USING TELEMETRY TO MEASURE EQUIPMENT MISSION LIFE ON THE NASA ORION SPACECRAFT FOR INCREASING ASTRONAUT SAFETY

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Failure Analysis

ABSTRACT

The surprise failure of two NASA Space Shuttles and the premature failures of satellite subsystem equipment on NASA satellites are motivating NASA to adopt an engineering discipline that uses telemetry specifically developed for preventing surprise equipment failures. The NASA Orion spacecraft is an Apollo module-like capsule planned to replace the NASA Space Shuttle reusable launch vehicle for getting astronauts to space and return to the earth safely as well as a crew escape vehicle stored at the ISS. To do so, NASA is adopting a non-Markov reliability paradigm for measuring equipment life based on the prognostic and health management program on the Air Force F-35 Joint Strike Fighter. The decision is based on the results from the prognostic analysis completed on the Space Shuttle Challenger and Columbia that identified the information that was present but was ignored for a variety of reasons. The goal of a PHM is to produce equipment that will not fail prematurely. It includes using predictive algorithms to measure equipment usable life. Equipment with transient behavior caused from accelerated of parts will fail prematurely with 100% certainty. For many decades, it was believed that test equipment and software used to in testing and noise from communications equipment were the cause of most transient behavior. With the processing speed of today's processors, transient behavior is caused from at least one part suffering from accelerated aging. Transient behavior is illustrated in equipment telemetry in a prognostic analysis. Telemetry is equipment performance information and equipment performance has been used to increase reliability, but performance is unrelated to equipment remaining usable life and so equipment should be failing prematurely. A PHM requires equipment telemetry for analysis and so analog telemetry will be available from all Orion avionics equipment. Replacing equipment with a measured remaining usable life of less than one year will stop the premature and surprise equipment failures from occurring during future manned and unmanned space missions.

KEY WORDS

Telemetry, Prognostic, Diagnostic, Analysis, Failure Analysis, Prognostic Analysis Predicting Failures, Non-Markov Reliability, Calculating Remaining Usable Life, Measuring Remaining Usable Life

INTRODUCTION

NASA is ushering in a new non-Markov paradigm in safety and mission assurance. The NASA Orion spacecraft has replaced the Space Shuttle for transporting astronauts to space and return home safely. The Orion will use a non-Markov reliability paradigm. NASA has decided that space missions are too expensive and too important to fail and is using adopting a prognostic and health management (PHM) program in the testing of the Orion spacecraft to prevent a catastrophic failure. Rather than using a diagnostic analysis to complete failure analysis after a surprise failure occurs, NASA will use a PHM to prevent surprise equipment failures from occurring like those on the Space Shuttle Challenger and Columbia accidents in 1986 and 2003.

FIGURE 1 THE NASA ORION MANNED SPACECRAFT

THE PROGNOSTIC AND HEALTH MANAGEMENT PROGRAM

[1]A prognostic and health management (PHM) program was developed across many industries to prevent catastrophic equipment failures using prognostic (predictive/preventive) practices for preventing equipment failures in addition to the diagnostic practices used after a surprise equipment failure occurs. A PHM is a new engineering and reliability paradigm that includes a non-Markov measurement of equipment remaining usable life. The PHM provides the tools, training and practices necessary to predict equipment failures stopping premature and surprise equipment failures. A PHM includes using predictive algorithms to measure equipment usable life with analog telemetry and identify the equipment that will fail prematurely for replacement before use and in space. Current predictive algorithms have been valid out one year allowing infant mortality failures to be stopped like those that occurred on the Challenger and Columbia accidents.

A prognostic analysis is a scientific analysis (vs. an engineering analysis) conducted on the results from the diagnostic analysis known as a failure analysis. The analysis of the results from a diagnostic analysis provides prognostic analysis. The results from a prognostic analysis conducted on a failure analysis provides the information that if interpreted properly by personnel trained in preventing a surprise failure, would have been used to prevent a failure. The result of a prognostic analysis identifies the prognostic markers/prognostic identifiers. The analysis of the results of a prognostic analysis is a prednostic analysis. A result of a prednostic analysis yields the remaining usable life.

Telemetry and data acquisition systems were developed at Edwards AFB in California to transmit the equipment performance data from jet aircraft in flight test to flight test engineers located remotely. Pilots were dying in crashes before they could debrief the flight test engineers and the performance of the aircraft before crashing could not be determined. Data acquisition systems used remote ground stations to receive telemetry and route it to flight test engineers located at other facilities. Jet aircraft equipment analog telemetry is crucial to aircraft design, because telemetry provides equipment performance information and performance drives the design of jet aircraft. Equipment analog telemetry provides access to equipment performance information invasively.

FIGURE 2 NASA ORION TELEMETRY & INSTRUMENTATION SYSTEM DESIGNED AT THE DRYDEN FLIGHT RESEARCH CENTER

Telemetry systems were added to spacecraft in the early 1960's hoping that telemetry could identify the equipment that failed performance testing. Telemetry increases spacecraft cost and complexity and thus risk and so became the source of great irritation to spacecraft company management. The generation, analysis and storage of telemetry during the manufacturing and testing process slows down in the test schedule increasing risk of missing the delivery date, and forces a large increase in resources needed and so is considered an overhead cost by program management. A slowdown occurs from analyzing test data during the spacecraft test plan. A slowdown increases risk of missing the delivery date and incurring a financial penalty. Because spacecraft equipment performance is not a design driver, and analog telemetry only measures equipment performance parameters, telemetry is not needed to improve satellite or launch vehicle performance. Telemetry is used in completing equipment testing required by the customer, for operating and maintenance of spacecraft and so telemetry is an overhead cost and one that is minimized by company program management. Telemetry is important to the engineer but not to the program management because it is not critical to mission success.

Telemetry is used in the completion of dynamic environmental factory acceptance testing to measure and confirm equipment performance, but some equipment does not get performance tested. Company personnel can decide the equipment that received telemetry. In the application of telemetry in the space industry, telemetry became a source of additional weight, electrical power, many miles of wire, extra equipment and causes a huge increase in vehicle complexity and uncertainty. Unlike aircraft, whose design driver is performance, a key satellite and launch vehicle design driver is reliability. For spacecraft and launch vehicles, there is only one chance to get everything right and successfully launch a rocket and its satellite/spacecraft payload to space. When something unexpected occurs on a launch vehicle during ascent, it usually results in a catastrophic failure and loss of the mission. This does not occur in the use of jet aircraft that are designed to be survivable in the event a surprise equipment event occurs. A jet aircraft can usually be salvaged in many ways. Not true for launch vehicles and satellites.

The NASA Space Shuttle is the most instrumented operational vehicle in the history of spaceflight. However, since telemetry was not considered by management to be mission critical, most of the Space Shuttle telemetry was stored for failure analysis in the event a failure occurred. NASA has decided that the Orion missions will be too important to fail, and so the Orion spacecraft will have all its equipment telemetry available for diagnostic and prognostic analysis in real-time, thus increasing Orion safety and mission assurance.

WHAT IS A PREDICTIVE ALGORITHM?

[3] A predictive algorithm includes a series of actions, including a scientific analysis, taken by personnel trained to prevent surprise failures from occurring. Using diagnostic analysis, personnel are trained to react with a diagnostic analysis after a failure occurs. Changing the paradigm from reaction to prevention requires training in completing a scientific analysis. Predictive algorithms simply relate past equipment, non-repeatable transient events that is identifiable in equipment engineering test data with equipment end of life. These actions use the same engineering data used to complete a diagnostic analysis to confirm equipment performance but uses predictive algorithms to convert equipment analog telemetry (performance measurements) into a measurement of unit remaining usable life.

A diagnostic analysis looks backward in time to determine past equipment behavior. A prognostic analysis looks back in time to predict future equipment behavior. A scientific analysis is necessary because the results from an engineering analysis only provide diagnostic information. The results from a diagnostic analysis cannot be used to measure equipment remaining usable life. A scientific (prognostic) analysis is completed on the results from diagnostic analysis. Predictive algorithms illustrate the presence of accelerated aging that is often identifiable in normal appearing data from fully functional equipment that will fail prematurely. Predictive algorithms offer spacecraft purchasers and spacecraft builders the tools necessary to purchase satellites and launch vehicle services that will not fail prematurely and suffer from surprise on-orbit failures. Using predictive algorithms and prognostic analysis, contractors and mission control personnel will identify the equipment that will fail prematurely (and predict when satellite subsystem equipment will fail).

A prognostic analysis should include the generation, recording and dissemination of diagnostic (investigative) information and the processing of each channel of information so that future events can be predicted based on past behavior. For equipment that is too expensive and too important to fail premature, the desired outcome is the prevention of a premature failure. A prognostic (proactive/predictive) algorithm is a well-defined set of instructions that when executed will identify the information necessary (prognostic markers) to prevent and/or prevent undesirable events in the future. [3]

Prognostic technology uses almost any analog measurement available today on flight equipment and in satellite/launch vehicle telemetry systems. However, instrumentation with at least a single analog measurement integrated into equipment is necessary to illustrate accelerated aging.
The number and types of analog measurements per unit often includes voltage, current and temperature. Although prognostic analysis is insensitive to measurement sampling frequency, very low sampling frequency can affect the accuracy of the of remaining-usable-life calculation.

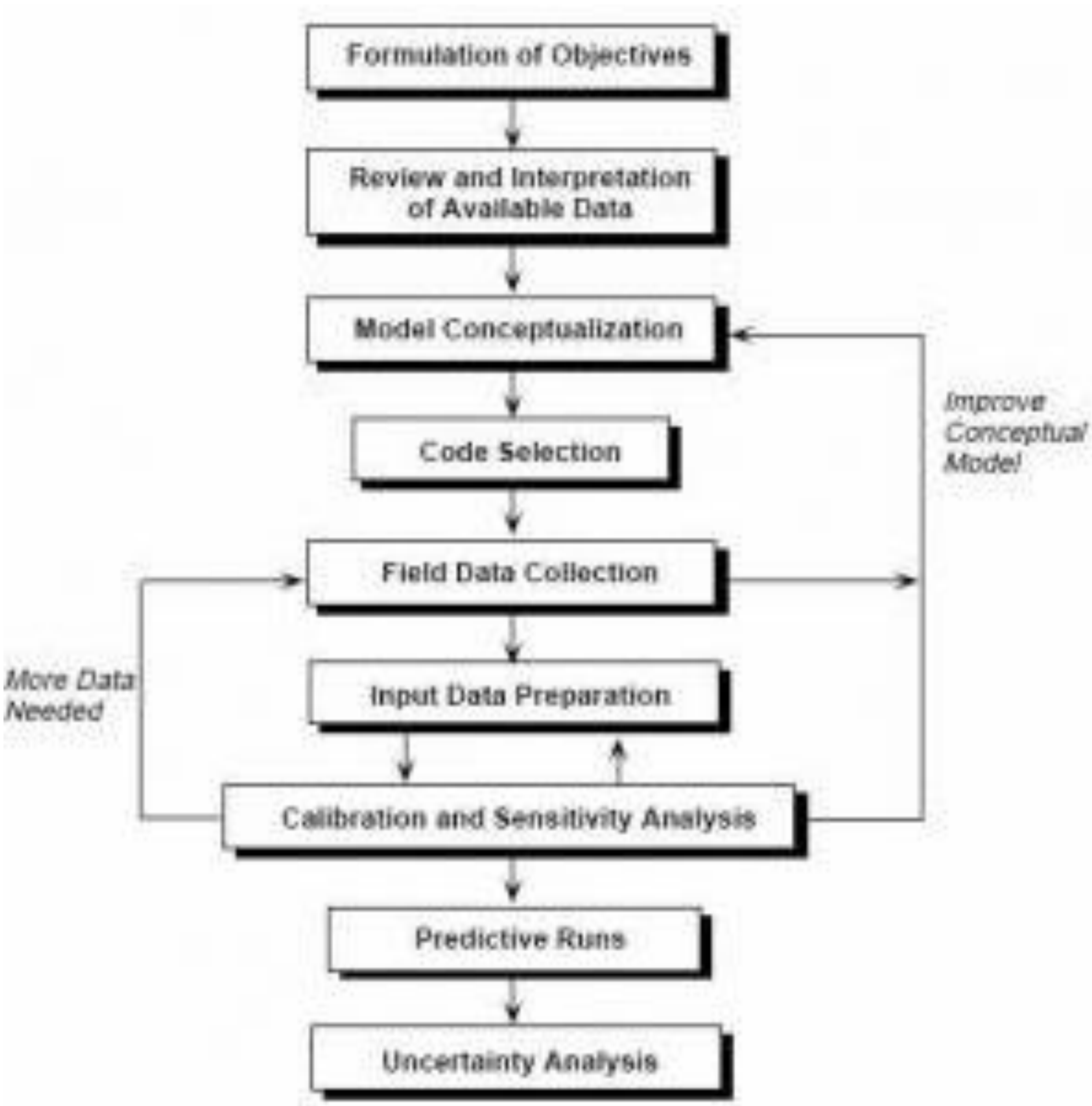

FIGURE 3 THE PROCESS USED TO DEVELOP A PROPRIETARY PREDICTIVE ALGORITHM

EQUIPMENT MISSION LIFE VS. REMAINING USABLE LIFE

A major requirement for a spacecraft is its mission life. Spacecraft mission life provides the information so that equipment suppliers can include the amount and cost of the expendables in the design. Spacecraft equipment that will operate normally for extended durations use piece-parts that are rated with longer life by their manufacturer. Companies choose their piece-parts suppliers very carefully, so that parts suppliers that produce too many parts that fail prematurely will not be used. Longer life satellites in addition to being far more expensive are usually physically larger, heavier and more costly from the extra equipment and expendables provided on-board. . Satellite mission life has greatly increased from 6 months in the 1960's to 20 years today. This increase in equipment mission life is from the desire from customers who can pay for longer life from the money earned from selling satellite services. Today's satellite design life can be over 20 years to meet a mission life of 15 years.

[4] A prognostic analyses is a scientific analysis that includes using equipment performance data such as telemetry to measure equipment usable life thus making equipment telemetry critical to mission success. A failure analysis is an engineering analysis and is used to quantify equipment behavior by looking at past information. A prognostic analysis uses the same past information used in a failure analysis to predict future equipment behavior with certainty.

The personnel who are testing the NASA Orion spacecraft will use equipment analog telemetry to measure the Orion avionics equipment performance and the equipment usable life usable life to prevent surprise equipment failures. The equipment that fails performance or usable life requirement will be replaced increasing safety and mission assurance.

Calculating remaining usable is a proprietary process and may be unique for each company/organization. The remaining-usable-life or the time-to-failure (TTF) for equipment can be calculated once accelerated aging has been identified by using the piece-part failure characteristics in equipment telemetry generated under test.

FIGURE 4 THE 100 LB LIQUID APOGEE ENGINE THAT SUFFERED FROM A FAILURE IN 2010 ON THE AIR FORCE AEHF-1 SATELLITE.

[5] Predicting an accurate time-to-failure (TTF) after the early signs of premature aging/failure are identified; we use the cumulative distribution curve developed from our proprietary database of equipment failures we have analyzed over 30-years on launch vehicles and satellites. Normal distribution curves model normal occurring failure rate behavior and are tools used before we understand and could quantify the failure rates at a complex system at the beginning-of-life, normal lifetime and end-of-lifetime failure rate. In the equipment failures we analyzed, we measured the duration of time between the failure precursor and the actual failure to generate the cumulative distribution. We have used this cumulative distribution to predict the duration of remaining usable with 100% accuracy.

Failures in electrical and electro-mechanical equipment occur over a very long period of equipment operational life, as long as 1 year. To understand why our cumulative distribution is an accurate method for measuring the equipment with the early signs of premature aging/failure present remaining usable life, understanding the use of normal (random) distributions will help.

[5] The integral of a normal distribution function is its cumulative distribution. The integral of all the probability functions are the cumulative distribution functions for the normal distribution functions. The cumulative distributions illustrate the likelihood that a piece-part failure in a population of piece-parts duration will occur. Knowing that piece-part failure rates should have a Gaussian distribution, piece-part manufacturers test a sample of piece-parts from a population and determine if their failure rate matches a Gaussian distribution.

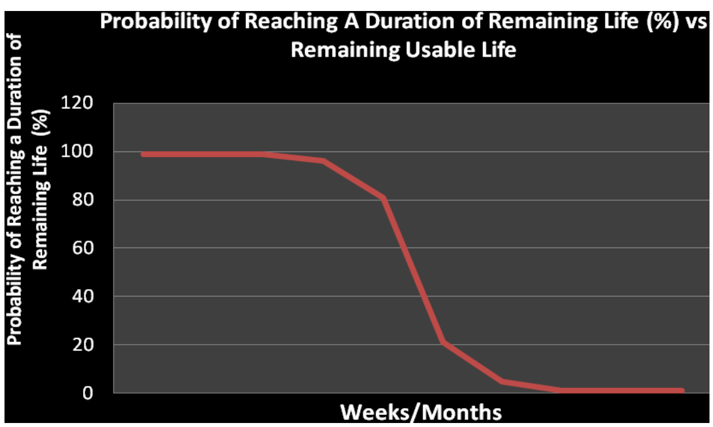

FIGURE 5 PROPRIETARY CUMULATIVE DISTRIBUTION USED TO PREDICT EQUIPMENT TIME-TO-FAILURE/REMAINING-USABLE-LIFE

MARKOV PROPERTY

In 1953, the United States Army-Air Force was developing intercontinental ballistic missiles (ICBMs) and could not stop the premature equipment failures that were occurring during performance testing. A group of mathematicians determined that the rates that equipment in a complex system, such as an aircraft or ICBM, failed was describable using a bathtub shaped curve. The rate at which equipment failed within the first year of use was defined as the infant mortality failure rate, equipment that filed at the end of life was called the end of life failures.

The mathematics was developed to model this behavior and is used today to define proprietary normal and cumulative distribution curves that parts suppliers use to define how unreliable their parts are. The shape of the bathtub curve has become the most widely accepted belief about equipment reliability.

[2] Markov models are used in the calculations for serviceable systems reliability parameters such as MTBF, MTTR, maintainability, serviceability and availability. The Markov property (random, instantaneous and memoryless) is necessary so that reliability engineers can use stochastic equations to quantify equipment, software, processes and systems reliability (a.k.a. PRA). [6]

[7] The mission life of equipment is the desired or minimum duration of time the equipment will function providing the services from the equipment it was designed to provide. Mission life is measured in time and not probability. How is reliability and mission life related? They are not related.

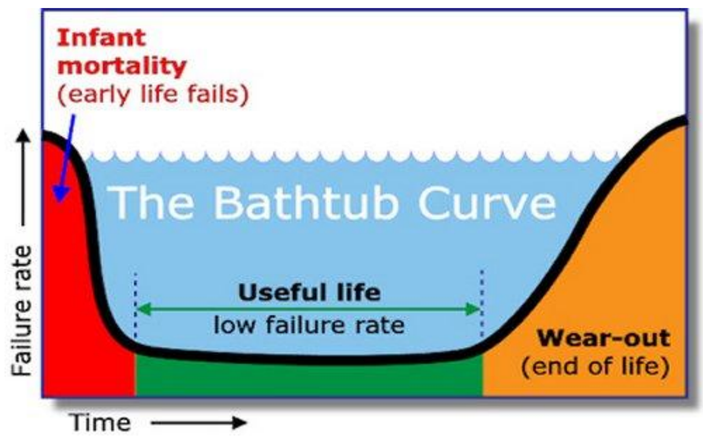

FIGURE 6 RELIABILITY ANALYSIS ENGINEERING'S BATHTUB CURVE

[6] When reliability is defined as a likelihood of occurring, the behavior it quantifies is assumed instantaneous and random whether the behavior is or not. This is having the Markov property and having the Markov property is the basis for many of the stochastic equations used in defining equipment needs and serviceability requirements

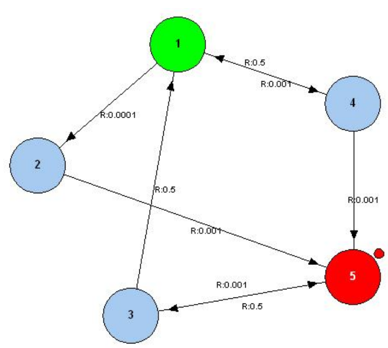

FIGURE 7 A MARKOV MODEL USED FOR CALCULATING THE LIKELIHOOD OF A STATE CHANGE

Do equipment failures occur instantaneously and random? No. Although equipment may exceed its performance specification or stop using electrical power quickly, the process of failing began many weeks or months prior to the event. The equipment began to fail the first time electrical power was applied or the mechanism was used for the first time.

[7] Parts used in equipment degrade in performance starting at beginning of life when power is first applied. When one part starts to degrade in performance much faster than the others, the part is suffering from accelerated aging. Accelerated aging is also the term we use to define to exposing parts or equipment to higher operating temperatures so that parts will degrade much faster. Accelerated aging occurs when at least one part in a circuit or mechanical assembly degrades in performance faster and causes non-repeatable, unique transient events. When telemetry is available from either electrical or mechanical equipment, the non-repeatable transients are visible when the behavior is processed using predictive algorithms. Equipment telemetry provides performance information. Predictive algorithms convert time series telemetry into a measure of equipment life. Data-driven predictive algorithms convert equipment performance information (e.g. volts, amps) into a measurement of remaining usable life. Integrating the normal probability distribution function yields the cumulative distribution function.

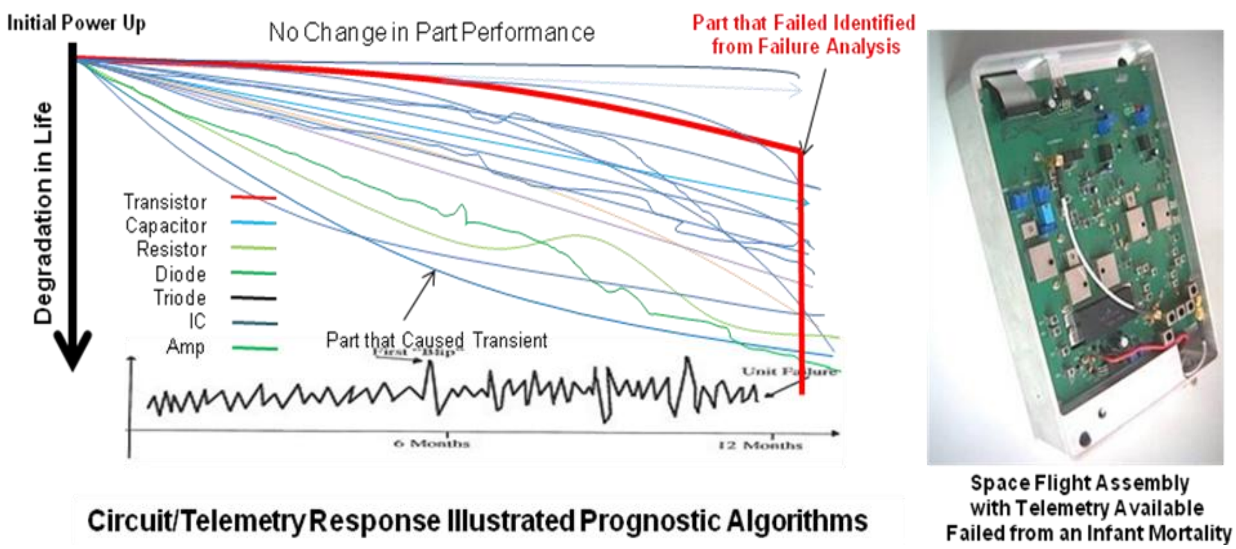

FIGURE 8 CIRCUIT/ASSEMBLY TRANSIENT BEHAVIOR OCCURRS AS PARTS AGE PREMATURELY IS THE REASON PREDICTIVE ALGORITHMS CAN MEASURE EQUIPMENT USABLE LIFE USING ANALOG TELEMETRY

[7] The analysis of time-series (diagnostic) data is a diagnostic analysis. The analysis of the results from a diagnostic analysis is a prognostic (predictive) analysis. The analysis of the results from a prognostic analysis is a prednostic (remaining usable life) analysis. A diagnostic analysis uses past (time-series) equipment data to understand past equipment behavior. A prognostic analysis uses past equipment (time-series) data to predict future equipment behavior.

CONCLUSION

The failure rates of electrical and mechanical parts used in Orion spacecraft avionics equipment are well known and predictable. Testing is used to identify the equipment that fails performance testing from parts that are degrading faster than desired for repair or replacement. A PHM will identify the equipment that will suffer from a premature failure by measuring equipment remaining usable life for identifying the parts suffering from premature aging/accelerated aging. A PHM increases Orion safety and mission assurance by preventing surprise equipment failures. In a PHM, equipment reliability is measured invasively using analog telemetry and not calculated mission life using PRA. The PHM identifies the equipment that will fail prematurely from accelerated aging using a prognostic analysis. A prognostic analysis is a scientific analysis that converts equipment telemetry a.k.a. performance information into a measurement of equipment remaining usable life. A prognostic and health management program includes a scientific analysis and will identify the equipment that will fail prematurely, stopping premature and surprise equipment failures on the Orion spacecraft while it is on the ground, during launch or in space.

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