Stopping Launch Vehicle Failures Using Telemetry to Measure Equipment Usable Life

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Abstract

Launch vehicle reliability is driven by infant mortality failures, which can be eliminated using a prognostic analysis prior, during and/or after the exhaustive and comprehensive dynamic environmental factory testing which conducted to increase equipment reliability. To move to the 100% "measured" reliability domain, launch vehicle dynamic environmental factory testing should be followed by a prognostic analysis to measure the usable life of all the equipment and identify the equipment that will fail when used. Current reliability uses a calculated value based on the stochastic equations identified in reliability standards such as MIL HDBK 217. "Measured" reliability means that the equipment usable life has been measured invasively using equipment analog telemetry and proprietary predictive algorithms as part of a prognostic and health management (PHM) program as well as calculated on paper. Equipment with a "measured" 100% reliability means that the equipment does not have any parts with accelerated aging and will function normally for at least one year with certainty. During typical equipment ATP when reliability engineers calculates reliability on paper, only equipment functional performance is measured and confirmed throughout the ATP and equipment performance is unrelated to either short-term or long term equipment reliability making testing alone inadequate to identify the equipment that will fail prematurely during launch. A prognostic analysis measures equipment usable life/reliability invasively, sharing test data used to measure and confirm equipment performance and provides a remaining usable life in days/months for equipment that will fail during launch for replacement allowing the production of launch vehicles that will not fail prematurely.

Introduction

The launch vehicle production process uses dynamic environmental acceptance testing and measures equipment performance to identify equipment that fails (during test) for repair and replacement[2]. It is hoped that testing and measuring launch vehicle equipment performance will (somehow) improve launch vehicle equipment reliability. A prognostic analysis measures launch vehicle equipment reliability invasively using data-driven, proprietary prognostic algorithms that illustrate accelerated aging in equipment operational data (telemetry) [3].

Figure 1 illustrates the poor reliability (successes/number of attempts) of most U.S. launch vehicles beginning in 1956 through 2004. Figure 1 also illustrates that each launch vehicle demonstrates a "steep learning curve" before the reliability increases over 85%. From game theory [2], these learning curves mean that no experience from other launch vehicles was shared between launch vehicles and that each launch vehicle/ICBM program was developed completely independently. The learning curves also mean that all future launch vehicles will experience the same learning curve if equipment usable life is not measured and confirmed before launch.

[1] According the Aerospace Corporation, space vehicle systems equipment that have been exhaustively and comprehensively performance tested suffer from at least 4 major unexpected, equipment failures during vehicle equipment integration and test (I&T) with equipment that already passed equipment-level dynamic environmental testing. One of the conclusions of the report is that after passing vehicle-level integration & test (I&T), there is a 70% likelihood of another major equipment failure within 45 days of use based on the 47-satellite sample in the study that was launched into space. Launch vehicle premature equipment failures occur frequently and are the causes of all failures in both Figure 1 and Figure 2 and can be prevented by measuring equipment usable life and replacing the equipment with accelerated aging present in performance data generated during manufacturing and factory acceptance testing (ATP).

These equipment failures occur during launch because during manufacturing and dynamic environmental test, only equipment functional performance is measured and confirmed and the equipment that does not meet performance is repaired or replaced before launch.

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Figure 1 illustrates the increase in early ICBM/launch vehicle reliability that occurred over a 48-year period when the on-board equipment usable life was not measured before launch but its reliability was calculated on paper to meet the contractual PRA requirement. Each of the reliability curves illustrate that no experience was shared and thus each new ICBM/launch vehicle had to start out with an unacceptable reliability and then improve at the cost of the taxpayer.

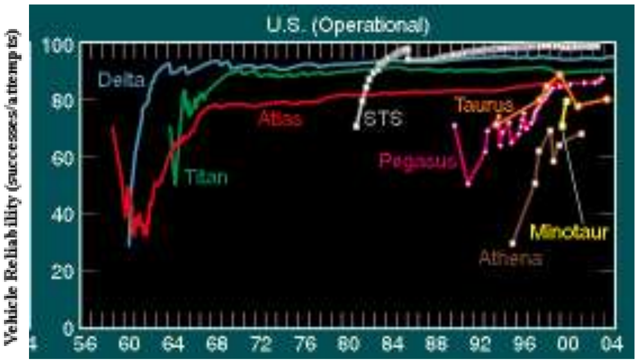


Figure 1 Forty-Eight Years of U.S. Launch Vehicle Reliability using Equipment Performance Testing to Increase Reliability (Aerospace Corporation, 2005[2])

Equipment performance should be measured and confirmed before launch at some point during production, however, measuring equipment performance is also used to increase equipment reliability yet, there is no technical relationship between equipment performance measured during test and either short-term or long-term launch vehicle equipment reliability. Thus for launch vehicle equipment to function during launch, its usable life should be measured and if equipment has accelerated aging present, it should be replaced.

Figure 2 The Air Force/NASA/Orbital Taurus XL is the Most Recent Launch Vehicle Suspended for use due to 3 Premature Failures in 9 Launch Attempts

Measuring launch vehicle equipment performance during test, and then hoping equipment testing somehow increases launch vehicle equipment reliability has been done since the ICBM/launch vehicle inception in the 1950' and the unreliability of launch vehicles as a result of measuring equipment during test and the high rate of infant mortality failures has been well documented. The proven unreliability of launch vehicles in Figures 1 and Figure 2 reduces the importance of testing alone to raise launch vehicle equipment reliability.

Figure 2 is the Orbital Taurus XL launch vehicle that was used to launch the NASA OCO satellite that failed during shroud deployment and has sustained three failures in nine launch attempts. NASA decided to suspend it use, which we informed NASA that Orbital has insured every launch and has not suffered any financial losses to the three failures thus demotivating Orbital to make any changes.

[4] A prognostic analysis shares the same test data (telemetry) collected during spacecraft level integration and test (I&T) and used to measure equipment performance to measure equipment first year reliability by providing a time-to-failure (TTF) for the equipment that will be failing from an infant mortality failure. A prognostic analysis illustrates accelerated aging, often present in normal appearing test data from fully functional equipment. The presence of accelerated aging in test data identifies the equipment that will fail during launch for replacement. Launch vehicle equipment reliability is dominated by infant mortality failures. A prognostic analysis completed after dynamic environmental acceptance and replacing the equipment with accelerated aging increases launch vehicle equipment reliability to near-perfect.

The spacecraft factory qualification and acceptance dynamic environmental acceptance test program (ATP) was added to the launch vehicle/ICBM production process in the early 1960 because launch vehicle reliability was low. With no other actions available to be taken to increase launch vehicle equipment reliability, organizations added the requirement to measure equipment performance hoping that measuring equipment performance during test program would increase launch vehicle reliability. Reliability analysis engineering for calculating the likelihood of equipment failures was also added in the early 1960's. During dynamic environmental testing completed at both the equipment and vehicle factory, only the equipment that fails during test are repaired or replaced. Testing successfully identifies 100% of the equipment that fails during test. If this equipment was not repaired or replaced, the failures would likely occur during launch.

During the production, integration and test, launch vehicle equipment reliability is dominated by infant mortality failures. Equipment failures occur on equipment that has successfully passed equipment-level testing demonstrating the testing alone is inadequate for producing equipment with near perfect reliability. Sometimes, launch vehicle equipment fails prematurely several times during factory I&T. It is repaired each time, violating the Markov property.

It is almost statistically impossible for one unit to suffer from multiple part failures unless the failure is being caused by something other than unreliable parts. Because the reliability engineers do not work on the test of spacecraft equipment, they are unaware that the same equipment will experience a failure several times before it is scrapped by material control personnel. It is statistically impossible for two or more failures to occur in the same unit if equipment failures have the Markov property. To increase launch vehicle reliability, launch vehicle equipment is exhaustively and comprehensive performance tested prior to use. Most launch vehicles still suffer a failure at about 15% of the time.

[5] In 2005, the Aerospace Corporation published a report stating that all launch vehicle contractors are responsible for equipment infant mortality failures for a variety of reasons[6]. We used a different strategy for eliminating infant mortality failures. We searched the test data for the early signs of premature aging/failure (a.k.a. accelerated aging). Its presence was documented in almost 40 issues of the Boeing GPS Monthly and Quarterly Orbital Test Report, CDRL Item A004 published between 1978 through 1988.

Accelerated aging is also known by a variety of names in different industries including deterministic behavior, prognostic markers, prognostic identifiers, cannot duplicates (CND), no failure found (NFF) and no failure identified (NFI) and failure precursors. These are sometimes found in test data and documented in production paperwork/documentation.

Figure 2 is a 10-year Weibull distribution for a complex system such as a launch vehicle used in reliability analysis engineering for illustrating the high rate of piece-part failure that occur within the first year of use known as an infant mortality failures. These failures occur after the complex equipment is exhaustively and comprehensively performance tested during such testing as dynamic environmental factory acceptance testing (ATP).

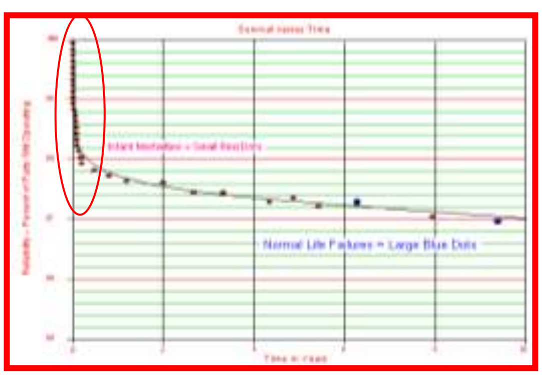


Figure 3 A Weibull Dsitribution Illustrating that the Reliability of a Complex System that uses PRA to Quantify Reliability is Dominated by Infant Mortality Failures

This means that equipment reliability is dominated by infant mortality failures after being tested or testing produces equipment that fails prematurely. However, dynamic environmental factory performance testing is used to reduce the number of infant mortality failures from occurring by exposing the spacecraft equipment to the most severe environments and conditions expected while the equipment is on the ground. The hope was when testing was adopted, that fewer failures would occur in space. Infant mortality failures continue to occur long after the first year of life because they occur on the equipment that replaces the equipment that failed prematurely. The Weibull distributions are believed valid for behavior, which is random and instantaneous. Equipment failures occur over a long duration and the parts that are suffering from premature aging can be identified using a prognostic analysis and so cannot be modeled using a Weibull distribution.

To identify the launch vehicle equipment with piece-parts that are suffering from accelerated aging we pioneered data-driven proprietary, prognostic (predictive) algorithms on Air Force GPS Block 1 satellites (circa 1980). Data-driven algorithms illustrate accelerated aging, often present in normal appearing data from fully functional equipment by personnel trained to discriminate transient behavior from accelerated aging from other normal occurring transient behavior. Using the presence of accelerated aging, we can explain why equipment that has passed dynamic environmental factory acceptance testing, will fail immediately when used. Dynamic environmental testing was added to space vehicle production to eliminate unreliable equipment and does eliminate some of the unreliable equipment. A prognostic analysis identifies the remaining equipment that will fail when used initially.

Prognostic Analysis

The analysis and training used to illustrate and identify the early signs of premature aging/failure is beyond what an engineer does in an engineering analysis, it's a scientific analysis in which the behavior is explained scientifically and is called a prognostic analysis is called a prognostic analysis. The results of an engineering analysis used to define the cause of an equipment failure in which insufficient information is available to define the cause, often referred to as a failure analysis. In a failure analysis, speculation is often used because there is not enough information to conclude what failed.

A prognostic analysis is a scientific analysis that does not rely on speculation or probabilities to explain behavior such is done in an engineering analysis does including a failure analysis. A failure analysis usually concludes that the failed part found after opening up the equipment caused the failure. A prognostic analysis concludes that the part that fails was simply the part that was the most susceptible to failure that the equipment the part is in is failing prematurely, and the unit contains several more parts with accelerated aging that will fail prematurely.

Prognostic technology simply accepts that equipment failures do not have the Markov property and that the early signs of premature aging/failure exist and will identify the equipment that will fail within one year of use. A prognostic analysis is a forensic analysis, which includes the illustration of accelerated aging that is often available in plain sight but misdiagnosed as noise or transient behavior of no consequence.

Prognostic technology was developed by companies who produce large quantities of like units and recognized that there were failure models that could be used to identify when other units were going to fail. The thrust of prognostic technology is the production of near perfect products that will not suffer infant mortality failures by identifying the units that will fail within one year of use while they are still at the factory for replacement.

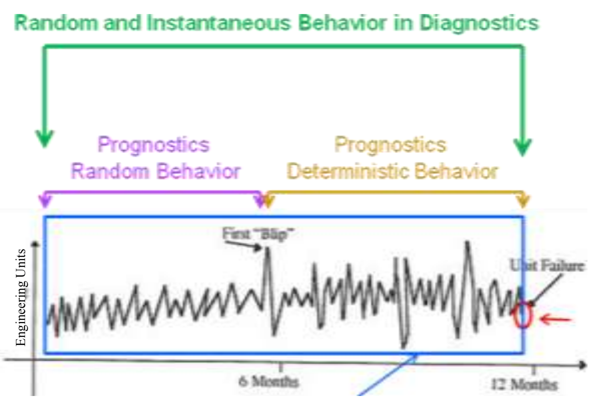


Figure 4 Comparisons between Beginning-of-Life and End-of-Life Based on Diagnostic Analysis and Prognostic Analysis

Figure 4 defines the duration of time between equipment/product beginning-of-life (BOL) and end-of- life (EOL) in a Markov paradigm and a non-Markov paradigm. In a diagnostic analysis, the duration is defined as being random and a failure occurs instantaneously and thus is neither predictable nor preventable. Using a prognostic analysis, the duration between the beginning of life and the first non repeatable transient observed in the data caused from accelerated aging is random but the duration between the first transient event and the equipment's end-of-life is deterministic (predictable). Random behavior is 100% unpredictable and thus non-deterministic. Deterministic behavior is 100% predictable and thus equipment failures using prognostic analysis and prognostic algorithms are predictable and preventable.

A prognostic analysis is a forensic analysis, which includes but is not limited to using operating equipment analog data and proprietary, data-driven or model-based algorithms to illustrate accelerated aging in test data or data of any kind. Accelerated aging is observable as latent, transient behavior among other normal transient behavior. Personnel must receive special training (prognostician) to discriminate transient, deterministic (predictable) behavior from other expected transient behavior. In complex systems such as a launch vehicle, the operational environment of the on-board equipment is very dynamic. Equipment may be cycling or set to cycle and thus the behavior of the equipment telemetry may include transient behavior as a result. Prognosticians must be able to discriminate between normal occurring transient behavior and accelerated aging.

A prognostic analysis can use existing and archived equipment analog telemetry, which is also used to measure equipment performance during test and during launch. Telemetry is sampled analog data that is often available from aerospace equipment in many forms and states. Launch vehicle equipment often has telemetry available, but often not all equipment provides telemetry. Telemetry is not paid for as a separately item and contractors decide which equipment provides telemetry

Launch vehicle equipment that is going to fail during launch will have deterministic behavior present in telemetry, when telemetry is available, which can be illustrated using data-driven proprietary prognostic algorithms and identified by personnel trained to discriminate the transient behavior from other normal occurring transient behavior (prognosticians) in a prognostic analysis. Telemetry is not always available from all equipment and so a prognostic analysis may be done on equipment that does not have telemetry available during I&T. Data from test equipment may be used if it has been archived. Generally, test equipment data is not archived during equipment trouble shooting activities.

What is Launch Vehicle Factory Dynamic Environmental Acceptance Testing and Why is it Important?

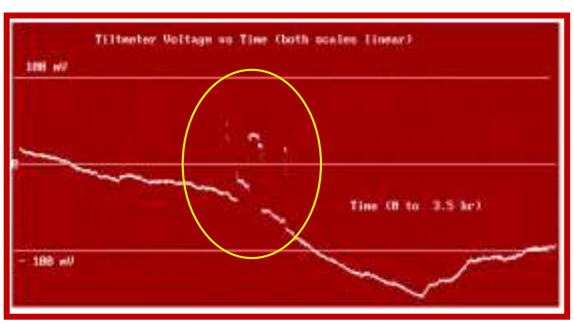
The launch vehicle dynamic environmental factory acceptance testing (a.k.a. ATP) includes exhaustive and comprehensive vibration, thermal, vacuum, shock, acoustic and EMI and EMC which are all used to increase the likelihood of inducing unreliable equipment to fail prematurely before use, thus increasing overall reliability of the electronic and electro-mechanical equipment. During dynamic environmental test, engineers use equipment telemetry to measure equipment performance. Engineers have been measuring launch vehicle equipment performance during test since the development of the dynamic environmental testing was integrated into the launch vehicle production plan. However, there is no relationship between equipment performance and equipment reliability and so the equipment that passes factory testing should be failing prematurely since the equipment reliability is never measured prior to, during or after testing.

Space vehicle factory acceptance testing includes subjecting equipment used in launch vehicles to the extreme environmental and operational conditions the on-board equipment will be exposed to on its journey to space. As a consequence, space vehicle environmental factory acceptance testing may induce some unreliable equipment to fail quicker so that it can be repaired or replaced while it is still on the ground. During factory acceptance testing, some space equipment does fail and is repaired or replaced, however, even after exhaustive factory equipment level and vehicle level acceptance testing, infant mortality failures still cause catastrophic failures during launch. The high infant mortality rate proves that space vehicle factory environmental acceptance testing alone is inadequate for eliminating infant mortality failures.

Because equipment failures are assumed to be instantaneous and random (having the Markov property) so that reliability analysis engineering can be used to quantify reliability, equipment failures have come to be believed as actually to be random and instantaneous by engineers and management[5]. To quantify reliability analysis, stochastic processes are used. Stochastic processes needs random and instantaneous behavior, thus our industry assumes equipment failures are random and instantaneous.

Since equipment failures are believed to be random and instantaneous, there is no value in evaluating data for failed equipment prior to the actual failure. Thus, when completing failure analysis on equipment failures, only information from around the time of the failure has been evaluated. Analyzing data at the time of a failure provides important information engineers can use to help decide which component may have failed instantaneously and randomly.

When a prognostic analysis is conducted prior to use, it will identify the equipment that will fail within one year of use with 100% certainty.



What are the Early Signs of Premature Aging/Failure/Accelerated Aging?

The early signs of premature aging/failure a.k.a failure precursors/deterministic behavior are latent, extremely hard to identify, transient behavior often present in normal telemetry from fully functional equipment, and any analog test data. No two failure precursors or deterministic behavior behave alike, thus the behavior observed preceding one failure will not be repeated and may be the reason for previously never having been identified and not leveraged to measure and increase equipment reliability.

Figure 5 Example of Non-Repeatable Transient Behavior Present in Equipment Analog Telemetry Misdiagnosed as Systemic Noise

Figure 4 illustrates an example of a non-repeatable transient event that is caused by at least one piece-part suffering from accelerated aging relative to the other parts in the unit inducing a transient in the circuit. Deterministic behavior or accelerated aging behavior is present only when piece-parts (electrical and/or mechanical) begin to degrade in operational performance in the circuit/assembly. Accelerated aging affects the steady-state behavior of the unit and when an NRTE occurs, it is identifiable in telemetry.

Changes in internal equipment behavior such as an NRTE are observable in equipment analog telemetry, since telemetry is embedded in electrical circuitry and mechanisms. Whatever the circuit or mechanism experiences, the telemetry interface sends the behavior to engineering personnel. Deterministic behavior has not been identified until now because it is almost identical to behavior from signal noise and other normal transient behavior from equipment cycling and sensor failure and diagnosed as systemic noise and to be ignored and overlooked.

Prognostic Technology

Prognostic technology includes pro-active diagnostics, active reasoning and model-based and data-driven proprietary prognostic algorithms for illustrating accelerated aging and the belief that equipment failures are a combination of random and deterministic behavior[7]. Prognostic technology includes the use of algorithms for illustrating the information in normal appearing data that prognosticians use to identify piece-parts and assemblies that have failed, is failing and will fail in the near future.

Model-based proprietary prognostic algorithms incorporates failure models of the system into the estimation of remaining useful life (RUL) and so are well suited for pattern recognition systems. Data-driven algorithms use existing operational data to determine normal behavior and discriminate normal from the early signs of premature aging/failure. In the launch vehicle environments, signal line noise may be present caused from degradation in Eb/No, RF noise from a variety of sources as well as equipment noise that generates the data used to conduct a prognostic analysis may be present and the proprietary prognostic algorithms must be able to identify, remove/replace this data.

The Markov property is named for a Russian mathematician and is defined solely of random and instantaneous behavior. The Markov property is a fundamental assumption in reliability analysis so that stochastic processes can quantify parts, equipment, systems, processes and software reliability in probabilistic values. Due to the wide spread use of reliability analysis engineering results in the aerospace industry, engineers may have come to believe that equipment failures really are instantaneous and random and thus cannot be predicted or prevented.

Prognostic technology acknowledges that electrical piece-parts and mechanical assemblies do not fail instantaneously but degrade in functional performance over time. We call the unexpected degradation in parts performance, "accelerated aging." This means that equipment failures may occur randomly but not instantaneously and so do not have the Markov property.

Prognostic technology resulted from personnel completing failure analysis on a large number of like-units and learning that equipment failures exhibit failure models and so do not fail randomly.

This new property is a combination of random and deterministic behavior because we can use algorithms to illustrate the information prognosticians use to predict equipment failures and once this information is identified, the same conclusion results. The widespread use of proprietary prognostic algorithms corrects the inadequacy that allows so many complex space systems to fail within the first year of use after production and launch.

Prognostics include the identification of the data used to predict equipment that is going to fail. Prognostic analysis is necessary because current diagnostic technology is inadequate to identify all equipment that will fail from infant mortality failures. Prognostic technology/analysis is the next logical step in advancing electronic and electro-mechanical equipment reliability and achieving near perfect reliability.

Prognostic technology and prognostic health management as part of equipment operations and maintenance is a critical technology for accurately predicting impending failures and providing a mechanism for replacing equipment and parts safely before failure for ground-based equipment and preparing for and executing recovery plans for space-based equipment.

Using prognostic analysis in the space flight equipment and at vehicle factories, upgrades space equipment processes by identifying more unreliable piece-parts and assemblies during equipment and vehicle factory acceptance test, reducing the time to test equipment, identifying equipment that has failed, is failing and will fail, increasing reliability and eliminating infant mortalities. The shorter equipment and vehicle test time reduces cost.

Markov Property

[5] The original defining property of Markov models is that the state transitions are instantaneous, random and memoryless, which is to say, the transition times are all distributed with constant rate parameters.

The time variable enters into the governing equations only in the differential sense, insofar as the derivatives of the state probabilities with respect to time appear. The equations are independent of the absolute value of time, so any arbitrary value can be taken as the time origin and are said to be homogeneous in time. Moreover, a single time parameter suffices for the coordination of the entire model and so such models possess temporal coherence.

Using the Markov modeling information in Figure 5 or Markov property on behavior that do not meet all the criteria is a recognition that the true behavior is not important enough to quantify accurately or is believed to be too complex to do so. When Markov is invoked, it often corrupts the decision making process. The best example of making the wrong decision believing that equipment failures have the Markov property occurred on the NASA Space Shuttle Challenger accident. The Challenger solid rocket motor failure was predicted by the SRM contractor manager, but his management and NASA management both ignored the prediction believing that equipment failures were instantaneous and random thus not predictable and not preventable.

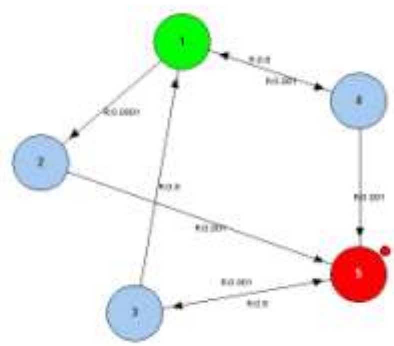


Figure 6 Example of Reliability Analysis Engineering Markov State Diagram

False Negatives

The accuracy of prognostic analysis and the determination of the time-to-failure increases with the availability of all possible equipment behavior collected and stored during all different operating conditions. Because there are many sources of data that can be interpreted as failure behavior, the more data available from each equipment operational environmental and operational condition the equipment will be used in used, the more reliable the results for calculating the remaining usable life.

A false positive, also known or false alarm occurs when a prognostician identifies a suspect failure precursor from telemetry that is caused by something other than a piece-part or component failure. False alarms reduce reliability of telemetry prognostics since people will discount the results.

Likewise, for a false negative to occur, missing the accelerated aging in data used to predict a failure could cause a surprise failure putting a spacecraft at risk. Table 1 is a list of proprietary data driven proprietary predictive algorithms used to identify accelerated aging in a full noise environment, when almost no equipment data is available and when there is too much data for analysis.

Table 1 List of Proprietary Data-Driven Predictive Algorithms for Measuring Spacecraft Equipment Remaining Usable Life

Algorithm	Purpose of Algorithm
Baseline Analysis	Identifies short and long term normal data behavior
Change Analysis	Determines change from normal behavior.
Comparison Analysis	Determines when a change in normal behavior is occurring
Day of Failure	Search large data sets for common behavior during the same time
Digital Processing	Replaces outliers improving image accuracy and resolution
Discrimination Analysis	Identify behavior that has changed from normal behavior
Mathematical Modeling	Generates normal behavior from an inadequate data
Multi-Variant Limit Analysis	Simultaneous analysis across several variables
Rate Change Analysis	Identifies magnitude of change of behavior
Remaining Usable Life	Determines remaining usable life
Statistical Sampling	Reduces amount of data without eliminating desired behavior
State Change Analysis	Identifies data to be evaluated
Super Impositioning	Identifies data to be analyzed further for failure signature
Super Precision	Improves data integrity
Telemetry Authentication	Improves data integrity
Virtual Telemetry	Creates normal data behavior when none is available
Data Integration	Creates image for analysis
Dataset Generation	Creates data set manually when access is not available

Table 2 List Proprietary Predictive Algorithms Needed at Locations that a Prognostic Analysis can be Completed

Algm No.	Eqmt Factory	Satellite Factory	LV Factory	Mission Control
1	X	X	X	X
2		X	X	X
3	X	X	X	X
4	X	X	X	X
5				X
6	X	X	X	X
7	X	X	X	X
8	X	X	X	X
9		X	X	X
10	X	X	X	X
11		X	X	X
12		X	X	X
13		X	X	X
14				X
15				X
16	X	X	X	X
17	X	X	X	X
18				X

Table 2 identifies which proprietary predictive algorithms are used at the many different locations that a prognostic analysis can be completed. The most demanding location to complete a prognostic analysis on a spacecraft is while the spacecraft is in space and the prognostic analysis is completed by the mission control team located at mission control. This is because there are many sources of transient behavior that mimic the transient behavior that identifies the presence of accelerated aging. Some of these sources include RF and electrical noise from the spacecraft equipment or ground-based communications systems caused from low S/No or low Eb/No that is not present at locations such as the equipment factory.

Our proprietary predictive algorithms include to algorithms to remove, replace or differentiate noise from accelerated aging. Predictive algorithms effectively demodulate the data behavior in time, amplitude, frequency and phase, illustrating the presence of accelerated aging caused from at least one electrical or mechanical part that is aging in performance faster than desired and is often present in normal appearing telemetry from fully functional equipment that passes performance testing. The algorithms will remove noise, generate baseline behavior when little baseline behavior is available and will remove excess data from sources that contain too much information to consider.

Spacecraft Equipment Analog Measurements Needed for Measuring Equipment Usable Life in a Prognostic Analysis

[6] Measuring equipment usable life can use almost any analog telemetry measurement available today on flight equipment and in launch vehicle telemetry systems or any other performance data. However, equipment instrumentation with at least a single analog measurement integrated into equipment (a.k.a. telemetry) is necessary to illustrate the presence of accelerated aging. Equipment with accelerated aging will fail prematurely with 100% certainty. The number and types of analog measurements per unit may include voltage, current and temperature. Although a prognostic analysis is insensitive to measurement type and sampling frequency, very low sampling frequency can affect the accuracy of the of remaining-usable-life calculation.

Calculating Remaining Usable Life (RUL)/Time to Failure (TTF) in a Markov Paradigm (PRA)

The remaining-usable-life or the time-to-failure (TTF) in a Markov paradigm is based on a probability distribution provided by parts suppliers. IN a Markov paradigm, the knowledge that a failure will occur cannot be known only the probability of a failure occurring.

The probability of a failure occurring in a Markov paradigm is defined by a proprietary distribution such as Figure 7. Figure 7 includes several common distributions and these distributions are used to define the likelihood of a part failure occurring. Parts suppliers do not and cannot sell parts that will not fail thus they define their parts quality as a distribution. The likelihood of a failure occurring is not the knowledge that a failure is occurring. When working in a Markov paradigm, the probability something is going to occur is the best definition possible.

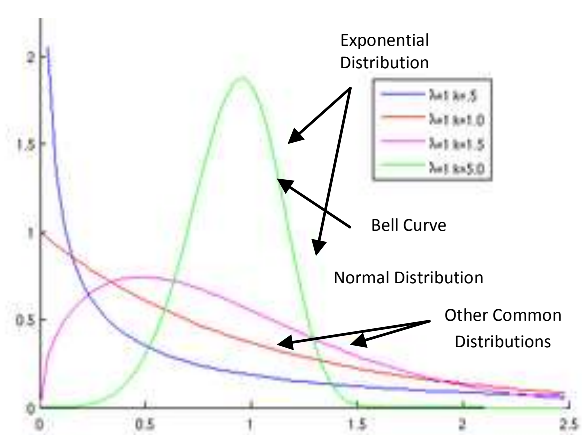


Figure 7 Examples of Common Probability Distributions with Various Shape Constants

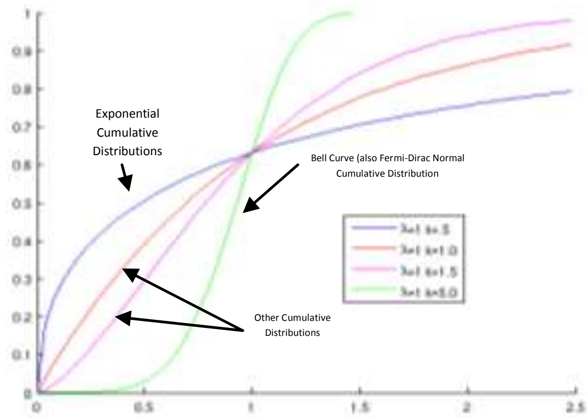


Figure 8 Examples of Cumulative Distribution Functions (Integral of the Normal Distributions)

In a Markov paradigm, the likelihood of any specific part failing is provided by the integral of the normal distribution called the cumulative distribution. Figure 8 is the cumulative distributions for the normal distributions in Figure 7.

The knowledge whether a specific part will fail is a certainty and not a probability and so probability distributions do not provide the knowledge whether a specific part will fail for equipment in a Markov paradigm.

Since the knowledge whether any specific part will fail prematurely cannot be known in a Markov paradigm, the remaining usable life (RUL)/time to failure (TTF) for a part in a batch of parts is the desired information to be known, a probability distribution is used and so the desired information cannot be known.

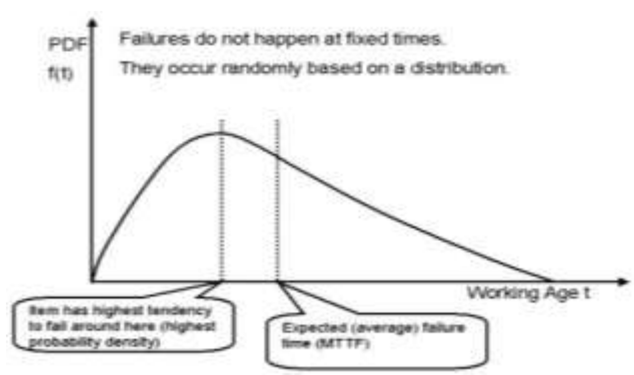


Figure 9 Traditional Unused Probability Distribution used to Predict the Time to Failure as a Probability in a Markov Paradigm.

[6] To calculate the TTF, f(t) is the probability density function (PDF). It is the usual way of representing a failure distribution (also known as an “age-reliability relationship”). As density equals mass per unit of volume, probability density is the probability of failure per unit of time. When multiplied by the length of a time interval at

time, t, the quotient is the probability of failure in that interval. The PDF is the basic description of the time to failure of an item. The PDF is often estimated from real life data. It resembles a histogram of the failures of an item in consecutive age intervals. All other functions related to an item's reliability can be derived from the PDF. For example:

F(t) is the cumulative distribution function (CDF). It is the area under the f(t) curve in Figure 9 from 0 to t. This is also called the unreliability, or the cumulative probability of failure. The survival function in a Markov paradigm is R(t) = 1-F(t).

In a Markov paradigm, h(t) is the hazard rate. At various times its also called the hazard function, conditional failure rate, instantaneous failure probability, instantaneous failure rate, local failure rate, a component of "risk", and is defined as h(t) = f(t)/R(t).

The conditional probability of failure, (R(t)-R(t+L))/R(t) is the probability that the part fails in a time interval [t to t+L] given that it has not failed up to time t and its behavior in time resembles the shape of the hazard rate curve. When the interval length L is small enough, the conditional probability of failure is approximately h(t) x L. H(t) is the cumulative hazard function and is the integral of h(t) from 0 to t, or the area under the hazard function h(t) from 0 to t. The mean time to fail (MTTF) is the average time to fail, expected time to failure, or average life.

$$\text{MTTF} = \int_0^\infty t f(t) dt$$

The results of these calculations using a PDF cannot identify a part that is going to fail prematurely nor how long a part will function normally. The answer to these questions is certainties and certainties cannot be defined using probabilities in a PRA that is used in a Markov paradigm.

Determining Spacecraft Equipment Remaining Usable Life (RUL) with Certainty in a Non-Markov Paradigm

In a non-Markov paradigm, whether equipment will fail prematurely or not from a part that is going to fail is a certainty and not likelihood. This is because a part that is going to fail prematurely exhibits the behavior we define as accelerated aging. A part suffering from accelerated aging is a part that will fail prematurely with 100% certainty.

Through experimentation, the part suffering from accelerated aging will eventually change so much that it no longer will function well enough in a circuit to maintain stable performance and it will cause a transient event. If telemetry is available and the telemetry is being recorded, the transient event can be observed by completing a prognostic analysis.

In a non-Markov paradigm, no distributions are used to calculate the probability of a failure occurring, whether a failure will occur or not is a certainty. If equipment has accelerated aging identified, the RUL/TTF can be determined in many ways. Generally, the algorithm that determines the RUL is proprietary and may be company and part specific.

This information is used to determine the probability of success (Ps) of a circuit with a failure precursor identified reaching its predicted remaining-usable-life. This information is in the form of a cumulative distribution derived from the actual remaining life that occurred on the many failures analyzed over a 30-year period.
Predicting an accurate time-to-failure (TTF) after accelerated aging are identified, we use the cumulative distribution curve in Figure 10 developed from our proprietary database of equipment failures we have analyzed over 30-years on launch vehicles and satellites.

In the equipment failures we analyzed, we measured the duration of time between the first transient 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.

[7] 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.

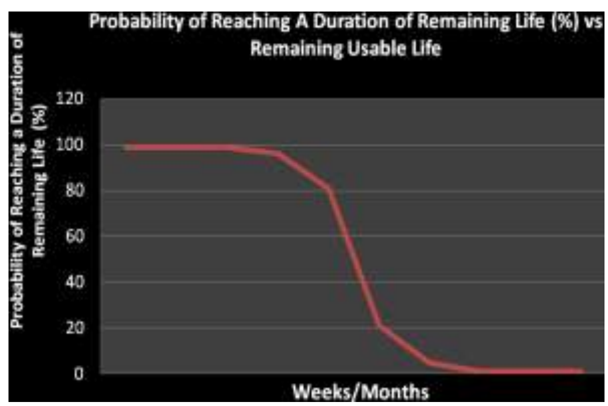


Figure 11 Proprietary Cumulative Distribution used to Determine Spacecraft Equipment Remaining-Usable-Life in a Non-Markov Paradigm

The integral of a normal distribution function is its cumulative distribution as illustrated in Figure 7. 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.

Our proprietary cumulative distribution curve is generated from 30 years of measuring the remaining-usable-life of high-reliability aerospace/vehicle equipment failures put into our database of equipment failures. The results are not random because they are based on actual equipment failures and so are a probability (Ps) of occurring based on many past failures and real durations of remaining usable life.

Using predictive algorithms to measure equipment usable life will identify the equipment that will fail prematurely for replacement before launch. Measuring equipment usable life before launch will stop the premature failures of launch vehicles making getting to space and working in space safe.

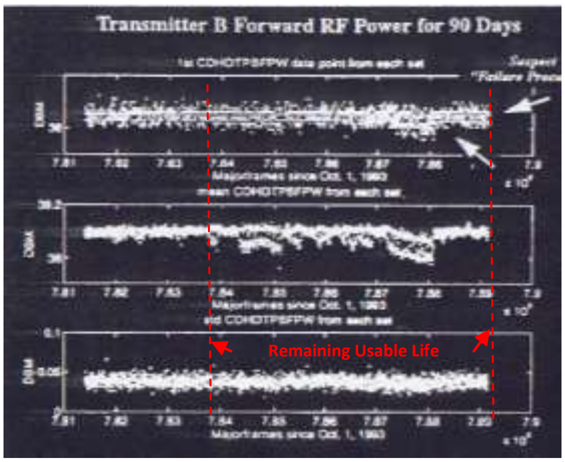


Figure 11 Results from Measuring the Remaining Usable Life on a TDRSS RF Transmitter B using the Forward RF Power Telemetry Measurement

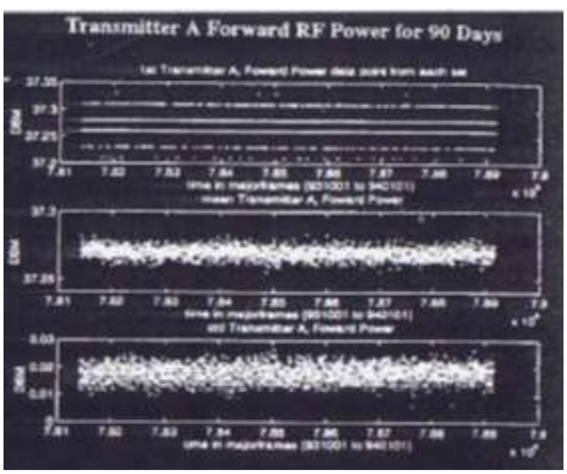


Figure 12 Post-Processing Results from the Search of TDRSS Transmitter Unit A Analog Telemetry for Transient Behavior using Proprietary Predictive Algorithms

[8] Figure 11 is the results from using proprietary predictive algorithms to complete a prognostic analysis searching for transient behavior in equipment telemetry. Figure 11 illustrates the results from a prognostic analysis completed on the spacecraft RF telemetry Transmitter B unit. The telemetry was evaluated normally using an engineering analysis by the equipment company engineers.

[8] Figure 12 is the results of the same prognostic analysis completed on Transmitter Unit A analog telemetry during the same time as was done for telemetry Transmitter Unit B. Both transmitters were on simultaneously and transmitting the same data. No transient behavior was observed and the Transmitter A telemetry and transmitter A did not fail prematurely.

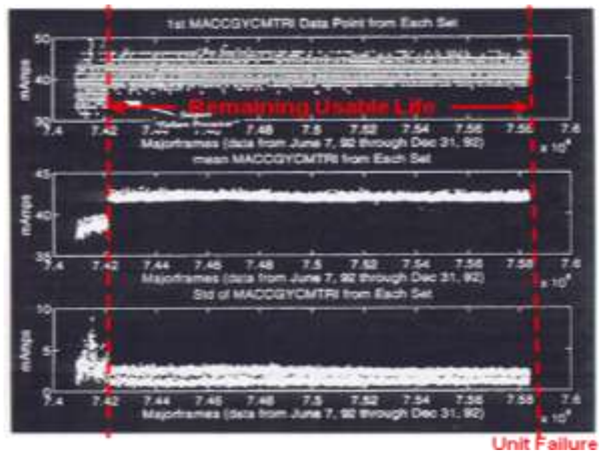


Figure 13 Results from Measuring Remaining Usable Life of a Spacecraft Rate Gyro Unit C using Gyro C Motor Current Telemetry Data

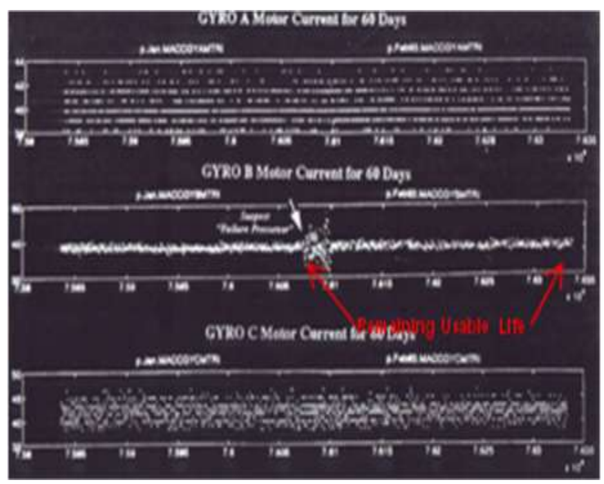


Figure 14 Results from Measuring Spacecraft Rate Gyro Unit A, B & C using Rate Gyro Motor Current Telemetry Measurement

The engineering analysis completed after the failures occurred found no behavior preceding the unit failure. The transient behavior appearing in telemetry was obvious. It was found using proprietary predictive algorithms to demodulate the transmitter telemetry behavior in a scientific analysis. The prediction of the remaining usable life using Figure 10 matched within 5% of actual unit life.

[8] Figure 13 is the results from a prognostic analysis completed on one of three NASA LEO space science spacecraft rate gyros. The analysis illustrates the presence of transient behavior/accelerated aging in the unit analog telemetry. The unit's telemetry was evaluated by the equipment vendor and no transient behavior was found during the engineering analysis. The prediction of the units remaining usable life was within 5% of actual.

[8] Figure 14 is the results from a prognostic analysis completed on one of 3 spacecraft rate gyros. The results show that the behavior of the unit changes abruptly and exhibited a transient event observable in unit analog telemetry. The prediction of its remaining usable life was for several months and it was within 5% of actual.

Conclusion

Spacecraft equipment remaining usable life can be determined using a variety of proprietary predictive algorithms. Spacecraft equipment is exhaustively and comprehensively performance tested during an ATP to meet contractual performance requirements before launch, but equipment usable life is not measured and confirmed before launch causing the reliability of spacecraft to be dominated by premature equipment failures.

Spacecraft equipment must also meet a contractual mission life requirement. Today, the equipment mission life is calculated on paper using stochastic equations in a probability reliability analysis. Stochastic equations use almost meaningless information to arrive at results that appear to be of value but are not. To stop the premature failures of launch vehicle equipment, all on-board equipment usable life must be measured and confirmed before use using proprietary predictive algorithms in a prognostic and health management program.

Launch vehicle manufacturers only measure equipment performance during dynamic environmental acceptance testing, but there is no relationship between equipment performance, measured during test and short-term or long-term equipment usable life thus launch vehicle equipment should be failing prematurely. Using a prognostic analysis to measure equipment usable life before, during and/or after equipment and vehicle dynamic environmental acceptance factory test allows the identification of spacecraft equipment that will fail immediately after test.

Expanding factory production activities to include measuring and confirming equipment and vehicle usable life with a prognostic analysis will allow launch vehicle suppliers to produce launch vehicles with near perfect reliability and eliminate launch vehicle failures caused from equipment with parts that are aging prematurely, making getting to space safe and reliable.

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