Stopping Catastrophic Infant Mortality Failures on Satellites and Launch Vehicles by Measuring Equipment Reliability using a Prognostic Analysis in Conjunction with Testing

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Introduction
To discover the cause and remedy of a long-term, ~25% catastrophic space vehicle infant mortality failure rate including a 70% likelihood of a mission critical equipment infant mortality failure rate within 45 days of arriving on-orbit causing surprise equipment failures on satellites that remove satellite payloads from service, we have gone out-side the aerospace industry. We have tailored prognostic technology, specifically for use on the dynamic operational environments that occur during use on satellites and launch vehicles. Prognostic technology was developed by industries that produce large quantities of like-units and recognized failure models existed in test data (including telemetry) and used them to develop model-based prognostic algorithms to identify the equipment that was going to fail in the near future. Model-based prognostic algorithms allow companies to produce equipment/products with near perfect reliability. Each industry develops their own unique prognostic algorithms based on failure models unique to their products. Only Failure Analysis has developed and proven data-driven prognostic algorithms, which are independent of the equipment and operational environment, for use with the unique dynamic equipment operational environments that exists on-board satellites and launch vehicles.

Why Do Infant Mortality Failures Occur on Satellites and Launch Vehicles and How Often?

In 2001 and 2005, Aerospace Corporation published the results of their studies explaining why satellite and launch vehicle equipment suffer from infant mortality failures after exhaustive and comprehensive factory acceptance testing. Their results blamed all contractors for a variety of (unsubstantiated) actions. We used a different strategy; we searched the equipment test data for the early signs of premature aging/failure (a.k.a. accelerated aging) found them and then developed prognostic algorithms that illustrate them and developed the training necessary for anyone to identify them from other normal transient behavior from fully functional equipment whose test data appears normal.

The state-of-the-art in producing satellites and launch vehicles include the use of equipment and vehicle testing to identify the equipment that fails during test. Throughout all testing, only equipment functional performance is measured. There is no relationship between equipment performance and reliability and so equipment that is only tested before use, should fail at a high rate because the correct information is not generated and evaluated during test. Because equipment reliability is dominated by infant mortality failures, failures that occur within one year of use, eliminating infant mortality failures means producing equipment with near perfect reliability.

Figure 1 illustrates that complex systems reliability is dominated by infant mortality failures (a failure that occurs within one year of use) due to the extreme high rate that occurs when only measuring equipment performance during testing done during ATP. Figure 1 illustrates, based on empirical data from real-life rates of infant mortality failures on complex systems, that up to one year burn-in is necessary to before all infant mortality failures would occur and the equipment be repaired or replaced before a system with near perfect reliability is produced.

Although the Air Force requires equipment telemetry be provided by satellite builders for mission control personnel and diagnostic analysis, which equipment to have telemetry is not identified and priced separately and so space vehicle suppliers get to decide which equipment provides telemetry. Prognostic analysis expands the use of telemetry from diagnostic analysis, including failure analysis, and performance measuring purposes to include measuring equipment reliability. Reliability is measured and for the units that will suffer from an infant mortality, and if the reliability (time-to-fail) of equipment is determined to be less than one year, prognostic analysis will
identify the remaining usable life for the equipment and the day-of-failure for planning and executing recovery/contingency plans purposes. This capability does not currently exist for Space Command satellites.

**FIGURE 1: INFANT MORTALITY FAILURES (OVAL) AND NORMAL LIFETIME FAILURES FOR A SATELLITE OVER 10 YEARS**

Table 1 summarizes the results of a study completed in 1988 by Aerospace Corporation to determine if factory testing is effective at increasing satellite equipment reliability. Table 1 indicates that 60 Air Force satellites were included in this study and tested using Air Force/Aerospace Corporation/contractor factory acceptance testing process by many different Air Force satellite builders.

<table>
<thead>
<tr>
<th>Air Force Satellite Program</th>
<th>No. of Satellites Tested</th>
<th>Acoustic</th>
<th>Thermal Cycling</th>
<th>Acoustic</th>
<th>Thermal Vacuum</th>
<th>Thermal Cycling</th>
<th>Acoustic</th>
<th>No. of Satellites in Space</th>
<th># Flight Failure in 45 Days</th>
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<tr>
<td>E2</td>
<td>4</td>
<td>5.5</td>
<td>--</td>
<td>2.8</td>
<td>--</td>
<td>0.5</td>
<td>4</td>
<td>0.5</td>
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<tr>
<td>D1*</td>
<td>3</td>
<td>0.3</td>
<td>--</td>
<td>1.7</td>
<td>--</td>
<td>--</td>
<td>3</td>
<td>2.0</td>
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</tr>
<tr>
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<td>2.0</td>
<td>--</td>
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<td>--</td>
<td>--</td>
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<tr>
<td>D3*</td>
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<td>0.9</td>
<td>1.4</td>
<td>1.6</td>
<td>--</td>
<td>--</td>
<td>7</td>
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<tr>
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<td>1.5</td>
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<td>0</td>
<td>--</td>
<td>1</td>
<td>0</td>
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<tr>
<td>B</td>
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<td>0.6</td>
<td>--</td>
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<td>11</td>
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<td>--</td>
<td>4</td>
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<tr>
<td>F2</td>
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<td>--</td>
<td>4.3**</td>
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<td>--</td>
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<td>--</td>
<td>--</td>
<td>2.0</td>
<td>6.0</td>
<td>1</td>
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<td>--</td>
<td>--</td>
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<td>2</td>
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</tr>
<tr>
<td>C</td>
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<td>--</td>
<td>--</td>
<td>3.0</td>
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<td>7</td>
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<td>15.7</td>
<td>1.1</td>
<td>28.3</td>
<td>15.0</td>
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<td></td>
<td></td>
<td></td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

*Spacecraft only, **Pre-environmental functional part of thermal vacuum

**TABLE 1: AIR FORCE SATELLITE EQUIPMENT FAILURES PER SATELLITE DURING AND AFTER FACTORY TESTING WAS COMPLETED (AEROSPACE CORPORATION)**
For the 60 Air Force satellites tested in Table 1, there were 240 (60 satellites x 4.0 failures per satellite in test) critical (but not all) satellite equipment failures during factory testing. The satellite equipment that failed during testing was repaired/replaced/salvaged or scrapped and the satellite eventually passed factory testing and launched. The 47 of the 60 Air Force satellites that were launched in this study, then suffered from 33 catastrophic equipment failures (70% failure rate), demonstrating that testing Air Force satellites may increase equipment reliability but does not identify all the on-board equipment that will fail once a satellite gets to space.

**FIGURE 2: HOW OFTEN SPACE COMMAND MISSIONS FAIL** (AEROSPACE CORPORATION)

For the 47 Air Force satellites in Table 1 that suffered an additional 33 catastrophic equipment failures (70% failure rate) once in space, the equipment that failed in space would have been identified and replaced at the satellite factory had a prognostic analysis been completed before shipping the satellites for launch. The failure rates are per satellite in Table 1 and many satellites of each type were included.

Figure 2 was generated by Aerospace Corporation and illustrates how often mission critical satellite equipment failures have occurred on many Air Force satellites and are likely to occur on all other Space Command satellites.

**Quantifying the Frequency of Catastrophic Infant Mortality Failures on Space Command Satellites**

Figure 3 includes the number of U.S. military satellites launched each year since 1959 through 2009 and the number of military satellites that failed from an infant mortality failure each year. Figure 3 illustrates that the more military satellites are launched, the more that fail from an infant mortality failure at around 25% failure rate. After attention is put on the problem by contractors, the rate of infant mortality failures decreases immediately indicating equipment failures are personnel related. The press has been our only source to identify Space Command’s classified satellites that have failed recently from an infant mortality failure.

The infant mortality rate for Space Command satellites is the same as for commercial satellites and launches (see Figure 3 and Figure 5). A failure in Figure 5 is based on an insurance claim made by the owner of the commercial satellite against its insurance policy for the launch and first year on-orbit.
FIGURE 3: 50 YEARS OF AIR FORCE SPACE MISSIONS AND 25% YEARLY INFANT MORTALITY FAILURE RATES ON AIR FORCE SATELLITES (FUTRON CORPORATION)

FIGURE 4: AIR FORCE/SPACE COMMAND LONG-TERM LAUNCH VEHICLE//ICBM RELIABILITY (AEROSPACE CORPORATION)

Figure 4 illustrates the long-term (44 years) reliability of most launch vehicles. The reliability curve for each launch vehicle is learning curves, effort vs. results. From game theory, these reliability curves illustrate that no experience from one U.S. launch vehicle program was used with any other launch vehicle. Each contractor and each launch vehicle program "re-invented the wheel" each time on each program. Most of the curves exhibit normal learning curve. The Delta is a steep learning curve whereas the Thor (Delta) had a normal learning curve.
Figure 5 illustrates the reliability of U.S. and international missiles and launch vehicles. The combination of Space Command satellites failing within one year of use and launch vehicles failing adds to an approximate 25% infant mortality failure rate for military missions (not launch vehicles or satellites alone).

Figure 6 illustrates the number of U.S. and international launch vehicle launches were attempted, and the large number of launches that succeeded and the significant number that failed (in the red rectangle) demonstrating the need to complete a forensic analysis prior to launch to identify the equipment that will fail during launch.
Recent Action Taken by AFSMC for Increasing Space Command’s First AEHF Satellite Reliability

After AFSMC procured satellites experienced several infant mortality failures on Lockheed Martin satellites, in early 2009, the AFSMC AEHF Program Office directed Lockheed Martin Space Systems Company (LMSSC), the builder of the AEHF satellites to complete another full factory dynamic environmental, acceptance test. The Air Force AEHF program office finally recognized that the Air Force/Aerospace Corporation/Lockheed Martin satellite dynamic environment factory acceptance test program is inadequate to identify all the equipment that will fail when used initially. Lockheed Martin had also produced an Air Force NRO satellite that failed after 8 seconds on-orbit in 2007. Space Command also delayed the launch of a SBIRS satellite until Lockheed Martin could verify that the SBIRS satellite would not suffer a catastrophic failure as the classified military satellite had that used a similar software based automatic safing system.

Increasing Satellite On-Orbit Payload Availability and Useful Life Using Prognostic Analysis

Currently, Space Command satellite on-orbit lifetime is guessed at by using statistical analysis whose results are in probabilities. This is because satellite equipment reliability is never measured before or after use. Although satellites and launch vehicles are completely, exhaustively and comprehensively tested by the builder, testing the equipment simply identifies the equipment that fails during test for repair or replacement. Equipment that will fail from an infant mortality failure passes factory testing and then fails. When prognostic technology is used, infant mortality failures are eliminated at the factory and on-orbit, satellite usable life is greatly extend. Current reliability analysis assumes infant mortality failure will occur and so do not accurately reflect the improvement in Space Command on-orbit satellite usable life that will occur when they are eliminated.

Figure 7 illustrates the significant decrease in failure rates for the Iridium-Next satellites when prognostic technology is used by stopping infant mortality failures and increasing usable life.

When equipment reliability is not measured, satellite mission life is determined using factors such as mean-mission duration, design life and mission life. This is because satellite and launch vehicle equipment may suffer from random infant mortality failures, random normal wear-out and random end-of-life failures. The “bathtub” curve in Section 7.0 is used in reliability analysis to illustrate the failure rates that these occur for complex, serviceable systems such as satellites that are serviceable because satellites often have available redundant equipment to use when a primary unit fails.

In Figure 7, Iridium and GLOBALSTAR satellites are mostly single string with an expected 7-year mission life based on the typical life of the commercial parts used. GPS satellites use full, 2 for 1 (2:1) and up to 4 for 1 (4:1) redundancy (for the atomic clocks) with GPS satellites that have various mean mission, design life and mission life.
**What is Prognostic Technology?**

Prognostic technology simply acknowledges that satellite and launch vehicle equipment failures are not instantaneous and random (having the Markov property) and so can be predicted and prevented. Different industries use prognostic technology, but the algorithms are equipment-specific and developed for use solely with the equipment from specific applications.

Prognostic technology was developed by industries that produce large quantities of like units. Company personnel recognized failure models existed to identify the equipment that was going to fail after testing was completed, producing equipment/products with near perfect reliability.

Prognostic technology incorporates active reasoning (anticipating problems), proactive diagnostics (design out potential failure unexpected modes) and model-based and/or data-driven algorithms to identify the fully operational equipment that will fail from an infant mortality failure for replacement before use.

Prognostic algorithms illustrate the early signs of premature aging/failure, often in normal appearing data (telemetry) from fully functional equipment, that if found, the equipment will fail with 100% reliability. A prognostic analysis uses the proprietary model-based and/or data-driven algorithms for first, illustrating the early signs of premature aging/failure and the training for personnel to discriminate the behavior from other normal behavior it mimics. Prognostic technology correlates transient, one-time, repeated or non-repeated behavior with the day it will fail.
Active reasoning is used to train personnel to anticipate problems that have normally been ignored due to cost, complexity of no known way to solve. Without active reasoning, new equipment is designed to ensure only that past problems will not reoccur. Active reasoning encourages other, unlikely conditions to be assumed so they can be designed out as well. Active reasoning is one tool of several that is used to attack Murphy’s Law, that when something can go wrong it will.

A prognostic analysis is a forensic analysis, which personnel search for the telltale signs of premature aging/failure in equipment test data including telemetry, as well as production documentation and procedures. A forensic analysis uses scientific method for identifying information from all areas of production and test that indicates the presence of behavior used to predict future behavior with 100% reliability. This information is often unknowingly identified by production personnel as “cannot duplicates” (CND), no failure found (NFF), no failure identified (NFI) and retest OK (RTOK). These are terms used to describe behavior seen in production that is not known by production and test personnel to be important information related to future equipment reliability and often just documented but then ignored.

From past failure models, the remaining-usable-life can be predicted accurately. When deterministic behavior is identified in operation information from products or equipment, the unit will fail and within one year of use and so, the presence of deterministic behavior is used to quantify the equipment reliability and remaining usable life.

Satellite and launch vehicle equipment (and most aerospace equipment) already use telemetry to measure equipment performance and status. Analog telemetry is data from an embedded circuit that illustrates what is occurring in a circuit or assembly. Telemetry is also the source of information used in prognostic algorithms to measure equipment reliability, expanding the use and importance of telemetry for producing equipment with near perfect reliability.

Prognostic algorithms provide a means of illustrating and then identifying the early signs of aging/failure for identification among other normal occurring equipment behavior that often mimics the early signs of aging/failure. When data acquisition sensors are embedded into the products/equipment, the early signs of aging/failure will be present in the data, but often occur such that they are usually misdiagnosed and ignored. The early signs of aging/failure are present in equipment/product telemetry but have gone unrecognized and misdiagnosed because:

- The early signs of (premature) aging/failure are present in normal appearing data from fully functional equipment and so the data usually doesn’t warrant further investigation/analysis
- The equipment with the early signs of failure passes factory acceptance testing because the equipment is functioning completely normally and all data appears normal and then fails within one year of use in the field.
- The early signs of aging/failure mimic other common occurring behavior in data associated with signal noise, noisy data, equipment cycling transients and sensor failure. Special training is required by personnel to discriminate the early signs of aging/failure from other common occurring behavior
- The early signs of aging/failure are not repeated, their pattern for one failure cannot be used to identify/compare/detect the early signs of failure from a previous equipment/product failure in identically designed units due to the minor variances within each part
- Reliability analysis requires equipment failures are random and instantaneous (Markov property) thus no behavior in test data prior to a failure is related to a failure. This means that equipment failures cannot be
predicted nor prevented. Random and instantaneous behavior is memory less, there is no state/condition/behavior prior to an event is associated with an event.

Deterministic behavior is behavior when present, means the outcome is exactly same. For equipment with the early signs of premature aging/failures, the end is complete equipment failure with 100% reliability. Deterministic behavior is known as other behavior in different industries such as failure precursors, transients, prognostic markers, prognostic identifiers. In the commercial and military aircraft industry, maintenance personnel call deterministic behavior “cannot duplicates” (CND), no failure found (NFF), no failure identified (NFI). When an aircraft pilot reports a transient behavior that cannot be duplicated by maintenance, the equipment and aircraft is sent back out to fail many months later. The transient behavior may not reoccur and the maintenance personnel will return the aircraft to service. We discuss in Section 11.0 the origin of transient behavior and surprise equipment failures and how prognostic analysis will stop surprise equipment failures from occurring.

What are the Early Signs of Premature Aging/Failure?

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. The origin of deterministic behavior is identified in Section 11.0. No two failure precursors or deterministic behavior are alike, thus the reason for previously never having been identified and not leveraged to measure and increase equipment reliability.

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.

What is a Prognostic Analysis?

A prognostic analysis leverages the “analysis” of time-series data to generate diagnostic information. Using that same “analysis” function, we analyze the diagnostic information to generate prognostic information. We then “analyze” the prognostic (predictive) information and generate prednostic (remaining usable-life) information. Equipment telemetry/test points provide internal access to the behavior of equipment/products. For industries that do not use telemetry, telemetry is developed to meet the needs of the industry and added into systems. For satellites and launch vehicles, telemetry has been the primary method for measuring the functional equipment performance. Prognostic analysis shares telemetry used to measure equipment performance to measure equipment reliability. Engineers trained in identifying the early signs of premature aging/failure in normal appearing telemetry from fully functional equipment, search telemetry behavior for the early signs of premature aging/failure present only in telemetry from equipment that will be failing within one year of the analysis.
Telemetry accesses the internal electrical and mechanical parts/circuit behavior and so telemetry behavior reflects circuit/parts telemetry is attached. Since telemetry is used in aerospace equipment to measure equipment functional performance, equipment used in satellites and launch vehicles can leverage the benefits of prognostic technology to measure equipment reliability before use with minimal design or production changes.

FIGURE 9: RESULTS FROM USING A PROGNOSTIC TECHNOLOGY MODEL-BASED MULTIVARIANT STATE ESTIMATION ALGORITHM TO ILLUSTRATE SUN MICROSYSMS SERVER FAN WEAR-OUT BEHAVIOR IN ENTERPRISE SERVERS TELEMETRY
A prognostic analysis is also a forensic analysis, where prognosticians (engineers trained to identify deterministic behavior) search for the telltale signs of premature aging/failure in all information related to the design, manufacture test and use of equipment and products. The prognostic markers/prognostic identifiers most often occur in time-series information such as telemetry/diagnostic data collected by test equipment and/or telemetry during either production or test. Telemetry is the most common source of test data from satellites and launch vehicles equipment. It is stored and archived for many years. However, the early signs of premature aging/failure can also be found in production paperwork documentation as notes made by the production and test personnel who kit, assemble and test the boards/assemblies and in written minutes of meetings and informal discussions.

A prognostic analysis can be done anytime with information (telemetry) from a complex system or equipment/product. The information generated depends on when the analysis is conducted relative to a failure. When a prognostic analysis is done on equipment prior to a failure, it is an invasive measurement of the reliability of the equipment because telemetry is embedded into electrical circuits and mechanisms. A prognostic analysis can determine if the equipment/product will function normally for at least one year. Just as diagnostic activities (e.g. troubleshooting, data collection, data reduction, data display, data analysis, failure analysis etc.) allows the identification of what has caused a problem/failures, a prognostic analysis identifies the problem/failure that is going to occur in the near future (up to 1 year in advance).

$200M \text{ L-21 NRO/Space Command/ Satellite Failed catastrophically, 8 Seconds after Arriving On-Orbit in 2006}$

**FIGURE 10: EXAMPLE OF PROGNOSTIC ALGORITHM FOR IDENTIFYING DETERMINISTIC BEHAVIOR IN NOISE, SENSOR FAILURE, CORRUPTED DATA AND EQUIPMENT CYCLING**
A prognostic analysis can only be accomplished by personnel trained to illustrate and identify the early signs of premature aging/failure (a.k.a. accelerated aging) called prognosticians, often done in normal appearing information from fully functional equipment that mimics other normal transient behavior called failure precursors, deterministic behavior, prognostic markers, prognostic identifiers. This is because the training and education is not normally acquired in the satellite and launch vehicle industry.

Prognostic markers/deterministic behavior mimic other behavior such as such as transients from equipment cycling, sensor failure, noise and corrupted data. Our training allows the discrimination of deterministic behavior from other normal occurring behavior. Today a failure analysis is conducted to identify what failed. Further investigation can identify why the unit failed such as a flawed part. Further investigation can identify why the flawed part was flawed and how to stop flawed parts from being used. These are all actions after a failure has occurred.

In a prognostic analysis, baseline behavior is determined first, in the event that insufficient information is available to develop and baseline behavior, algorithms are provided to generate virtual baseline behavior from on an understanding and definition of what the baseline behavior should be. After the amount of information available for a prognostic analysis is known, the data is compiled using our data summation algorithm.

In a prognostic analysis, the equipment telemetry is evaluated looking for noise, corrupted data and other behavior that may mimic deterministic behavior that can be caused by transients from normal equipment cycling, noise and sensor failure. If signal or data noise is present, our algorithms will replace/remove it with contiguous data, corrupted data will be replaced and/or removed. In the event that there is insufficient data to develop a baseline,
algorithms are available to use whatever data is available and fill in where data is missing and predict future normal behavior.

If there is too much telemetry/data, data reduction algorithms will use special sampling algorithms that are synchronized with existing harmonic behavior so that the behavior of the large data set will exist in the sampled data set. An algorithm for discriminating deterministic behavior from normal baseline behavior identifies the deterministic behavior. In the event that deterministic behavior is suspect, the operational history of all the actions that has an influence of the baseline behavior will be conducted looking for specific actions taken at exactly the same time that the deterministic behavior is identified. In the event that no actions can be associated with the suspect deterministic behavior, an algorithm to determine whether the suspect behavior is from noise or sensor failure is used. These algorithms will determine the cause of the suspect behavior from either a failed sensor or noise. After the deterministic behavior is identified, another algorithm will identify the remaining usable life and predict the day of failure.

FIGURE 12: $5K COMMERCIALY AVAILABLE WINDOWS/PC PROGNOSTIC ANALYSIS SYSTEM

Guessing at Satellite Equipment Reliability with Reliability Analysis Engineering Probabilistic Results

Reliability analysis engineering is an engineering field that is the study of reliability: the ability of a system or component to perform its required functions under stated conditions for a specified time. Its results are reported as a probability.

Guessing at equipment and vehicle reliability before launch began in 1959, with the U.S. ICBM’s and modified ICBMs that were used as launch vehicles continued to be highly unreliable often demonstrating a 50% failure rate at the time. Catastrophic failure rates were as high as 25% even after dynamic environmental testing.

Reliability analysis engineering provides a probability of an event will occur and is not a measure of reliability. As applied to the

Several Common Distributions Used in Reliability Analysis Engineering
aerospace industry, reliability analysis requires that equipment failures be considered instantaneous and random and this belief leaked into the minds and decisions of both aerospace technical and management personnel. When failures are instantaneous and random, no behavior that occurred prior to the vent is related to the event. This is also known as memory less. When events are instantaneous and random, they also cannot be predicted nor prevented and so this was the argument that could be used to stop contractors from researching the root causes of equipment failures.

Reliability analysis results provide a probability of meeting a design life or mission life. In the calculation to determine the likelihood, past equipment reliability performance is included along with information from equipment parts suppliers to calculate the probability of a satellite to operate long enough to meet the mission life. At no time during the production and test of equipment going to space is the reliability ever measured. Until prognostic technology and the prognostic analysis, no one has ever looked for the early signs of premature aging/failure that are always present prior to equipment failure.

Predicting the Day of Failure/Remaining-Usable-Life for Satellite and Launch Vehicle Equipment with the Early Signs of Premature Aging/Failure Present in Telemetry Identified

In reliability analysis, large quantities of parts and equipment are used. When individual performance of parts and equipment is not measured, the stochastic process in reliability analysis provides probabilities of events occurring based on commonly acceptable distribution curves. These distribution curves model many behaviors.

FIGURE 13: WEIBULL DISTRIBUTION FOR COMPLEX SYSTEM'S INFANT MORTALITY FAILURES (DOTS) AND NORMAL LIFETIME FAILURES (TRIANGLES) FOR 10 YEARS

FIGURE 14: WEIBULL HAZARD DISTRIBUTION FUNCTIONS THAT MODEL THE BATH TUB CURVE (BOL, N AND EOL)
Several Weibull distributions are used to model the shape of the standard bathtub reliability curve in Figure 14. The infant mortality failure rates are modeled accurately for a 10-year period in Figure 13. The failures in time (FITS) reflect real world behavior due to the minor differences of parts, their failure rate behavior is never repeated.

In probability theory and statistics, the Weibull distribution is a continuous probability distribution named after Waloddi Weibull, who described it in detail in 1951, although it was first identified by Fréchet (1927) and first applied by Rosin & Rammler (1933) to describe the size distribution of particles. The probability density function of a Weibull random variable \( x \) is:

\[
f(x; \lambda, k) = \begin{cases} 
\frac{k}{\lambda} \left( \frac{x}{\lambda} \right)^{k-1} e^{-(x/\lambda)^k} & x \geq 0 \\
0 & x < 0 
\end{cases}
\]

Where \( k > 0 \) is the shape parameter and \( \lambda > 0 \) is the scale parameter of the distribution. Its complementary cumulative distribution function is a stretched exponential function. The Weibull distribution is related to a number of other probability distributions; in particular, it interpolates between the exponential distribution (\( k = 1 \)) and the Rayleigh distribution (\( k = 2 \)).

FIGURE 15: EXAMPLES OF DISTRIBUTION FUNCTION PROBABILITY DISTRIBUTION FUNCTIONS WITH VARIOUS SHAPE CONSTANTS

To predict an accurate remaining-useful-life after the early signs of failure are detected, we use the cumulative distribution curve in Figure 17 developed from our proprietary database of high-reliability aerospace/vehicle equipment failures we have analyzed over 30-years. Distribution curves model normal occurring behavior and are tools used to 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.

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 13 is a Weibull distribution illustrating the infant mortality failures (dots) for a complex system such as an aircraft continue to occur as parts and equipment are replaced due to failure and normal lifetime failures (triangles) are occurring simultaneously. Weibull distributions are accepted in many industries as
modeling the failure rate behavior of complex system/aircraft failure rates at all stages life/use. Figure 13 also illustrate an 8-month burn-in duration would decrease a large number of infant mortality failures (dots).

![Image of cumulative distribution functions](image)

**FIGURE 16: EXAMPLES OF CUMULATIVE DISTRIBUTION FUNCTIONS (INTEGRAL OF THE NORMAL DISTRIBUTIONS) FOR PROBABILITY DISTRIBUTION FUNCTIONS IN FIGURE 27**

The Bell cumulative distribution curve in Figure 16 is also known as the Fermi-Dirac distribution in nuclear physics. The Fermi-Dirac describes the probability that one can expect particles to occupy the available energy levels in a given system. Each curve in Figure 15 is the normal distribution curve such as the exponential distribution in Figure 29.

The integral of a normal distribution function is it cumulative distribution. The integral of all the probability functions in Figure 15 are the cumulative distribution functions for the normal distribution functions in Figure 16. Figure 16 cumulative distributions illustrate the likelihood that a piece-part failure in a population of piece-parts duration will occur. Knowing that piece-parts 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 to find if manufacturing flaws or design flaws are in the population of piece-parts.

The Weibull hazard distributions in Figure 14A, 14B and 14C are often used due to their flexibility—they mimic the behavior of other well-defined natural occurring distributions like those in Figure 15. Figure 14A is the Weibull hazard distribution model for infant mortality failure rates for complex systems. Figure 14B is the Weibull hazard distribution model for the failures in time during normal usable lifetime of a complex system such as the “normal” or Bell distribution in Figure 15 and the exponential distributions. Figure 14C is the Weibull hazard distribution model for the end-of-life failures for complex systems.

In the relationship below used to define the normal distributions, if equipment/piece-part failure rate decreases over time, then k is < 1. If the failure rate is constant over time, then k is = 1. If the failure rate increases over time, then k is >1. An understanding of the failure rate may provide insight as to what is causing the failures:

- A decreasing failure rate (gamma = 0.5 in Figure 14A) would suggest "infant mortality" failures. That is, defective items fail early and the failure rate decreases over time as they fall out of the population.
- A constant failure rate (gamma = 1 in Figure 14B) suggests that items are failing from random events.
- An increasing failure rate (gamma = 5 in Figure 14C) suggests "wear out" - this means that parts are more likely to fail as time goes on.

Where $k > 0$ is the shape parameter and $\lambda > 0$ is the scale parameter of the distribution. The Weibull distribution is related to a number of other probability distributions; in particular, it interpolates between the exponential distribution ($k = 1$) and the Rayleigh distribution ($k = 2$). The cumulative distribution function for the Weibull distribution in Figure 14 for $x \geq 0$, and $F(x; k; \lambda) = 0$ for $x < 0$ is:

$$F(x; k, \lambda) = 1 - e^{-(x/\lambda)^k}$$

The failure rate $h$ (or hazard rate) is given by:

$$h(x; k, \lambda) = \frac{k}{\lambda} \left(\frac{x}{\lambda}\right)^{k-1}.$$  

Our proprietary cumulative distribution (a.k.a Fermi-Dirac distribution) curve in Figure 17 is generated from 30 years of measuring the remaining usable life of high-reliability aerospace/vehicle equipment failures we put into our database of failures. The results are not random because they are based on actual equipment failures and so are a probability ($P_s$) of occurring based on many past failures and real durations of remaining usable life.

![Graph showing probability vs remaining life](image_url)

**FIGURE 17: OUR PROPRIETARY CUMULATIVE DISTRIBUTION CURVE USED TO DETERMINE REMAINING USABLE LIFE FOR EQUIPMENT WITH THE EARLY SIGNS OF PREMATURE AGING/FAILURE A.K.A ACCELERATED AGING**

The early signs of aging/failure/cannot duplicates/failure precursors/prognostic markers/prognostic indicators are caused from the degradation in the functional performance of parts/piece-parts used in electrical and mechanical equipment and products and their effect of their degraded performance on the other parts in the circuits. If a part’s, functional performance degrades much faster than other parts in the circuit/assembly, it will eventually affect the circuit/assembly behavior it is in by causing transient behavior in equipment telemetry. When a part's performance has degraded so that the circuit/assembly it is in can no longer function as designed, transients will occur and these transients will expose the other parts to unpredictable operating condition stresses not designed to operate. The effect of the transient(s) on any other part is unpredictable. The transients may increase the degradation in part performance or may not. If the relationship between failure precursors and piece-part degradation provided in 20 were known in 1986 and 2004, neither the Space Shuttle Challenger nor the Columbia tragedies killing 14 astronauts would have occurred.
Since all electrical/mechanical parts in a circuit/assembly degrade at different rates, there will be one part that will degrade the quickest. This part initiates the early signs of aging/failure but is usually not the part that fails. These parts with the accelerated aging behavior are the source of cannot-duplicates/early signs of aging/failure etc. One part will degrade in functional performance until its performance causes transients to occur. The transients' effect on other parts is unpredictable but the part that eventually fails as a consequence of the exposure to the transients will generally not be the part that started the transients. If the part that fails is replaced, other parts that were not replaced that have been exposed to the transients previously may fail and need to be replaced. Eventually parts can continue to fail so often that the circuit/unit will be scrapped because its reliability will be so low that personnel are uncomfortable using it.

**Etiology of the Early Signs of Premature Aging/Failure**

Today’s diagnostic tools, techniques, and practices use diagnostic analysis including failure analysis to find the part that fails hoping to understand why an equipment failure occurred. When equipment fails, the belief is that a part or parts failed causing the failure. In the subsequent failure analysis, a part is found that has failed, thus confirming the belief that a part failed and caused the equipment to fail. A prognostic analysis shows that the part that fails is the result of the equipment failing and is not the cause of the equipment failure but the result of the equipment failure.

The parts fail from a change in operating characteristics of the circuit/assembly they are in, causing them to fail. When a failed part is replaced, often another part that has been stressed by the change in operating characteristics of the circuit will fail too. This sequence is repeated in production until material control in convinced that the unit is unreliable. The unit has been unreliable once the first part fails.

**FIGURE 18: RELATIONSHIP BETWEEN PARTS AGING/PERFORMANCE DEGRADATION AND THE PRESENCE OF DETERMINISTIC BEHAVIOR IN EQUIPMENT TELEMETRY**

Often in the exhaustive and comprehensive satellite and launch vehicle production and acceptance environmental testing, vehicle equipment will fail and the part that failed is identified and replaced. This equipment is then reused and it fails again. Another part is found to have failed and is replaced and the equipment is reused. Diagnostics cannot explain how a single unit can have serial failures. This series of events will continue to occur until about five piece-part failures when material control personnel will decide the reliability of the equipment is too low and the unit is scrapped.
According to diagnostic analysis and reliability analysis, part failure is random. It is statistically impossible for a single unit to have many parts fail. This is because equipment failures are not caused by parts failing, parts failing is caused by the equipment failing. Part failure is the symptom that the equipment is failing.

The early signs of aging/failure/cannot duplicates/failure precursors/prognostic markers/prognostic indicators are caused from the degradation in the functional performance of parts/piece-parts used in equipment and products and the effect of the degradation of performance on the other parts and the circuit. If a part’s, functional performance degrades much faster than other parts in the circuit/assembly, it will eventually affect the circuit/assembly behavior it is in by causing transient behavior in equipment telemetry. When a part’s performance has degraded so that the circuit/assembly is in can no longer function as designed, transients will occur and these transients will expose the other parts to unpredictable operating condition stresses not designed to operate. The effect of the transient(s) on any other part is unpredictable. The transients may increase the degradation in part performance or may not.

Since all electrical/mechanical parts in a circuit/assembly degrade in performance at different rate, there will be at least one part that will degrade faster than all other parts. The behavior of this one part we identify with the early signs of aging/failure may initiate a series of transient behavior when another part that is the most susceptible to failure, fails.

The part(s) with the accelerated aging behavior are the source of cannot-duplicates/early signs of aging/failure etc. One part will degrade in functional performance until its performance causes transients to occur. The transients effect on other parts are unpredictable but the part that eventually fails as a consequence of the exposure to the transients will generally not be the part that started the transients. If the part that fails is replaced, other parts that were not replaced that have been exposed to the transients previously may fail and need to be replaced. Eventually parts can continue to fail so often that the circuit/unit will be scrapped because its reliability will be so low that personnel are uncomfortable using it.

**Air Force/Aerospace Corporation Dynamic Environmental Space Vehicle Factory Acceptance Testing Development and Use**

In the late 1950’s U.S., missile and launch vehicle reliability continued to suffer, often achieving only 50% reliability. To improve equipment reliability, the U.S. government and industry agreed to expose the on-board equipment the launch environment believed to occur before delivery for use. This was done to identify and repair/replace/salvage/scrap any equipment that did not survive these conditions.

A series of vibration, thermal, vacuum, temperature, acoustic and EMI and EMC environments that space equipment is exposed to during launch and in space were agreed on and today these series of environments are included in the acceptance tests specified in the contract between the purchaser and the builder of Space Command space assets. It was hoped that the resulting vehicle that was delivered for use was far more reliable.

When ICBM/launch vehicle reliability was below 75% in the late 1950’s, to increase the likelihood that all equipment will function as expected after getting to space and while in space, dynamic environmental testing was added for satellites and launch vehicles. Dynamic environmental testing is completed at the equipment level and at the vehicle level.
The structural design of space systems is dictated by the rigors of the liftoff and ascent environments during launch as well as the extreme thermal conditions and operational requirements of spacecraft equipment and payloads on orbit. At liftoff and for the next several seconds, the intense sound generated by the propulsion system exerts significant acoustic pressure on the entire vehicle. This pressure induces vibration, externally and internally, in the space vehicle structures. In addition, the vehicle experiences intense vibrations generated by engine ignitions, steady-state operation, and engine shutdowns as well as sudden transients or "shocks" generated by solid rocket motor jettison, separation of stages and fairings, and on-orbit deployments of solar arrays and payloads.

Space vehicles will also experience wide fluctuations in temperature from the time they leave the launch pad to the time they settle into orbit. Both individually and in combination, the mechanical environments of pressure, vibration, shock and thermal gradients impose design requirements on all components. Ensuring the survivability of the equipment and hardware poses challenges that are met by extensive preflight tests encompassing acoustic, shock, vibration and thermal environments.

Dynamic environmental testing is performed at varying magnitudes and durations to verify the design of space systems will function when it arrives in space and function during its entire planned mission life and to screen flight hardware and verify the quality of workmanship meets industry standards. The first step in this process is the definition of the maximum expected environments during launch and on-orbit operation. Data from previous flights and ground tests are analyzed to generate predictions for a specific mission. These environments are then flowed down from the space vehicle level to the various subsystems and components for use as design requirements and, later, as test requirements.

**Four Inadequacies of Satellite and Launch Vehicle Factory Acceptance Testing Corrected by Prognostic Technology**

Prognostic analysis measures all equipment reliability before shipping the equipment/vehicle for use. The equipment with accelerated aging are identified and replaced with equipment that do not have accelerated aging when reliability is measured. The inadequacies of dynamic environmental factory testing can be ignored when measuring individual equipment reliability rather than rely on flight history of old equipment and the probabilistic results from reliability analysis to quantify reliability.

Inadequacy # 1. Thermal, vacuum, shock, vibration, EMI/EMC and acoustic testing environments are completed serially, although the satellite and launch vehicle experiences environments simultaneously. From RF engineering, we know the compounding of low-level energy from many sources can cause significant problems. Inter-modulation energy suppression requirements for space systems do not stop problems. The inter-action of difference sources of energy from each environment are suspected by some to be the cause of infant mortality failures.

Inadequacy # 2: Normal in-orbit satellite subsystem equipment telemetry behavior once the satellite gets to orbit is not available nor provided by satellite builder. This is because satellite builders do not simulate all satellite equipment configurations and sun-angle conditions, satellites are handed over to mission control not knowing a-prior what normal satellite equipment telemetry behavior should look like. Normal expected satellite telemetry behavior is not available for mission control team to have for comparison with actual telemetry behavior forcing a long delay before determining normal behavior resulting in catastrophic infant mortality failures on Air Force satellites. Satellites have failed while mission control personnel were observing the telemetry as catastrophic failure went unidentified.
Inadequacy #3: Satellite equipment passes factory testing and then fails from an infant mortality failure causing huge financial losses and mission data outages demonstrating the causes and fix of infant mortality failures are unknown. After exhaustive and comprehensive factory test, satellite subsystem equipment still fails catastrophically within 1 year of use. Normal (8 month) burn-in times for parts and equipment are often ignored. Redundancy increases the likelihood of satellites meeting mission life satellite mass/launch vehicle requirements for oversized lift capabilities.

Inadequacy #4. After an infant mortality failure occurs, test personnel cannot identify when deterministic behavior begins. When deterministic behavior is present in equipment that fails from an infant mortality failure, prognostic technology allows searching back in time to identify the deterministic behavior was first present, which personnel and which organization failed to identify it. This information defines liability.

**Prognostic Technology Reduces 7 Sources of Risk & Uncertainty that Occur at Satellite and Launch Vehicle Factories**

Because equipment’s reliability is compromised by management decisions that are considered unacceptable, prognostic analysis measures equipment reliability and the equipment that will suffer a failure prematurely will be identified and replaced before use, nullifying any high-risk decisions that management may make without informing the satellite owner. Documented actions by satellite and launch vehicle management include:

1. Satellite suppliers have no liability after space vehicle delivery – as long as they use their “best effort.” Today’s best effort is changing with prognostic technology. Builders will be able to affect the reliability of their equipment for up to one year in advance.

2. With no/few contract monitors at the facilities, companies may be committing waste, fraud & abuse unchecked (see Aerospace Corporation report in Crosslink). Program managers will often make many technical decisions rather than use a subsystem engineer to keep cost down. This is done most often at companies that produce very similar satellites for decades such as commercial, geostationary communications satellites. These satellites are often produced in a similar fashion for decades changing only the number of transponders and using different transponders from different suppliers and thus personnel design and test pretty much the same satellite, program after program after program. Prognostic analysis completed after factory test will measure equipment reliability so that the reliability of the on-board equipment will be known before payment.

3. Satellite and launch vehicle supplier’s program managers are under tremendous pressure to earn all short-term contract profit and meet end-of-year profit levels, which may mean accepting/making high risk that effect initial vehicle reliability. Both Boeing and Lockheed Martin have announced publically that if their companies do not meet end of year profit level, they will be sold. This statement provides all the reason for program managers to take short cuts and make poor decisions that affect the reliability of on-board equipment. When the satellite delivery schedule is at risk, program managers may decide to skip some equipment qualification/acceptance testing.

4. Some satellite and launch vehicle company program managers are making technical decisions without consulting subsystem manufacturing engineers keeping engineering cost down that may affect satellite equipment reliability.

5. The common reduction in space vehicle engineering and test personnel necessary as business decreases that update and maintain the space vehicle design and test software and must remember all past actions that must be taken for future launches to be successful leave the company on a regular basis. Often when business increases, companies try to rehire experienced personnel, but are often forced with hiring highly educated personnel but who must be trained in working in the uniqueness of the space vehicle industry. Companies attempt to keep their most valuable employees but as business decreases, the number of long-term personnel is decreased. Company management often believes that it is the company management that maintains the company memory. It is the employees that do the work and must remember all the actions that must be taken on new vehicles based on experience that is the company memory.

6. Space vehicle suppliers most often use temporary employees as test technicians from local employment agencies to evaluate equipment telemetry complete space vehicle factory acceptance testing and meet customer defined test schedule. Temporary personnel, who may be highly experienced and well educated usually, have not participated in testing space vehicle equipment prior and who must meet the space vehicle test schedule for which they had no input. These temporary employees are not invested in the outcome of their work and are highly motivated to
overlook equipment transient behavior in test data so they do not have to slow down progress to meet their imposed test schedule. These temporary test technicians/employees will be working at another company when any problems occur as a result of their actions.

7. Today’s space industry-management personnel are directed by company/corporate executives to treat the design and test of space vehicles as if they were any other commodity/manufactured product such as a refrigerator or microwave oven. This is done so that less educated and experienced employees can be used to make decisions on customer space vehicle equipment, decreasing wages and overhead cost.

Conclusion

Equipment, and thus space vehicle reliability is dominated by infant mortality failures because the equipment that will suffer from an infant mortality failure often passes acceptance testing that is completed to eliminate unreliable equipment. During dynamic environmental factory acceptance testing which may force some poor quality equipment to fail prematurely, only equipment functional performance is measured and there is no relationship between equipment performance and short-term or long-term equipment reliability and so testing alone is inadequate for producing equipment with near perfect reliability. A prognostic analysis which identifies the early signs of premature aging/failure (a.k.a. accelerated aging) in equipment analog telemetry that will suffer from an infant mortality failure with 100% certainty (as well as predicting the unit’s remaining usable life) for replacement will allow the production of satellites and launch vehicles with near perfect reliability. A prognostic analysis shares the test data used only to measure equipment performance during test to measure equipment reliability invasively, allowing equipment with the early signs of premature aging/failure to be identified and replaced before launch moving space vehicle production to the 100% reliability domain.