding the fundamental failure mechanisms for a product can be made before application of all three of the above mentioned prognostic approaches.

If the canary device embedded in a product does not fail due to the most critical failure mechanism that affects the product, then the canary device is less useful for prognostics. This is because, though the canary device may detect a hazard for the product, by that time the degradation of the product due to the critical failure mechanism may have reached a point beyond which corrective actions may not be able to extend the life of the product.

For the precursor monitoring approach if the failure mechanisms and modes are not known then the selection of sensors for monitoring, the location of monitoring and the models to analyze the collected data may be selected erroneously. If the precursor is not based on the fundamental understanding of failure mechanism of the product, the erroneous parameter may be monitored. Thus monitoring such a parameter may not provide the appropriate precursor and hence the right prognostic distance for implementation of corrective actions.

If the stress and damage model are not developed to take into account the uncertainties of the usage and environmental conditions, the recorded data could lead to a erroneous estimation of impending failure. Maintenance data is gathered by many organizations and is often used as inputs to the stress and damage models for estimation of the degradation in a product. Maintenance data is often not directly usable since it is often very extensive and may contain data for unscheduled removals, component replacements, in process failures and rework. It may also contain data for different intermittent failures. Though it is good to have maintenance data as a source of information, the utility of such data is limited when it does not contain information on the failure mechanisms.

Knowledge of the failure mechanisms that are likely to cause the degradations that can lead to eventual failures in the product is important. There are different failure signatures for different failure mechanisms and without knowledge of the failure mechanisms it is impractical to expect hundred percent success in implementation of prognostics. For all of the above-mentioned approaches it is necessary to have initial information of the possible failures (including the site, mode, cause and mechanism) in the product. Without such knowledge it is not feasible to design a canary or select which precursor to be monitored.

IV. Failure Modes, Mechanisms And Effects Analysis (FMMEA)

Failure modes, mechanisms and effects analysis (FMMEA) is a physics-of-failure (PoF) approach based on assessing the root cause failure mechanisms of a given product [7]. A potential failure mode is the manner in which a failure can occur—that is, the ways in which the item fails to perform its intended design function, or performs the function but fails to meet its objectives [7][8][9]. Failure modes are closely related to the functional and performance requirements of the product. Failure mechanisms are the processes by which a specific combination of physical, electrical, chemical, and mechanical stresses induces failures.

The Failure Mode and Effects Analysis (FMEA) methodology is a procedure to recognize and evaluate the potential failure of a product and its effects, and to identify actions that could eliminate or reduce the likelihood of the potential failure to occur [10]. Many organizations within the electronics industry have employed or required the use of FMEA, but in general this methodology has not provided satisfaction, except for the purpose of safety analysis [11]. A limitation of the FMEA procedure is that it does not identify the product failure mechanisms and models in the analysis and reporting process. Failure mechanisms and their related physical models are important for planning tests and screens to audit nominal design and manufacturing specifications, as well as the level of defects introduced by excessive variability in manufacturing and material parameters.

Failure modes, mechanisms and effects analysis (FMMEA) is a methodology that has been developed to address weaknesses in the traditional FMEA process [11]. The purpose of FMMEA is to identify potential failure mechanisms and models for all potential failures modes, and to prioritize failure mechanisms. To ascertain the criticality of the failure mechanisms a risk priority number (RPN) is calculated for each mechanism. The RPN is the product of the occurrence and severity of each mechanism. Occurrence describes how frequently a failure mechanism is expected to result in failure. Severity describes the seriousness of the effect of the failure caused by a mechanism and detection describes the probability of detecting the failure modes associated with the failure mechanism. High priority failure mechanisms determine the environmental and operational stresses that need to be controlled. Models for the failure mechanisms help in the design and development of the product.

FMMEA is based on understanding the relationships between product requirements and the physical characteristics of the product (and their variation in the production process), the interactions of product materials with loads (stresses at application conditions) and their influence on the product susceptibility to failure with respect to the use conditions. This involves finding the failure mechanisms and reliability models to quantitatively evaluate the susceptibility to failure. In addition to the information gathered and used for traditional FMEA, FMMEA uses life cycle environmental and operating conditions and the duration of the intended application with knowledge of the active stresses and potential failure mechanisms. A schematic diagram showing the steps in FMMEA is shown in Fig. 1. Ganesan et. al., [11] have provided detailed description of the FMMEA methodology. The output of the process is a list of prioritized failure mechanisms along with the failure modes that the mechanisms precipitate and the sites of precipitation.

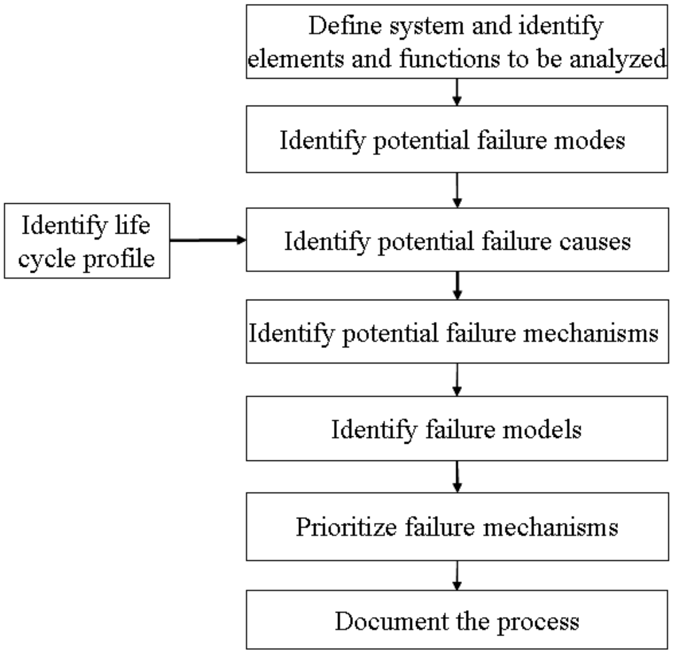

Fig. 1. FMMEA Methodology

FMMEA is a major improvement over traditional deign for reliability methods since it internalizes the concept of failure mechanism at every step of decision making. Utilization of failure mechanisms as the basis of reliability assessment has been accepted by major technical organizations such as EIA/JEDEC, SEMATECH, and IEEE. Examples of standards that require estimation of the failure mechanism for reliability analysis from JEDEC are given in references [12]-[17]. SEMATECH publications [18]-[21]utilize the concepts of failure mechanism based reliability assessments for semiconductors. IEEE Standard 1413.1 [9] promotes reliability prediction method of using the load (stress) and damage models which determine when a specific failure mechanism will occur for a product in a given environment.

V. FMMEA Based Prognostics and Remaining Life Methodology

In this section a FMMEA based methodology is presented that combines the advantages of the physics-of-failure and data-driven approaches. The advantages of a physics of failure approach include the ability to provide accurate damage estimate for a given load condition and failure mechanism, no baseline or algorithm training needs, and the ability to estimate remaining life under different loading conditions. The advantages of data driven methods include the ability to accurately detect anomaly based on defined baseline, classify and trend the behavior of the system based on different features of data, reveal patterns or relationships between parameters, such as correlation, covariance and the ability to identify leading parameters that contribute to change in the system. Fig. 2 presents the hybrid FMMEA base prognostics approach.

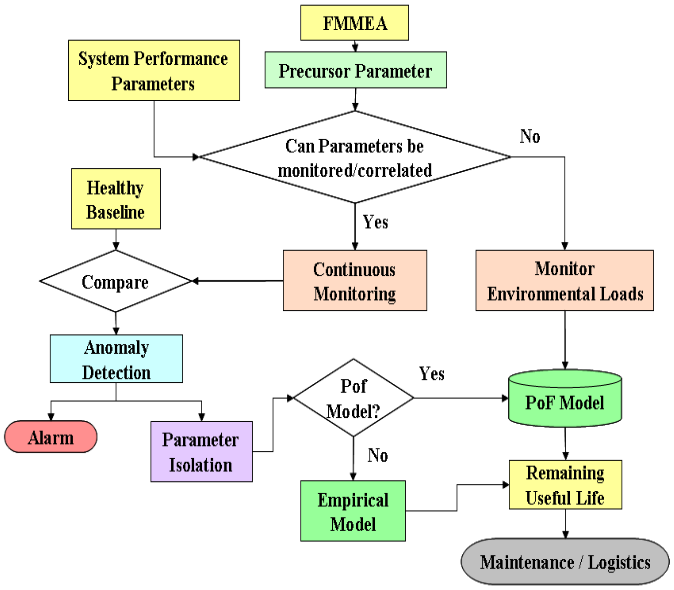

Fig. 2. Hybrid approach

The first step in this approach is to conduct an FMMEA of the product for which the prognostics will be implemented. This provides the critical precursor parameters that when monitored will provide appropriate prognostic information. Some of the parameters identified through FMMEA may not be able to be monitored due to lack of sensors, lack of PoF models, or even due to little or no correlation between parameters that could contribute to the system failure. In such cases system performance parameters if correlated to the physical parameters may be monitored for prognostic purposes. The data collected from continuous monitoring of the identified parameters must be compared to the baseline of healthy behavior for that particular product.

The detection of anomalous behavior of the products monitored parameters will serve as alarm for the product's user. This also leads to isolation of the parameters that contribute most to the anomalous behavior. At this point if there exists a PoF model to model the degradation due to the specific parameter, the remaining useful life of the product at that point in the operational phase can be calculated. If there is no PoF model then an empirical model can be developed to calculate the remaining life based on the collected data. Information of the remaining useful life can be used for appropriate maintenance and logistics actions.

The advantage of this methodology is that the remaining useful life of the product is estimated at the very first instance of anomalous behavior unlike estimates at discreet points in time as part of a scheduled maintenance action. In the event that the precursor parameters can not be monitored nor are there any system performance parameters that can be monitored then the environmental loads on the product can be monitored and used in known PoF models to calculate the approximate remaining useful life of the product.

This approach helps identification of precursor parameters, their correlation with system performance parameters, continuous monitoring of product health, early detection of failure trends and the longest prognostic distance to the time to failure. The following section presents two schemes to implement the FMMEA based approach.

VI. IMPLEMENTATION OF FMMEA BASED APPROACH

Two applications are proposed for implementation of FMMEA base prognostics for new products, and for fielded/ legacy systems, respectively. These prognostics methods utilize FMMEA to determine the possible failure mechanisms that could manifest in a given product. Depending on the life cycle stage of the product, the methodology to implement prognostics can be selected. Knowledge of the ranked failure mechanisms will help in selecting the canary device, appropriate precursor parameters and stress and damage models such that an accurate advanced warning of the impending failure is obtained.

Fig. 3 shows a schematic of the FMMEA-based prognostics approach for a new product. The process begins with conducting a FMMEA for the product. This involves defining the product/system and identifying the elements and functions to be analyzed. Then all the potential failure modes and causes that can affect the product should be identified. If there are similar products already in the market then the maintenance data if available, can be utilized to identify the failure modes. Identifying the potential life cycle environmental and operational conditions is a necessary input for estimating the potential failure causes. Once the failure modes are identified the next step is to identify the failure mechanisms that govern the failures and prioritize the failure mechanisms. The prioritization of the failure mechanisms for a new product can be assisted by the availability of maintenance data from similar fielded products.

Overall after conducting an FMMEA of the product, the product designers will have knowledge of the critical failure mechanisms for the product. The critical failure mechanisms determine the environmental and operational stresses that need to be controlled. Knowing the critical failure mechanisms and the associated failure modes for each mechanism, a list of parameters to be monitored can be generated. Knowledge of the critical failure mechanisms and the appropriate parameters to be monitored will help in the selection of the right sensor or canary for the product. Sensor(s) should be selected such that it will accurately measure the change in the parameter(s) linked to the critical failure mechanism(s). Canary device(s) should be selected such that it fails due to the critical failure mechanism(s) only. Since the product is in the design stage it will be easier to integrate the sensor(s) or canary device(s) into the product design. If the precursor parameters can not be measured then correlated system parameters can be monitored.

After the product is manufactured and fielded, the sensors embedded in the product will provide continuous in situ measurement of the monitored parameters. The data collected serves as inputs for the prognostics algorithms or PoF models. The data obtained from the in situ monitoring of the product will also help update the life-cycle profile. Based on the remaining useful life estimates, the necessary maintenance activities for the product can be scheduled. Such an approach to prognostics of a product will provide a complete and more realistic remaining useful life and prognostic distance for the product. The FMMEA is updated when the prognostics process continues, resulting in updated critical failure mechanisms list. The updated lists can be used to determine if the precursors and their limiting values are still appropriate for the product.

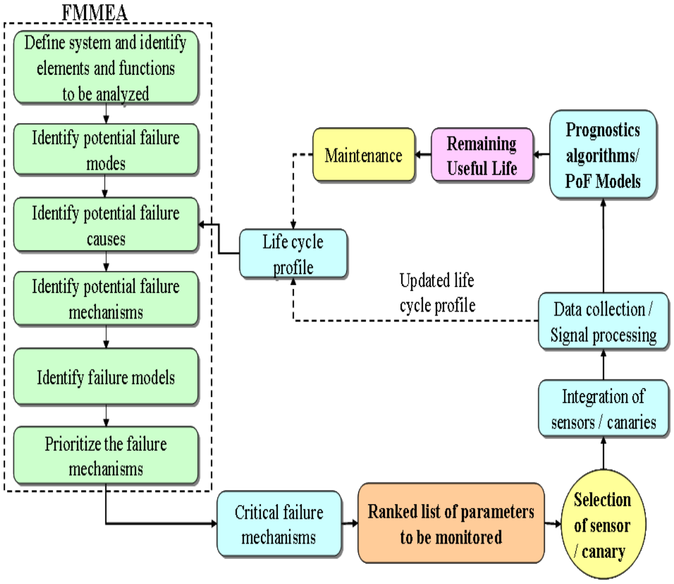

Fig. 3. FMMEA based prognostics application for a new product.

Fig. 4 shows the FMMEA based methodology for fielded products and legacy systems. For fielded/ legacy products the first step is to identify the products life cycle environmental and operational conditions. Maintenance data if is available can provide good information about the operational loads experienced by the product. Knowledge of the products life cycle loads and maintenance data will assist in conducting a FMMEA for the product. The outcome of the FMMEA is knowledge of the critical failure mechanisms of the product and a ranked list of parameters that should be monitored in order to get accurate information of the state of health of the product.

A legacy system may or may not have sensors or canary devices embedded in the system. If the legacy system/ fielded product already contain some sensors then the data collected from these sensors should be correlated to the relevant failure mechanisms. If the collected data can be correlated to the failure mechanism then this information can be used as inputs for prognostic algorithms and models. Based on the remaining useful life estimates, the necessary maintenance and logistics activities for the legacy system can be scheduled.

If the collected data can not be correlated to the critical failure mechanisms identified by the FMMEA process, retrofitting the legacy system/ fielded product with sensors should be considered. If it is possible to retrofit the legacy system with sensors, selection of the proper sensors to measure the critical parameters is necessary. If it is possible to update the software for existing sensors, such that after a software update the sensor can record the changes to the critical parameters of the legacy system, then such a software update should be incorporated. The selection of sensors or the update to the software for the sensor should be based on the knowledge of the critical parameters for the legacy system that needs to be monitored. Once the sensor(s)/ canary device(s) is selected, it has to be incorporated into the legacy system /fielded product. When the product is back in operation the new sensor(s) will record the variations in the critical parameter and this data can be used to obtain a prognostics update of the system.

If it is not possible to retrofit the fielded product with new sensors or even update the software for existing sensors then a stress and damage model approach should be adopted to estimate the degradation of the product. The information on the life cycle loading conditions and the critical failure mechanisms for the product are the required inputs for the stress and damage models. The remaining life of the product can be estimated from the amount of degradation accumulated in the product due to the life cycle loading conditions.

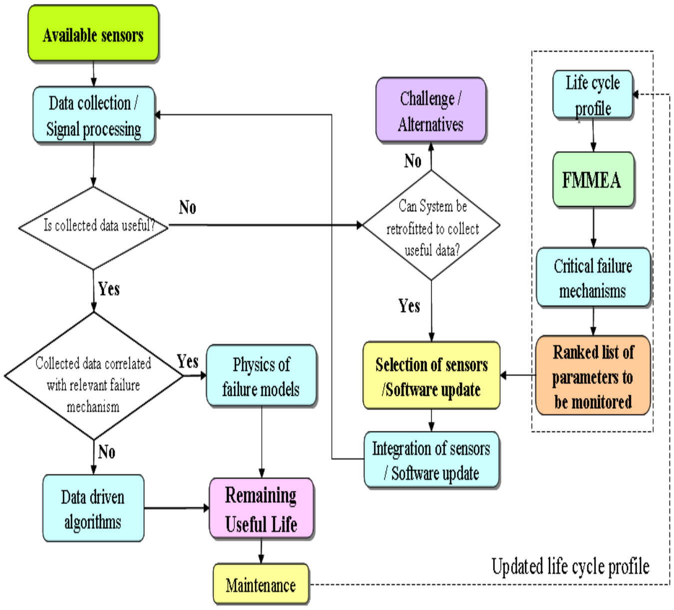

Fig. 4. FMMEA based prognostics application for legacy systems

VII. SUMMARY AND CONCLUSION

The traditional approaches to prognostics include use of canaries and fuses, precursor monitoring, and modeling life cycle environmental stress to compute the accumulated damage in the product. Currently the prognostic process development and parameter selections tended to focus on empirical results, experience, and maintenance data, rather than on the physical processes that lead to failures. If the precursor parameter to be monitored, canary device or damage model is not based on the fundamental understanding of failure mechanisms, the prognosis of the product could be erroneous. Knowledge of the failure mechanisms that are likely to cause the degradations that can lead to eventual failures in the product is important.

In this paper, a hybrid approach combining the advantages of data-driven and physics-of-failure techniques is described. This methodology uses the failure modes, mechanisms and effects analysis (FMMEA) as the foundation upon which the subsequent steps depend. The failure modes, mechanisms and effects analysis is used to determine the possible failure mechanisms that could manifest in a product and prioritize the critical failure mechanisms. Based on the critical failure mechanisms appropriate parameters to be monitored are identified. Conducting an FMMEA for a product will assist in the proper selection of sensor(s), canary device(s) and also in determining the appropriate damage models for the product. Two schemes for implementing the FMMEA based prognostics approach for new products, and for fielded/ legacy systems, respectively have been proposed.

This approach is beneficial to the industry as it identifies the critical failure mechanism(s) for the product and identifies the parameter(s) that should be monitored. It will help the industry to select the appropriate canary devices or sensors for monitoring the health of their products. Such a prognostic approach when implemented will yield the accurate impending failure warning and will help a company initiate the appropriate maintenance or repair activity.

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