Making Getting to Space Safe by Upgrading the Satellite and Launch Vehicle Factory Testing with a Prognostic Analysis

Len Losik[1], Ph.D
Failure Analysis, Salinas CA

Abstract

Satellites and launch vehicle equipment continue to suffer from catastrophic premature failures. The space vehicle equipment and vehicle factory dynamic environmental acceptance testing helps to encourage unreliable equipment to fail and is used to identify equipment that has failed during test for repair or replacement but has proven to allow some equipment through that fails prematurely causing the most celebrated failures in the industry. The continued occurrences of premature failures on launch vehicles and on-orbit satellites demonstrates that testing alone is inadequate for identifying all the equipment that will be failing within the first year of use and thus must be augmented. A prognostic analysis uses proprietary data-driven algorithms for searching for accelerated aging, which precedes a failure when equipment telemetry is available and by converting telemetry into a reliability measurement. A prognostic analysis measures equipment reliability by illustrating the latent, transient accelerated aging present in equipment telemetry that will fail prematurely within one year of use. A prognostic analysis will identify all equipment that will fail prematurely prior to shipment of the spacecraft to the launch pad. A prognostic analysis completed after final factory testing will eliminate failures during launch, launch pad delays, on-orbit infant mortalities, surprise on-orbit failures and extend on-orbit satellite and equipment usable life making getting to space and working in space safe.

I. Introduction

Space vehicle reliability and safety 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% reliability domain, launch vehicle dynamic environmental factory testing should be followed by a prognostic analysis to identify the equipment that

Figure 1. Forty-Eight Years of Reliability of U.S. Launch Vehicles using Testing to Increase Reliability (Aerospace Corporation)

[1]President and Chief Technical Officer of Failure Analysis, 12 Glen Falls Circle, Salinas CA 93906, Senior Member

will fail when used. During equipment test, only equipment functional performance is measured and equipment performance is unrelated to short-term equipment reliability making testing alone inadequate to identify the equipment that will fail during launch.

A prognostic analysis measures equipment reliability invasively sharing test data used to measure equipment performance and provides a time-to-failure (TTF) in minutes/hours/days/months for equipment that will fail during launch, allowing the production of launch vehicles with near-perfect reliability, decreasing risk and making getting to space safe and reliable.

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-drive, prognostic algorithms that illustrate accelerated aging in equipment operational data (telemetry)[3].

Figure 1 illustrates the reliability (successes/number of attempts) of most U.S. launch vehicles beginning in 1956 when they were first under development as an ICBM through 2004 as a launch vehicle.
According the Aerospace Corporation, space vehicle systems equipment 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. Then, after passing vehicle-level I&T, there remains a 70% likelihood of another major equipment failure within 45 days of use. Launch vehicle equipment failures occur frequently and are the causes of all failures in both Figure 1 and Figure 2. These equipment failures occur during launch because during dynamic environmental test, only equipment functional performance is measured, which should be measured at some point during production, however, measuring equipment performance is used to increase equipment reliability yet, there is no relationship between equipment performance measured during test and either short-term or long-term launch vehicle equipment reliability

Measuring launch vehicle equipment performance during test, and then hoping testing increase 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 equipment reliability.

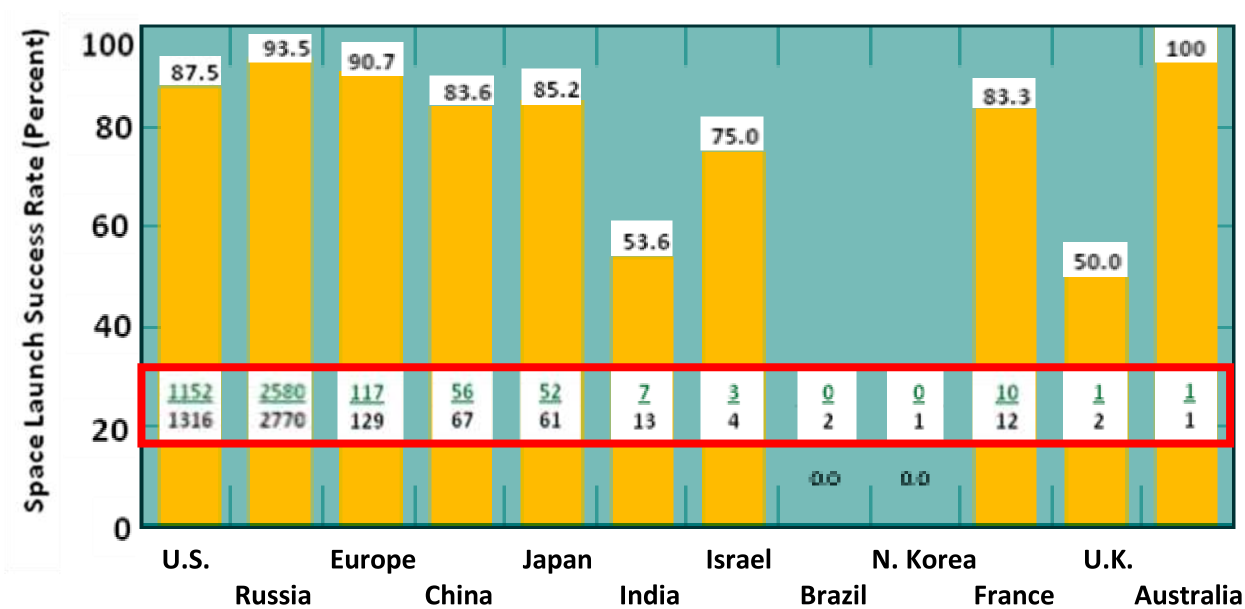

Figure 2: U.S. and International Launch Vehicle Successful (Green) and Unsuccessful (Black – Green) Launches from 1985 to 1999 (Aerospace Corporation, 2001)

A prognostic analysis shares the same test data (telemetry) collected during I&T and used to measure equipment performance to also 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.

Figure 2 illustrates the success (black) and failure rates (black-green) for U.S. and international launch vehicles by country illustrating catastrophic failures occur on almost all launch vehicles at very high rates. The majority of the failures occur in the launch vehicle propulsion subsystem. The launch vehicle propulsion subsystem is also the least instrumented subsystem on a launch vehicle.

The 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 will fail many times and be repaired during the production and test process, violating the Markov property. To increase launch vehicle reliability, launch vehicle equipment is exhaustively and comprehensive tested prior to use and yet most launch vehicles will suffer a failure at about 15% of the time.

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[4]. 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.

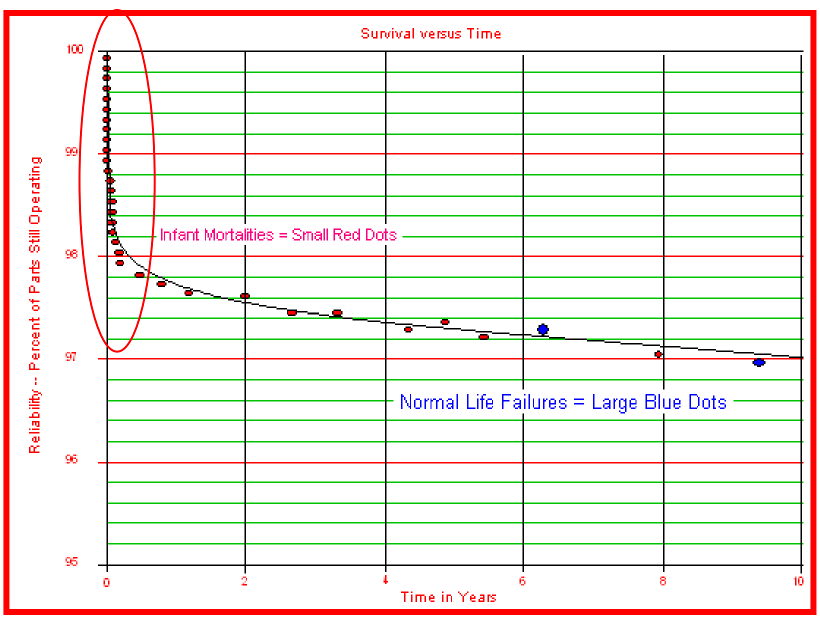

Figure 3. Initial Infant Mortality Failures (Oval) for a Complex System Over a 10 Year Life Eliminated Using Prognostic Analysis

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 3 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 within the first year of use. These failures occur after dynamic environmental acceptance testing is completed. Dynamic environmental testing is used to reduce the number of infant mortality failures from occurring. Infant mortality failures continue to occur long after the first year of life because they continue to occur in the equipment that replaced the equipment that failed.

To identify the launch vehicle equipment with piece-parts that are suffering from accelerated aging we then developed and used data-driven prognostic algorithms. Data-drive algorithms illustrate accelerated aging, often in normal appearing data from fully functional equipment by personnel trained to discriminate them from other normal occurring transient behavior. Using the origin of accelerated aging, we explain why equipment that has passed dynamic environmental 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 rest of the equipment that will fail when used.

II. Prognostic Analysis

The analysis and training used to illustrate and identify the early signs of premature aging/failure is a prognostic analysis. 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.

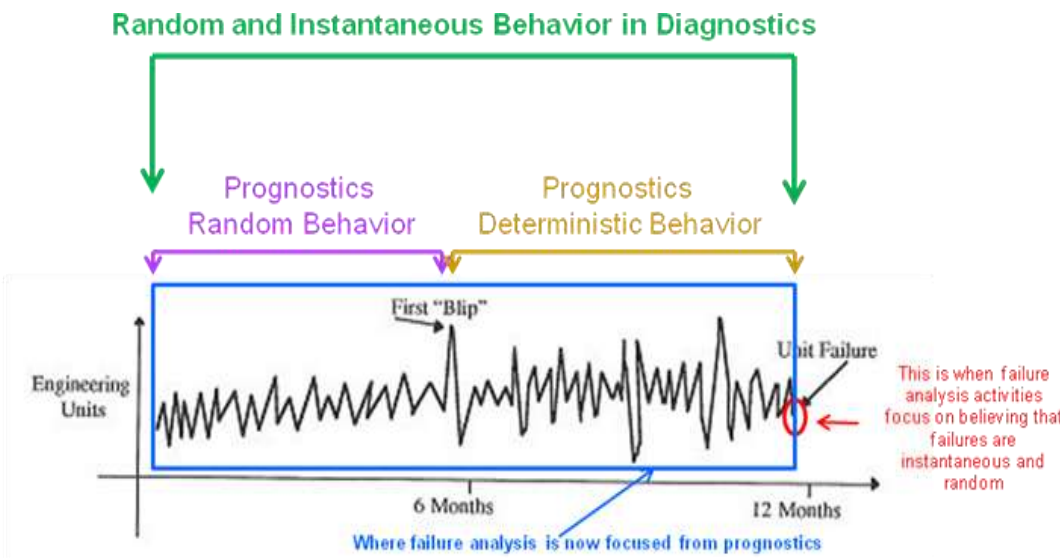

Figure 4. Comparison between Definition of Duration between Equipment Beginning-of-Life and End-of-Life Based on Diagnostic Analysis and Prognostic Analysis

Figure 4 identifies the definition of the duration of time between equipment beginning-of-life (BOL) and end-of- life (EOL). Using just diagnostic analysis, the duration is defined as being random and a failure occurs instantaneously and thus is neither predictable nor preventable. Using prognostic analysis, the duration between the beginning of life and the first transient observed in the data caused from accelerated aging is random but the duration between the first transient and the equipment's end-of-life is 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 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.

A. 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 also 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.

B. 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 illustrates an example of transient behavior that is caused by parts suffering from accelerated aging relative to the other parts in the unit inducing a transient in the circuit. Deterministic behavior is present only when piece-parts (electrical and/or mechanical) begin to change functional performance in the circuit/assembly they are in and affects the steady-state behavior of the unit. Changes in internal behavior observable in telemetry require embedded interface such as telemetry provides. 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.

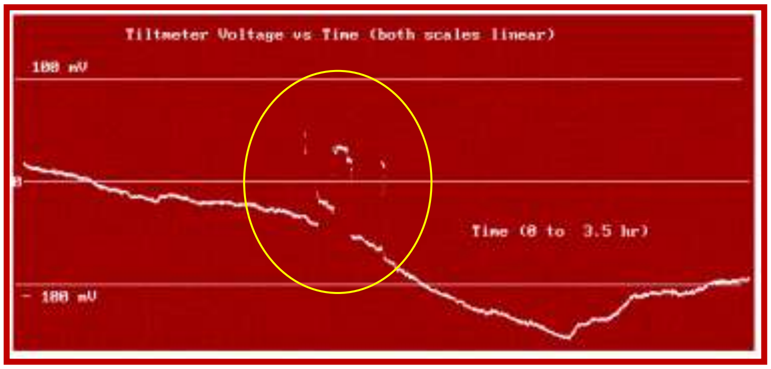

Figure 5. Example of the Transient/Early Signs of Premature Aging/Failure/Prognostic Markers/Prognostic Identifiers in Telemetry Caused from Accelerated Aging in all Types of Equipment

III. Prognostic Technology

Prognostic technology was developed after companies that produce large quantities of like-products recognized failure models usable to identify units that would fail prematurely. It includes pro-active diagnostics, active reasoning and model-based and data-drive prognostic algorithms for illustrating accelerated aging and the belief that equipment failures are a combination of random and deterministic behavior[6]. 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 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 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 instantaneously and thus can be predicted and prevented.

Algorithm	Purpose of Algorithm	Equipment Factory	Satellite Factory	LV Factory	Launch Pad	Mission Control
Baseline Analysis	Identifies short and long term normal data behavior	X	X	X	X	X
Change Analysis	Determines change from normal behavior.		X	X	X	X
Comparison Analysis	Determines when a change in normal behavior is occurring	X	X	X	X	X

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

Table 1. Complete List of Data-Driven Prognostic Algorithms for Illustrating Accelerated Aging and Predicting a Failure including Calculating the Remaining Usable Life/Time-to-Failure in Launch Vehicle Equipment in a Full Noise Environment with or without Equipment Operational Data for Analysis

Table 1 identifies the proprietary, data-driven algorithms necessary to illustrate accelerated aging at all possible location for satellites and launch vehicle equipment. Training is necessary to discriminate accelerated aging in telemetry from other normal occurring transient behavior.

PROGNOSTICS	DIAGNOSTICS
Identifies equipment failures that have occurred, is occurring and will occur and when it has occurred and will occur	Identifies failures that have occurred and when they occur
Identifies equipment failure in process and when	Only identifies equipment failures after they have already occurred
Identifies equipment failures that will occur in the future	Only identifies equipment failures after they have already occurred
Requires major changes in analysis attitude and behavior	Training is done from example
Overcomes shortcomings in diagnostic techniques	Diagnostics were developed from ground test equipment
Prognostician actively monitors data to provide knowledge of whether a failure has occurred, is occurring or when a failure is likely to occur	After the fact response, if error messages are used, diagnostician waits for error message if any action is taken

All events are considered failure precursors until ruled out by research – analyst doesn't stand by and watch failures occur	Data is recorded and analysis is completed post event
A fault propagation model is assumed to encompass parametric data related to acceptable operating ranges, behavior and identification of degradation of functions over time.	Suspect behavior is considered system noise, any action is taken after completion of events
Requires highly skilled and trained personnel, must have in-depth knowledge of what is being actively monitored	Allows lower skilled personnel, doesn't require in-depth understanding of what's being monitored, diagnostician just sits and waits to complete event
Requires training across several disciplines	Common throughout many industries
Stops life threatening situations from occurring	Inadequate for mission critical events

Table 2. Comparison of Characteristics between Active Reasoning used in Prognostic Analysis and Passive Reasoning used in Diagnostic Analysis

Table 2 defines the difference between characteristics of active reasoning and passive and conducting a prognostic analysis and diagnostic analysis. In factory acceptance test, engineers cannot explain what behavior in the data to expect and so their reaction to events is reactionary.

ACTIVE REASONING	PASSIVE REASONING
Reduces fault detection time as well as improve the accuracy of fault diagnosis.	Evaluates symptoms after the event
Evaluates symptoms continuously	Records the data and look at it later
Does fault reasoning	Spurious symptoms could mislead fault localization analysis.
Does high fidelity evaluation	Spurious symptoms are also regarded as observation noise
Does action selection	Depends on monitoring agents to detect and report abnormality using alarms or symptom events
Takes passively observed symptoms as input and returns fault hypothesis as output.	Search for root faults based on the observed symptoms
Process of searching for the best fault explanation of the observed symptoms.	Diagnostic explains a failure based on observed symptoms
Improves the robustness of fault localization system by analyzing lost, positive and spurious symptoms.	Diagnostics Improves the robustness of fault localization system by analyzing lost, positive and spurious symptoms.
Assumes each event is deterministic	Assumes an event is noise

Table 3 Comparison between Prognostic Active Reasoning and Diagnostic Passive Reasoning

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 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. A 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 by taking the necessary actions to prevent equipment failures rather than just react to them after they occur.

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.

IV. Markov Property

The original defining property of Markov models is that the state transitions are memoryless, which is to say, the transition times are all distributed with constant rate parameters. This means that no behavior preceding an event having the Markov property is related to the event. 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 Markov state 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. For the convenience of using Markov models, equipment failures must be instantaneous and random.

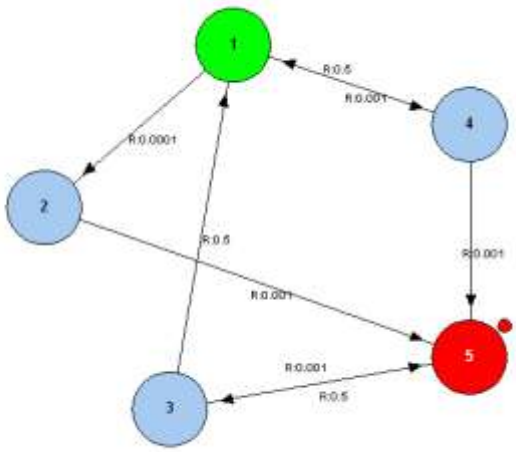

Figure 6. Example of Reliability Analysis Engineering State Diagram Including Probability of State Change used to Calculate Likelihood of a Failure Occurring in a Complex systems

V. False Positives and False Negatives

The accuracy of prognostic analysis and the determination of the time-to-failure increases with the capture of all possible equipment behavior 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 as a false detection 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.

The list of prognostic algorithms provides the tools to prognosticians to identify accelerated aging in a full noise environment, when almost no operational equipment data is available and when there is too much data for analysis at all locations in the launch vehicle design, production and test environments making prognostic analysis fully robust.

VI. Analog Measurements Needed for Using a Prognostic Analysis

Prognostics technology uses almost any analog measurement available today on flight equipment and in 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.

VII. Calculating Remaining Usable Life (RUL)/Time to Failure (TTF)

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.

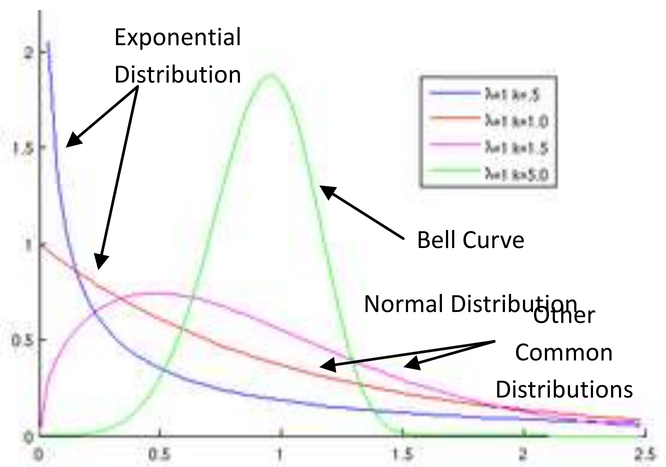

Figure 7. Examples of Common Probability Distribution Functions with Various Shape Constants

To accurately predict remaining-usable-life for equipment that has been predicted to fail, Failure Analysis maintains a database of previous flight equipment failures that were analyzed over a 30-year period.

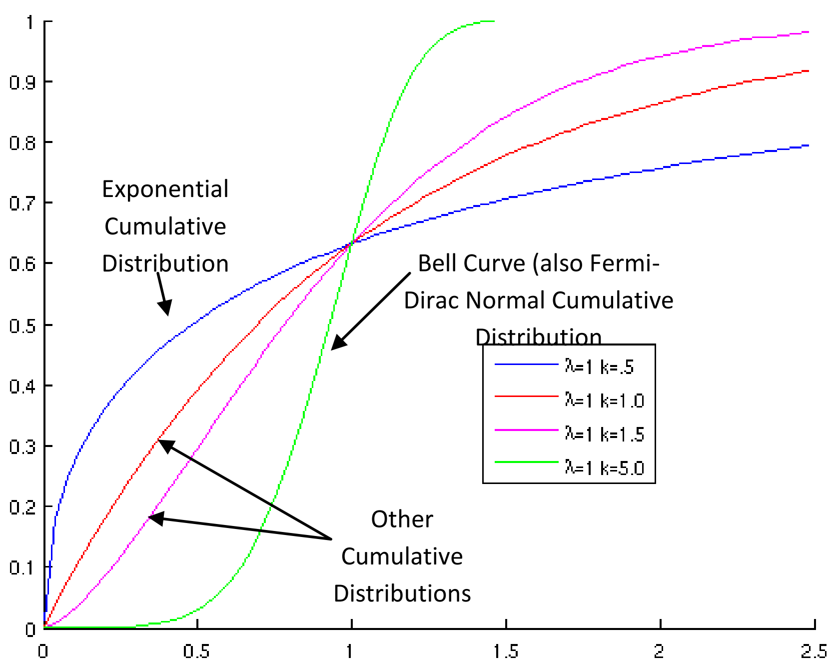

Figure 8: Examples of Cumulative Distribution Functions (Integral of the Normal Distributions) for Common Probability Distribution Functions

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 the early signs of premature aging/failure are identified, we use the cumulative distribution curve in Figure 9 developed from our proprietary database of equipment failures we have analyzed over 30-years on launch vehicles and satellites[7].

Distribution curves model normal occurring behavior and are tools used to before understand and quantify the failure rates at a complex system such as an aircraft 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.

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.

The Weibull hazard distributions are often used due to their flexibility—they mimic the behavior of other well-defined natural occurring distributions. Our proprietary cumulative distribution curve below in Figure 9 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.

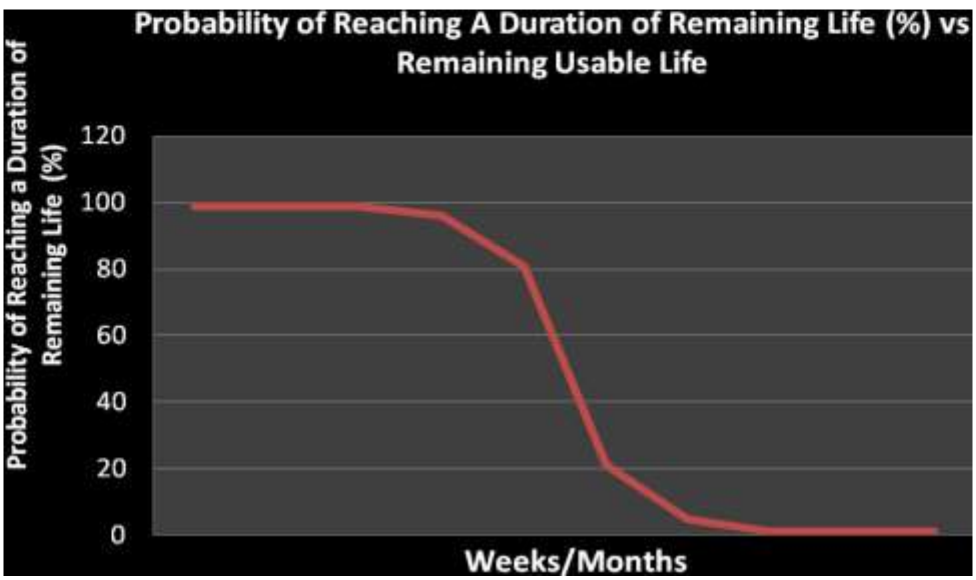

Figure 9: Proprietary Cumulative Distribution used to Determine Time-to-failure/Remaining-Usable-Life for Equipment with the Early Signs of Premature Aging/Failure/Accelerated Aging Identified

VIII Results of Prognostic Analysis Conducted on the NASA/U.C. Berkeley Extreme Ultra-Violet Explorer, Low-Earth-Orbiting Astrophysics Satellite

Between 1994 and 1995, the NASA/U.C. Berkeley EUVE low earth orbiting astrophysics satellite was utilized to demonstrate the capability of predicting on-orbit spacecraft equipment failures using data-driven prognostic algorithms[8]. The NASA EUVE satellite bus was built by Fairchild Aerospace (now Orbital) as one in a group of 10 common-core, multi-mission spacecraft bus for many GSFC science missions.

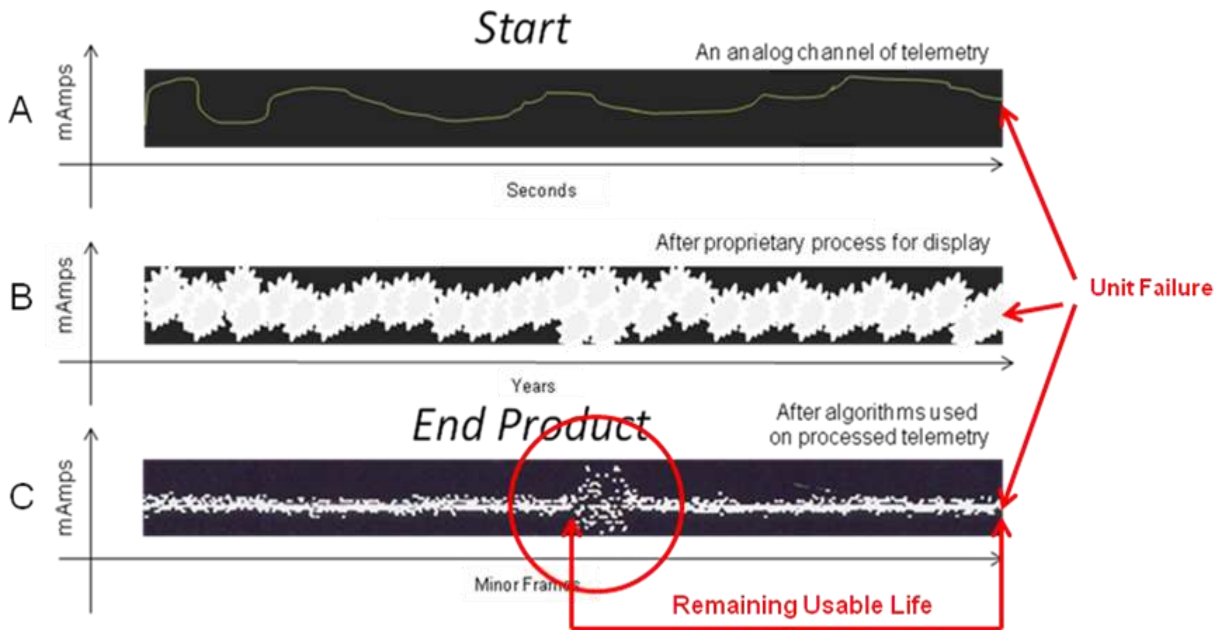

Figure 10. Results of a Prognostic Analysis Conducted on the NASA EUVE LEO Satellite Honeywell Rate Gyro Unit Using Stored and Real-Time Telemetry

VIII. Conclusion

Launch vehicle manufacturers only measure equipment performance during dynamic environmental testing, but there is no relationship between equipment performance, measured during test and short-term or long-term equipment reliability. Using a prognostic analysis to measure equipment reliability before, during and/or after equipment and vehicle dynamic environmental acceptance factory test allows the identification of any equipment that will fail prematurely after test. Expanding space vehicle factory production activities to include equipment and vehicle testing with a prognostic analysis will allow space vehicle suppliers to produce launch vehicles and satellites with 100% reliability and eliminate premature equipment failures on satellites and launch vehicle.

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