STOPPING LAUNCH VEHICLE FAILURES USING TELEMETRY TO MEASURE EQUIPMENT USABLE LIFE

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Failure Analysis

ABSTRACT

Launch vehicle equipment reliability is driven by infant mortality failures, which can be eliminated using a prognostic analysis prior, during and/or after the exhaustive and comprehensive dynamic environmental factory acceptance testing. Measuring and confirming equipment performance is completed to increase equipment reliability by identifying equipment that fails during test for repair/replacement. To move to the 100% reliability domain, equipment dynamic environmental factory testing should be followed by a prognostic analysis to measure equipment usable life and identify the equipment that will fail prematurely. During equipment testing, only equipment performance is measured and equipment performance is unrelated to equipment reliability making testing alone inadequate to produce equipment with 100% reliability. A prognostic analysis converts performance measurements into an invasive usable life measurement by sharing test data used to measure equipment performance. Performance data is converted to usable life data provides a time-to-failure (TTF) in minutes/hours/days/months for equipment that will fail within the first year of use, allowing the production of equipment with 100% reliability.

KEY WORDS

Predicting Failures, Telemetry Analysis, Prognostic Analysis, Failure Analysis, Prognostic Technology, Calculating Remaining Usable Life, Mission Life, Measuring Reliability.

INTRODUCTION

Some equipment production process such as those in the aerospace industry uses dynamic environmental acceptance testing, hoping to increase equipment reliability. The measurements are performance related, e.g. how well something is working. These performance measurements are used during test, to identify the equipment that fails performance measurements but performance is unrelated to reliability. The equipment that fails (during test) is then repaired/replaced/salvaged or scrapped[2]. It is hoped by all that testing equipment and measuring performance will (somehow) improve equipment reliability, but based on the high rate of infant mortality failures that occur in most industries that produce electrical and electro-mechanical equipment, it does not. A prognostic analysis uses equipment telemetry to measure equipment reliability invasively using data-driven, prognostic algorithms that illustrate accelerated aging present in equipment operational data (telemetry) that will fail within one year of use with 100% certainty [3].

According the Aerospace Corporation report published in 1989 titled "The Effectiveness of Satellite Environmental Acceptance Tests" by Otto Hamberg and William Tosney, space vehicle systems equipment that passes full factory acceptance testing will suffer from at least 4 major equipment failures during vehicle equipment integration and test (I&T) with equipment that already passed equipment-level dynamic environmental acceptance testing. Then, after passing vehicle-level dynamic environmental acceptance testing, there is a 70% likelihood of another major equipment failure within 45 days of use.

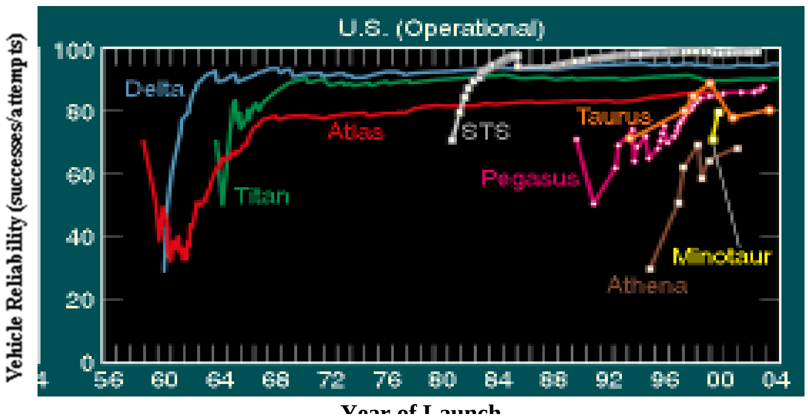

FIGURE 1 FORTY-EIGHT YEARS OF RELIABILITY OF U.S. LAUNCH VEHICLES USING TESTING TO INCREASE RELIABILITY (AEROSPACE CORPORATION)

Launch vehicle equipment failures occur frequently and are the causes of all failures in both the launch vehicle and its payload. These surprise failures occur during launch because the dynamic environmental testing, only equipment functional performance is measured, which should be measured at some point during production. Measuring equipment performance is used to increase equipment reliability yet; there is no relationship between equipment performance and either short-term or long-term launch vehicle equipment reliability

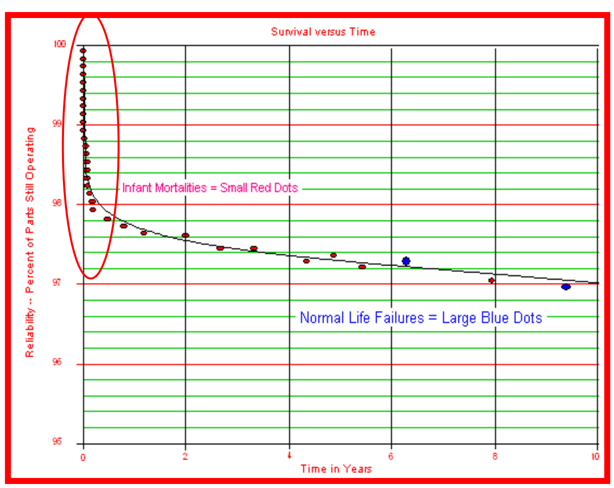

FIGURE 2. INITIAL INFANT MORTALITY FAILURES (OVAL) FOR A COMPLEX SYSTEM OVER A 10 YEAR LIFE ELIMINATED USING PROGNOSTIC ANALYSIS

Measuring launch vehicle equipment performance during test, and then hoping testing increases launch vehicle equipment reliability has been done since the ICBM/launch vehicle inception in the 1950's and the extremely actual reliability of launch vehicles as a result of measuring equipment performance during test and the high rate of infant mortality failures is well documented. The proven unreliability of launch vehicles illustrates that testing equipment alone is inadequate for producing equipment with 100% reliability.

A prognostic analysis shares the same test data (telemetry) generated during I&T used to measure equipment performance to also measure equipment first year usable life. In the prognostic analysis, equipment performance data is converted into a measurement of usable life. 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 prematurely with 100% certainty for replacement. Launch vehicle equipment reliability is dominated by infant mortality failures. A prognostic analysis completed after dynamic environmental acceptance and replacing the equipment with accelerated aging increases launch vehicle equipment reliability to near-perfect.

The dynamic environmental acceptance test program (ATP) was added to the aerospace/launch vehicle/ICBM production process in early 1960 because launch vehicle reliability was low. With no other actions available to be taken to increase launch vehicle equipment reliability, government and military organizations agreed to add the requirement to measure equipment performance during ATP hoping that measuring equipment performance during the test program would increase equipment reliability. Reliability analysis engineering used 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 is repaired or replaced. Testing successfully identifies 100% of the equipment that fails during test. If this equipment was not repaired or replaced, the same 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 several times and be repaired several times during manufacturing process. This is in violation of the Markov property. To increase launch vehicle reliability, launch vehicle equipment is exhaustively and comprehensively tested prior to use and yet most launch vehicles will suffer a failure at about 10% of the time.

In 2005, the Aerospace Corporation published a report of equipment that fails prematurely 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 the launch vehicle test data for the early signs of premature aging/failure (a.k.a. accelerated aging). Its presence in satellite and launch vehicle equipment was documented in almost 40 issues of the Boeing GPS Monthly and Quarterly Orbital Test Report, CDRL Item A004 published between 1978 through 1988 to the Air Force Space and Missile Center (AFSMC).

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

A Weibull distribution models the infant mortality, normal wear out and end of life failures for complex systems and large population of electrical and mechanical parts assuming that equipment and parts failures are instantaneous and random (Markov property). For aerospace equipment, infant mortality failures occur after dynamic environmental acceptance testing is completed demonstrating that equipment testing alone is inadequate for producing equipment with 100% reliability. Dynamic environmental testing is used to reduce the number of infant mortality failures from occurring because no one has been able to develop any other means of improving equipment reliability. 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 initially.

To identify the equipment with piece-parts that are suffering from accelerated aging, we then developed and used data-driven prognostic algorithms. Data-driven 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.

PROGNOSTIC ANALYSIS

The analysis used to illustrate accelerated aging includes the tools and education that is not normally acquired in the industry and the training to identify the early signs of premature aging/failure and discriminate them from other normal occurring transient behavior 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 if found will identify the equipment that will fail within one year of use. A prognostic analysis is also 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 and any other forms of documenting the presence of transient behavior such as production paper work.

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 3 identifies the definition of the 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. When behavior is random and instantaneous, no information prior is related to any behavior and the result is neither predictable nor preventable. From prognostic analysis, the time between the beginning of life and the first transient observed in the data caused from accelerated aging is random, but the time between the first transient and the equipment's end-of-life is deterministic. Deterministic behavior is 100% predictable and thus equipment failures from accelerated aging illustrated using prognostic analysis and prognostic algorithms are predictable and preventable.

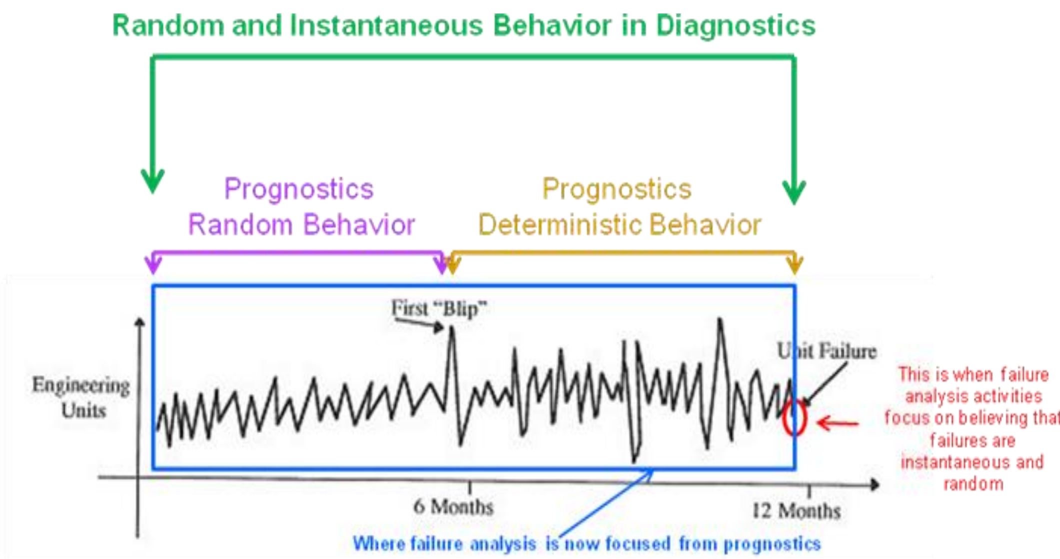

FIGURE 3 THE DEFINITION OF THE DURATION BEGINNING-OF-LIFE AND END-OF-LIFE BASED ON DIAGNOSTIC ANALYSIS AND PROGNOSTIC ANALYSIS

A prognostic analysis is a forensic analysis, which includes, but is not limited to using all 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 often present among other normal occurring transient behavior. Personnel must receive special training (prognostician) to discriminate transient, deterministic (predictable) behavior from other expected non-deterministic transient behavior. In complex systems such as a launch vehicle or satellite, the operational environment of the on-board equipment is very dynamic. Transients may occur from equipment cycling or set to cycle or a failed sensor and thus the behavior of the equipment telemetry may include transient behavior as a result that is not deterministic behavior. Prognosticians can discriminate between normal occurring transient behavior and accelerated aging.

Launch vehicle equipment that will fail during launch will have deterministic behavior present in telemetry usually many weeks/months prior to the actual failure, when telemetry is available, the accelerated aging 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 integration & test while the equipment remains on the ground prior to launch. Analog test (performance) data from test equipment may be used if it has been archived. Generally, test equipment data is not archived during equipment trouble shooting activities.

WHAT 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

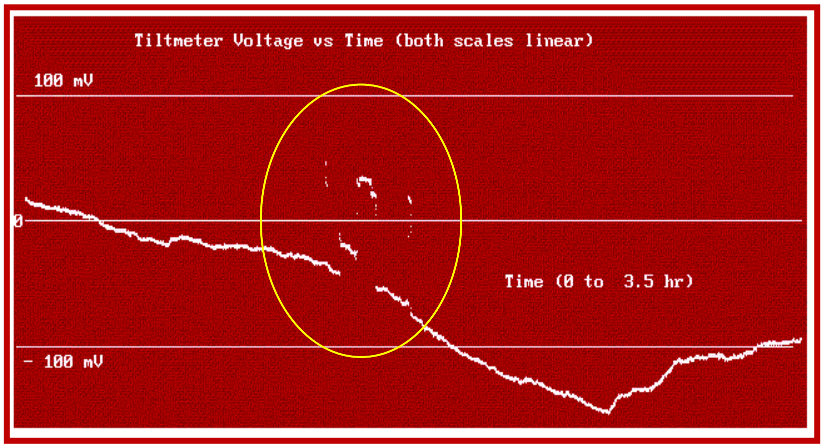

FIGURE 4 EXAMPLE OF ACCELERATED AGING PRESENT IN ALL TYPES OF EQUIPMENT

Figure 4 illustrates an example of deterministic, transient behavior 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 and instantaneously 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 prognostic technology because it mimics signal noise and other normal transient behavior from equipment cycling and sensor failure.

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. Unlike calculations such as MTBF and MTTF are statistical results, the equipment that has accelerated aging identified will fail prematurely with 100%

certainty. The calculation of the TTF is probabilistic result based on a proprietary database of equipment failures analyzed over a 30-year period.

To accurately predict a 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. 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 5 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.

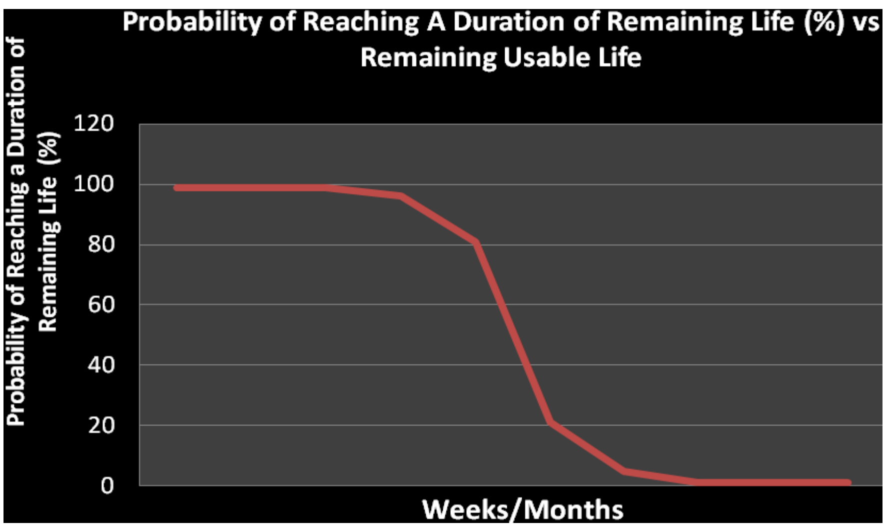

FIGURE 5 PROPRIETARY CUMULATIVE DISTRIBUTION USED TO DETERMINE TIME-TO-FAILURE/REMAINING-USABLE-LIFE

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 in Figure 5 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.

RESULTS FROM THE PROGNOSTIC ANALYSIS CONDUCTED ON THE NASA/U.C. BERKELEY EXTREME ULTRA-VIOLET EXPLORER ASTROPHYSICS SATELLITE

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.

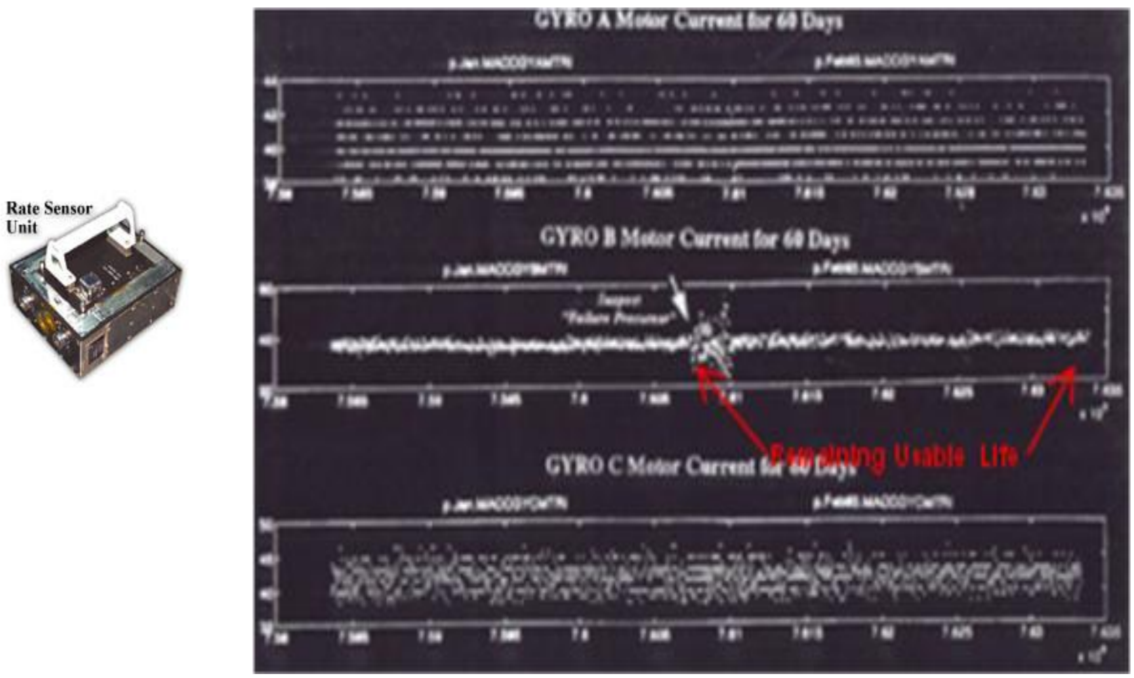

FIGURE 6 RESULTS OF A PROGNOSTIC ANALYSIS CONDUCTED ON THE NASA EUVE/HUBBLE TELESCOPE RATE GYRO UNIT ILLUSTRATING ACCELERATED AGING AND TIME-TO-FAILURE/REMAINING-USABLE-LIFE

CONCLUSION

Equipment manufacturers only measure equipment performance testing, but there is no relationship between equipment performance and short-term or long-term equipment reliability. Using a prognostic analysis to convert performance measurements before, during and/or after equipment factory test allows the identification of any equipment that will fail prematurely after test. Expanding factory production activities to include equipment and vehicle reliability measurements using a prognostic analysis allows the production of equipment with near 100%

reliability eliminating infant mortality failures of all kinds. The equipment reliability measurements results include the calculation of the equipment with accelerated aging time-to-failure (TTF)/remaining usable life (RUL).

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