The Engineering Practices Necessary for Producing Equipment that Meets both Performance and Mission Life Requirements

Len Losik[1], Ph.D
Failure Analysis, Salinas CA 93906

Abstract

The tools, technologies, practices, policies, procedures and procurement process developed and implemented over 50 years to produce highly reliable spacecraft and equipment have yielded spacecraft and launch vehicles whose reliability and availability is dominated by premature equipment failures and surprise equipment failures that increase risk and decrease safety, mission assurance and effectiveness. Large, complex aerospace systems such as aircraft, launch vehicle and satellites are first subjected to most exhaustive and comprehensive acceptance testing program used in any industry and yet suffer from the highest premature failure rates of any other industry. Desired/required spacecraft equipment performance is confirmed during factory testing, however equipment mission life requirement is not measured but calculated manually and so the equipment that will fail prematurely are not identified and replaced before use. Spacecraft equipment mission-life is not measured and confirmed before launch as performance is but calculated using stochastic equations from probability reliability analysis engineering standards such as MIL STD 217. The change in the engineering practices used to manufacture and test spacecraft necessary to identify the equipment that will fail prematurely include using a prognostic and health management (PHM) program that includes using predictive algorithms to convert equipment telemetry into a measurement of equipment usable life. This is done as part of a prognostic and health management (PHM) plan. A PHM makes the generation, collection, storage and engineering and scientific analysis of equipment performance data "mission critical" rather than just nice-to-have information. To ensure that highly reliable space vehicle equipment will not fail prematurely requires engineering personnel to measure equipment remaining usable life invasively after factory equipment and vehicle integration & testing is completed, so that the equipment that will fail within the first year of use can be identified and replaced. A prognostic analysis is a scientific analysis and uses predictive algorithms and equipment performance data of any type including equipment analog telemetry to measure equipment usable life invasively. Predictive algorithms covert equipment analog telemetry into a measurement of equipment remaining usable life. If equipment mission life is measured and confirmed just as equipment performance is measured and confirmed, the systems engineering process will produce equipment that meet both the contractual equipment performance and equipment remaining usable life prior to delivery for use.

I. Introduction

[1] The systems engineering process was developed many decades ago hoping it would allow the development and production of small, medium and large complex aerospace and defense systems that was desired originally by the funding agency and met all the needs of the end user of the system including performance, reliability, serviceability and usable/mission life. The systems engineering method provides a process for concept development, requirements definition, identification and traceability, the traceability of all information related to the effort and the opportunity for companies to use the same process so that new organizations and existing suppliers would not have a cost or technological advantage over others and encouraging many bidders. The systems engineering method also

[1]President and Chief Technical Officer, 12 Glen Falls Circle, Salinas CA 03906, Senior Member

allows “requirement creep” for adding new requirements as a program matures and surprise benefits and capabilities are discovered and desired by the customer. It use by bidders allowed a “level playing field” for the customer to award contracts to companies and suppliers that offered the best products and services.

The requirements for a system include hardware and software physical, functional performance confirmation and electrical and mechanical interfaces. For space systems, except launch vehicles, mission life is a requirement. Today, spacecraft may have a mission life of 15 years and so identifying the equipment that will fail prematurely will increase the likelihood of meeting the 15-year mission life using a minimum of redundant equipment. Requiring suppliers to meet the mission life allows suppliers to know the amount of expendables including equipment with backup equipment (a.k.a level of redundancy) in the event that subsystem equipment would fail prematurely, a vehicle could function as desired the entire duration operating on backup systems. The exact amount of expendable equipment is required to be known by all bidders because the cost of expendables often greatly affects the final purchase price so knowing the exact amount to bid “levels the playing field” for bidders of large complex systems.

System and equipment mission life became overly important in the production of ICBM’s in the early 1950’s because ICBMs failed prematurely so often. The ICBM development and test effort was contractor driven because the military had few personnel with experience in ICBM design and test. The main branch of the military in the 1950’s was the combined Army-Air Force who had fought and won World War I and World War II. In the 1950’s, the jet age and ICBM era stretched the Army-Air Force personnel resources. The Air Force was separated from the Army in the 1960’s and was given responsibility for the development of both jet aircraft, ICBMs, military launch vehicles and satellites in California.

In the 1950’s and early 1960’s, the new jet aircraft and ICBM’s were failing prematurely so often that many tools and practices were added to the procurement contracts for companies to complete hoping to decrease the number of premature failures. These include the systems engineering method, probability reliability analysis (PRA) was borrowed from the merchant shipping industry, dynamic environmental qualification and acceptance testing, quality control and management, equipment telemetry and data acquisition systems. Telemetry was developed by the jet aircraft flight test community in the late 1950’s to measure aircraft equipment performance and relay the information to flight test engineers in real-time to a remote location in the event that the pilot was killed during a flight test and couldn’t debrief the test engineering staff. Telemetry was back fitted to ICBM’s and launch vehicles and added to spacecraft in the 1960’s. Telemetry is used on spacecraft to measure and confirm equipment performance before use as well as operate and maintain spacecraft while in space. Engineer’s complete diagnostic analysis including failure analysis after a failure occurs. Diagnostic analysis uses past performance data to understand and quantify past equipment behavior. Tests similar to the dynamic environmental acceptance testing these have been incorporated in many industries hoping that their use will increase initial product/equipment reliability. A PRA is used when sufficient information does not exist to quantify the behavior using any other method.

Figure 1. Forty-Eight Years of Actual Reliability of U.S. ICBMs and Launch Vehicles (Aerospace Corporation [3]).

Table 1. Summary of Surprise Equipment Failures that Occurred on the Equipment Integrated into 60 Satellites while Completing Dynamic Environmental Factory Vehicle ATP. All Equipment had already Passed Dynamic Environmental Factory Acceptance Equipment ATP (Aerospace Corporation [11]).

		Number of Equipment Failures per Dynamic Environmental Acceptance Test							
Space Command/ Air Force Satellite Program Name	**No. of Satellites Tested per Program**	**Acoustic**	**Thermal Cycling**	**Acoustic**	**Thermal Vacuum**	**Thermal Cycling**	**Acoustic**	**No. of Satellites in Followed to Space**	**No. of Surprise Equipment Failure within 45 Days On-Orbit**
E2	4	--	5.5	--	2.8	--	0.5	4	0.5
D1*	3	0.3	--	--	1.7	--	--	3	2.0
D2*	1	0	2.0	--	2.0	--	--	1	1.0
D3*	9	0.9	1.4	--	1.6	--	--	7	0.6
D4/D5*	2	0.5	1.5	--	0	--	--	1	0
B	16	0.6	--	--	1.2	--	--	11	0.6
G	4	1.0	--	--	3.8	--	--	3	2.0
F1	5	--	1.0	0.4	0.4	--	--	4	0.3
F2	3	--	4.3**	0.7	1.3	--	--	1	0
H1	2	0.5	--	--	5.5	--	--	2	1.0
H2a	1	2.0	--	--	2.0	6.0	--	1	1.0
H2b	2	0.5	--	--	3	9.0	--	2	0.5
C	8	1.1	--	--	3.0	--	--	7	0.5
Total:	**60**	**7.4**	**15.7**	**1.1**	**28.3**	**15.0**	**0.5**	**47**	**18**
Weighted Average				**4.0**				**0.7**	

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

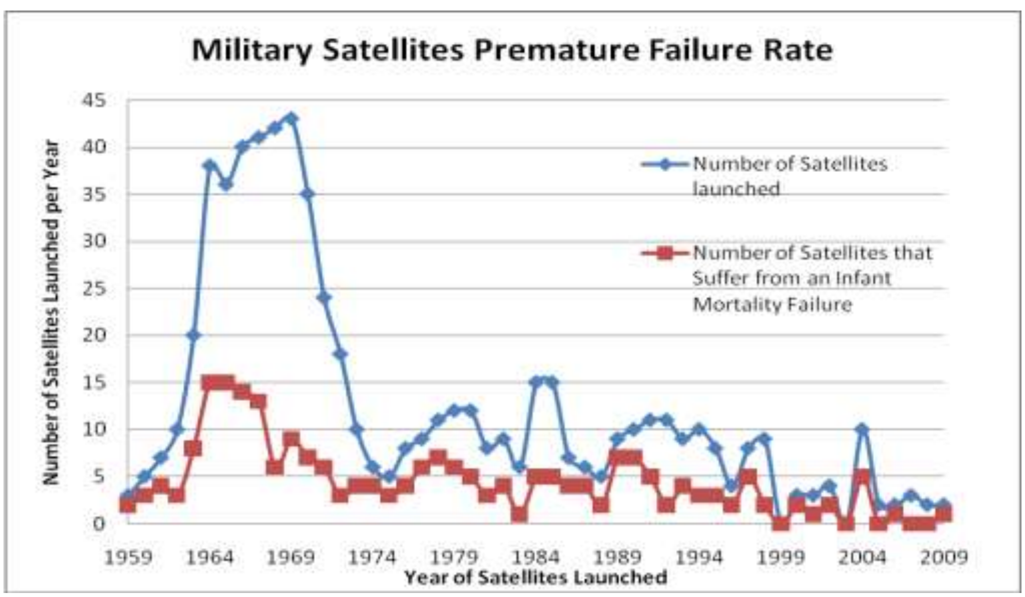


Figure 2. The Number of (Unclassified) Military Satellites Launched and the Number of Unclassified Military Satellites that Failed Prematurely Starting from 1959 (Futron Corp. [15]).

Jet aircraft are designed to be serviceable by maintenance personnel, but ICBM's and spacecraft are not serviceable and so have only one chance of getting it right but fail prematurely regularly. Each time an ICBM failed in development and test, the Army-Air Force would purchase 50 or 100 more just to ensure that more were available. Unable to measure equipment usable life, calculating the likelihood of meeting the mission life was done using PRA. For convenience, reliability is defined as the likelihood of meeting the desired mission life, which is unrelated to a measured mission life.

Since equipment failed prematurely and the premature failures could not be stopped, calculating the likelihood that the mission life could be done by all suppliers using the stochastic equations in PRA, Suppliers provided redundant equipment per direction or based on the stochastic equations in PRA. Since premature failures of equipment could not be stopped but compensated for buying many more than needed, probability reliability analysis was added so that contractors/suppliers could calculate the likelihood of the mission life being achieved.

II. Reliability Analysis Engineering

Reliability analysis engineering is used to quantify equipment reliability as a probability of success occurring or probability of a failure occurring. This is not the desired information when we require equipment to operate for many years. For spacecraft with many years of hoped for service, we want to know whether the equipment will fail prematurely, within the first year of use or whether the equipment will operate for its intended mission life of 7 years or fail sometime during its normal lifetime.

Does knowing the likelihood of a failure occurring sometime during its operational life provide the desired knowledge of mission life? No. Fifty years ago, the likelihood of a failure occurring obtained from calculations identified in a reliability analysis engineering standard Mil STD 217 was the best result engineers could generate.

Reliability analysis engineering uses stochastic equations to quantify equipment reliability as a probability of an event (failure) occurring. Stochastic equations arrive at results that seem to important but are calculated from random information that is unrelated to the desired information. In probability theory, a stochastic process, or sometimes a "random process" is the counterpart to a deterministic process (or deterministic system). Instead of dealing with only one possible solution of how the process might evolve under time (as is the case, for example, for solutions of an ordinary differential equation), in a stochastic or random process there is some indeterminacy in its future evolution described by probability distributions. This means that even if the initial condition (or starting point) is known, there are many possibilities the process might go to, but some paths may be more probable and others less so.

[2]When reliability is defined as the likelihood of a failure occurring, the reliability of a system using a stochastic equation of four elements in series, where each element has a reliability of 0.98 is:

$$R_s = R_1 \times R_2 \times R_3 \times R_4$$

or

$$R_s = 0.98 \times 0.98 \times 0.98 \times 0.98 \text{ therefore:}$$

$$R_s = 0.922$$

The equation appears meaningful and the results are high, but neither result is related to the desired knowledge of equipment useful life of the four elements. Just as a coin may land with a 50% probability on either heads or tails, the actual number will be much different in a large number of coin tosses.

Reliability analysis engineering is an engineering field that is the study of reliability: the quantification 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 using stochastic calculations began in 1959. The U.S. ICBM's and modified ICBMs used as launch vehicles continued to be highly unreliable often demonstrating a 50% premature failure rate. Catastrophic failure rates were as high as 25% even after dynamic environmental testing.

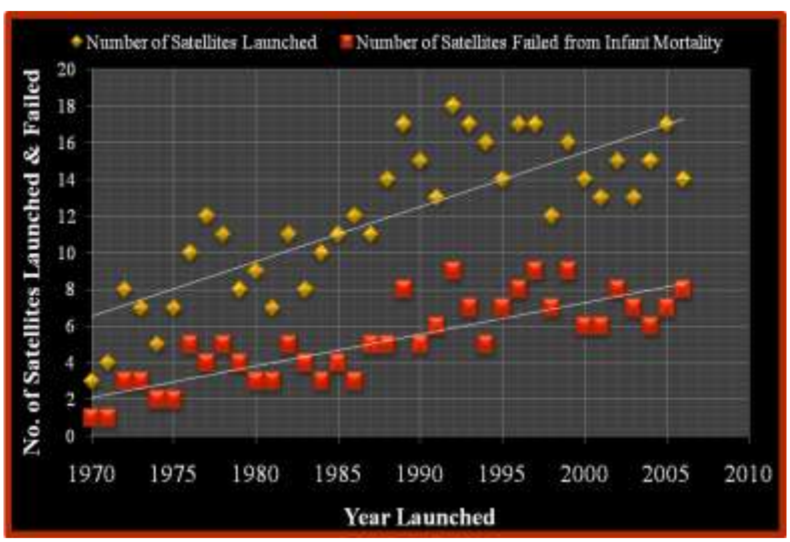
Reliability analysis engineering provides a probability of an event will occur and so is not a measure of usable life or mission life. As applied to the aerospace industry, reliability analysis requires that equipment failures be considered instantaneous and random and this belief has leaked into the minds and decision makers 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.

Table 3. Actual Reliability (Successes/Attempts) of Air Force Launch Vehicle using PRA, Quality Control Program and Factory Equipment Performance Testing to Increase Reliability[4]

Vehicle	Successes	Launches	Averaged Lifetime Reliability	Calculated Rate Reliability	Operational Dates
Delta 2	144	146	.99	.98	1989-2009
STS	127	129	.98	.98	1981-2009
Minotaur 1	8	8	1.00	.90	2000-2009
Atlas 5	7	8	.94	.90	2002-2009
Delta IV-M	7	7	1.00	.89	2002-2009
Pegasus	3	5	.88	.86	1991-2009
Taurus	6	8	.75	.70	1994-2009
Delta IV-H	0	1	0	0	2004-2009
Falcon	1	2	.50	.43	2006-2009

Table 4: Summary of Predicted and Achieved Reliability of Retired U.S. Launch Vehicles using PRA, Quality Control Program and Factory Equipment Performance Testing to Increase Reliability[4]

Vehicle	Successes	Launches	Averaged Lifetime Reliability	Calculated Rate Reliability	Operational Dates
Atlas 2/2AS	63	63	1.00	.98	1991-2004
Titan 2	17	17	1.00	.95	1964-2003
Atlas 3	6	6	1.00	.88	2000-2005
Titan 4B	15	17	.88	.84	1997-2005
Titan 2	6	7	.86	.78	1964-2003



Filure 3. Number of Civil and Commercial Satellites Launched per Year (Gold) and the Number that Failed Prematurely (Red). (Frost & Sullivan [12]).

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. A prognostic analysis is a scientific analysis. A failure analysis is an engineering analysis. In an engineering analysis, the cause of a failure is provided in a list of potential causes. In a scientific analysis, the source of the behavior is identified with certainty.

III. Factory Acceptance Testing Programs

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. The hope was that the surviving equipment after dynamic environmental acceptance testing would be higher than if the equipment had not been exposed to the extreme conditions. Equipment performance is measured and confirmed before, during and after testing is completed, usually by analyzing equipment telemetry. Since telemetry is an overhead cost, less than 95% of the equipment will have telemetry data available from test. Since equipment performance data is the only measurement that is made during dynamic environmental factory acceptance testing, and performance is unrelated to equipment usable life, the reliability of equipment subjected to factory dynamic environmental acceptance testing is dominated by premature failures.

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 all 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.

[3] Dynamic environmental acceptance testing is performed at varying magnitudes and durations to verify the design of complex space systems will meet contractual performance specifications when it arrives in space will meet contractual equipment performance specifications during its entire mission life. Testing also screens space flight hardware to verify the quality of workmanship meets industry standards.

The first step in this process is exposing equipment to the worst-case expected environments during launch and on-orbit operations. Data from previous flights and ground tests are analyzed to generate predictions for a specific mission. This information is used in the stochastic equations in a reliability analysis engineering required completed by the procurement contract. 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.

Contracts for spacecraft and launch vehicles include a financial penalty for missing the delivery date but do not include a financial penalty for a premature failure. Financial incentives may be lost but there will be no out-of-pocket financial losses. The contract for spacecraft was developed because equipment was failed prematurely and they could not be stopped and test equipment and software was the source of most transients. This may motivate companies to misdiagnose all transient events as noise so that the test schedule will not be slowed from searching for the sources of transient behavior. Today, the huge increase in processing speed decreases the likelihood of transients occurring from test equipment so that transients that occur are from the equipment under test.

A. Space Vehicle Acoustic Testing

A principal source of dynamic loading of space vehicles occurs during liftoff and during atmospheric flight at maximum dynamic pressure. It is caused by the intense acoustic pressure generated by turbulent mixing of exhaust gases from the main engines and rocket motors with the ambient atmosphere. Acoustic testing exposes all equipment to the worse case acoustic environment generated by all space vehicles or major subsystems and strives to simulate the acoustic pressure expected during liftoff and all other subsequent mission phases. Space vehicles also contain complex components that are susceptible to acoustic noise, and these must be tested by exposing them to the worse case acoustic environment first before launch to ensure all potential failure modes and workmanship defects have been properly screened out prior to system integration.

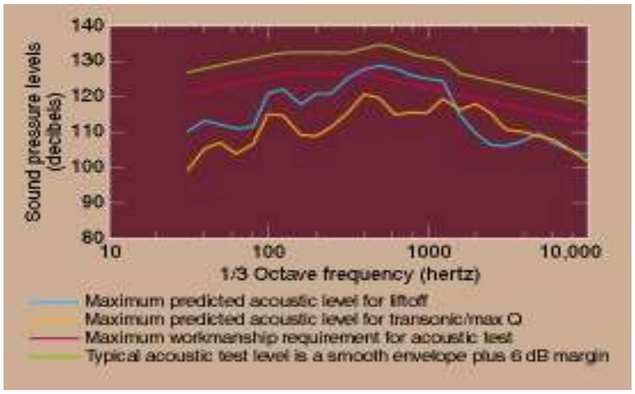


Figure 5: Typical Acoustic Radiated Energy Levels Used During Contractor Spacecraft Factory Acceptance Testing Specified In Contract (Aerospace Corporation [13])

B. Space Vehicle Vibration Testing

As the launch vehicle lifts off from the stand and throughout powered flight, the vibration caused by the operating engines excites the vehicle and spacecraft structure. Additional vibration is caused by the fluctuating acoustic pressure experienced during liftoff, transonic flight, and the maximum-dynamic-pressure phase of flight.

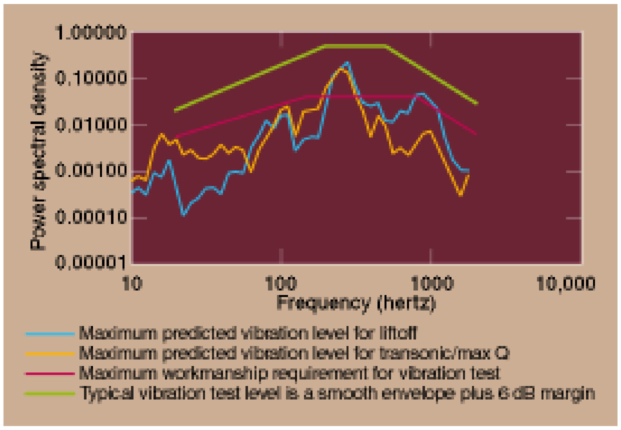


Figure 6: Typical Vibration Energy Levels Used During Contractor Factory Acceptance Testing Specified In Contract (Aerospace Corporation [13])

Vibration testing helps demonstrate that hardware can withstand these conditions. Random vibration tests are conducted on an electro-dynamic vibration machine or "shaker," which consists of a mounting table for the test item rigidly attached to a drive-coil armature. A control system energizes the shaker to the desired vibration level. Feedback for the control system is provided by a series of accelerometers, which are mounted at the base of the test item at locations that correspond to where the launch vehicle adapter would be attached.

C. Space Vehicle Shock Testing

Stage, fairing and vehicle separations are often accomplished by means of pyrotechnic devices such as explosive bolts, separation nuts, bolt cutters, expanding-tube separation systems, clamp bands, ordnance thrusters and pressurized bellows. When activated, these devices produce powerful shocks that can damage equipment and structures. The characteristics of these shocks depend on the particular separation mechanism, but the energy spectrum is usually concentrated at or above 500 hertz and is measured in a frequency range of 100 to 10,000 hertz. A typical shock response spectrum plot is used to gauge the damage potential of a given separation event.

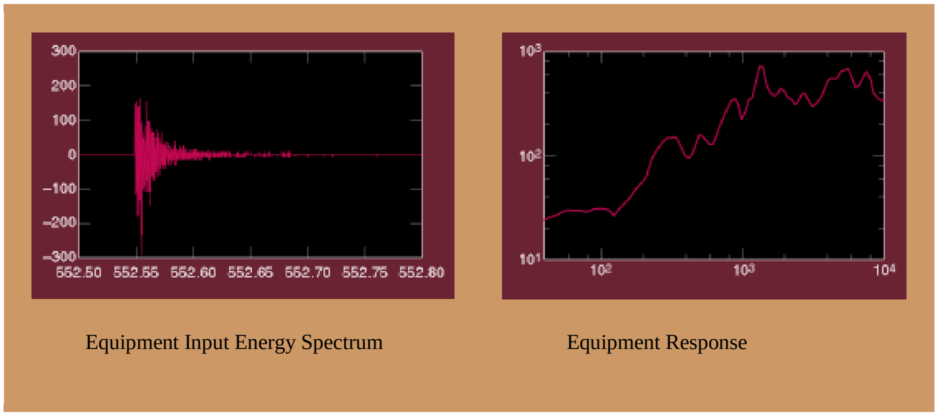


Figure 7: Typical Shock Energy Input and Response Levels Behavior during Contractor Factory Acceptance Testing (Aerospace Corporation [13])

Separations or deployments generate brief impulsive loads even if no pyrotechnic devices are used. Non-explosive initiators may produce significant shock levels simply through the release of structural strain. Experience has shown that shock can induce a hard or intermittent failure or exacerbate a latent defect. Commonly encountered hardware failures include relay transfer, cracking of parts, dislodging of contaminants, and cracking of solder at circuit-board interfaces.

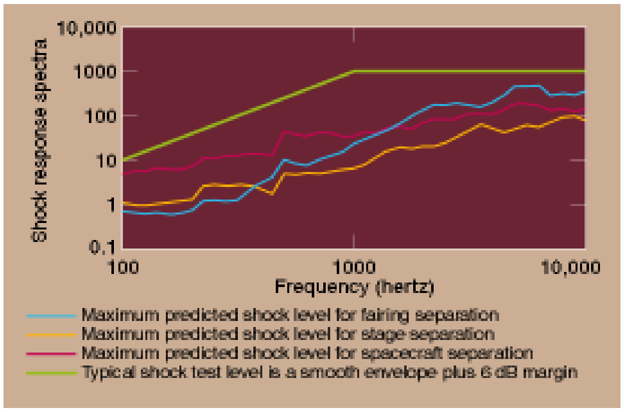


Figure 8: Typical Shock Energy Levels Used During Contractor Factory Acceptance Testing Specified In Contract (Aerospace Corporation [13])

D. Space Vehicle Thermal Testing/Vacuum Testing

Launch vehicles and spacecraft must endure a wide range of temperatures associated with liftoff and ascent through the atmosphere, direct impingement of solar radiation, and travel through the extreme temperatures of space. The thermal environment is generally considered the most stressful operating environment for hardware in terms of fatigue, and it has a direct bearing on unit reliability and yet no parts used in space applications are tested to operate in the thermal cycling conditions that occur in space. For example, the use of materials with differing coefficients of thermal expansion has resulted in unsuccessful deployments of mechanical assemblies and payloads.

Out gassing increases significantly with temperature, and the resulting contaminants will more readily adhere and chemically bond to colder surfaces. Electronic parts are especially sensitive to the thermal conditions and are subject to problems such as cracks, delaminating, bond defects, discoloration, performance drift, coating damage and solder-joint failure.

Satellite and launch vehicle thermal testing is used to screen out components with physical flaws and demonstrate that a device can activate and operate in extreme and changing temperatures. The four most common thermal tests are thermal cycling, thermal vacuum testing, thermal balance testing, and burn-in testing. Thermal cycling subjects the test article to a number of cycles at hot and cold temperatures in an ambient-air or gaseous-nitrogen environment; convection enables relatively rapid cycling between hot and cold levels.

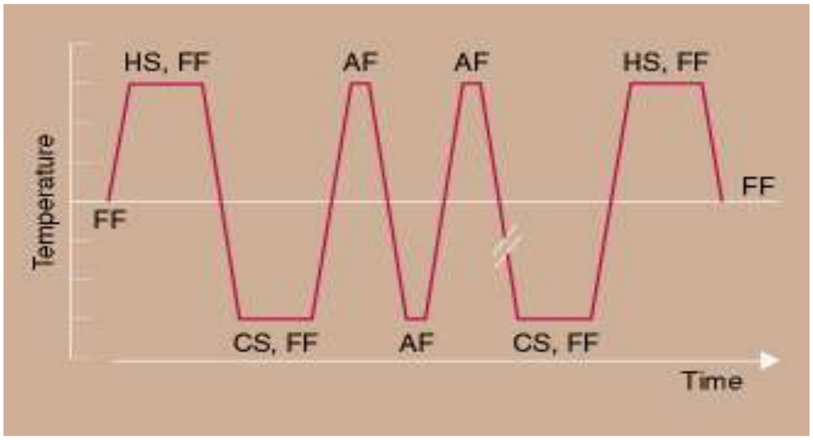


Figure 9: Typical Thermal/Vacuum Profiles Used During Contractor Factory Acceptance Testing Specified In Contract (Aerospace Corporation [13])

Thermal vacuum testing does the same thing, but in a vacuum chamber; cycles are slower, but the method provides the most realistic simulation of flight conditions. In thermal balance testing, also conducted in vacuum, dedicated test phases that simulate flight conditions are used to obtain steady-state temperature data that are then compared to model predictions. This allows verification of the thermal control subsystem and gathering of data for correlation with thermal analytic models. Burn-in tests are typically part of thermal cycle tests; additional test time is allotted, and the item is made to operate while the temperature is cycled or held at an elevated level.

For electronic units, the test temperature range and the number of test cycles have the greatest impact on test effectiveness. Other important parameters include dwell time at extreme temperatures, whether the unit is operational and the rate of change between hot and cold plateaus. For mechanical assemblies, these same parameters are important, along with simulation of thermal spatial gradients and transient thermal conditions.

Thermal test specifications are based primarily on test objectives. At the unit level, the emphasis is on part screening, which is best achieved through thermal cycle and burn-in testing. Temperature ranges are more severe than would be encountered in flight, which allows problems to be isolated quickly.

At the payload, subsystem and space vehicle levels, the emphasis shifts toward performance verification. At higher levels of assembly in flight-like conditions, end-to-end performance capabilities can be demonstrated, subsystems and their interfaces can be verified and flightworthiness requirements can be met. On the other hand, at the higher levels of assembly, it is difficult (if not impossible) to achieve wide test temperature ranges, so part screening is less effective.

E. Space Vehicle EMC/EMI Testing

Electromagnetic compatibility (EMC) includes the identification and measurement of the unintentional generation, propagation and reception of electromagnetic energy with reference to the unwanted effects (Electromagnetic interference, or EMI) that such energy may induce. The goal of EMC is the correct operation, in the same electromagnetic environment, of different equipment, which uses electromagnetic phenomena, and the avoidance of any interference effects.

In order to achieve this, EMC pursues two different issues. Emission issues are related to the unwanted generation of electromagnetic energy by some *source*, and to the counter-measures, which should be taken in order to reduce such generation and to avoid the escape of any remaining energies into the external environment. Susceptibility or immunity issues, in contrast, refer to the correct operation of electrical equipment, referred to as the *victim*, in the presence of unplanned electromagnetic disturbances.

Interference, or noise, mitigation and hence electromagnetic compatibility is achieved primarily by addressing both emission and susceptibility issues, i.e., quieting the sources of interference and hardening the potential victims. The coupling path between source and victim may also be separately addressed to increase its attenuation.

IV. Equipment Performance Measuring and Confirmation

Equipment and vehicle performance requirements are included in procurement contracts for all aerospace and defense equipment. Equipment performance requirements will define how well equipment must function. When equipment is designed, it is designed to meet specific performance requirements. To ensure that equipment meets or exceeds its performance requirements, the performance requirements are confirmed during the final factory testing programs called acceptance test program or ATP. When equipment does not meet or exceed its performance requirements, it is repaired and/or replaced. Some equipment fails several times during the ATP. It is repaired each time in violation of PRA. If equipment fails five or more times, material control personnel will scrap the equipment and replace it, saying that its reliability is too low.

V. Measuring and Confirming Equipment Remaining Usable Life/Mission Life

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

When reliability is defined as a likelihood of occurring, the behavior it quantifies is assumed instantaneous and random whether the behavior is or not. This is having the Markov property and having the Markov property is the basis for many of the stochastic equations used in defining equipment needs and serviceability requirements.[5] Do equipment failures occur instantaneously and random? No. Although equipment may exceed its performance specification or stop using electrical power quickly, the process of failing began many weeks or months prior to the event. The equipment began to fail the first time electrical power was applied or the mechanism was used for the first time.

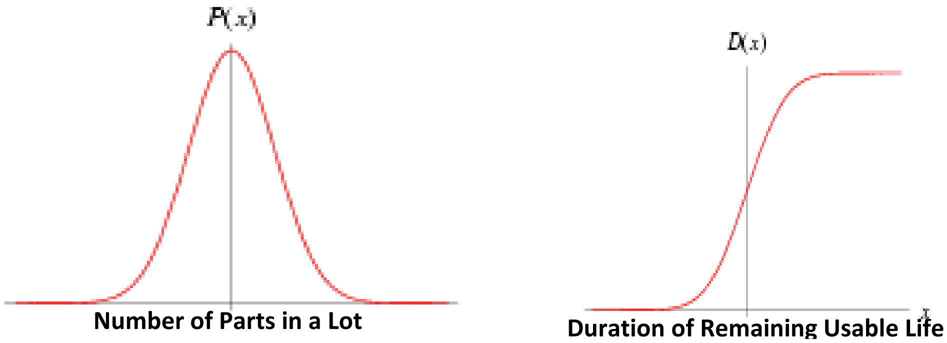


Figure 10. Proprietary Piece-Part Probability Distribution Function Generated by Parts Suppliers that Defines the Likelihood of a Part Failing Prematurely and the Integral of the Piece-Part Normal Distribution

Curve Function known as the Cumulative Distribution Curve that Defines the Likelihood of Any Specific Part Achieving a Duration of Mission Life

Everyone knows that parts degrade in performance starting at beginning of life when power is first applied. When one part starts to degrade in performance much faster than the others, the part is suffering from accelerated aging. Accelerated aging is also the term we use to define to exposing parts or equipment to higher operating temperatures so that parts will degrade much faster. Accelerated aging occurs when at least one part in a circuit or mechanical assembly degrades in performance faster and causes non-repeatable, unique transient events. When telemetry is available from either electrical or mechanical equipment, the non-repeatable transients are visible when the behavior is processed using predictive algorithms. [6] Telemetry provides performance information. Predictive algorithms convert time series telemetry into a measure of equipment life. Data-driven predictive algorithms convert equipment performance information (e.g. volts, amps) into a measurement of remaining usable life. Integrating this function probability distribution function yields the cumulative distribution function.

There is no circuit or mechanism performance analysis completed by the design engineer in the design and test phase of equipment that evaluates circuit/assembly performance/behavior as parts degrade in performance from accelerated aging. The worst-case circuit analysis (WCCA) is only a cost-effective means of screening a design to ensure with a high degree of confidence that potential defects and deficiencies are identified and eliminated prior to and during test, production, and delivery. It is a quantitative assessment of the equipment performance, accounting for manufacturing, environmental and aging effects and does not consider behavior as parts age thus is inadequate for assessing the likelihood of transient behavior occurring as equipment is in use. In addition to a circuit analysis, a WCCA often includes stress and de-rating analysis, Failure Modes and Effects Criticality Analysis (FMECA) and Reliability Prediction. The WCCA does not evaluate equipment behavior as parts degrade in performance over use.

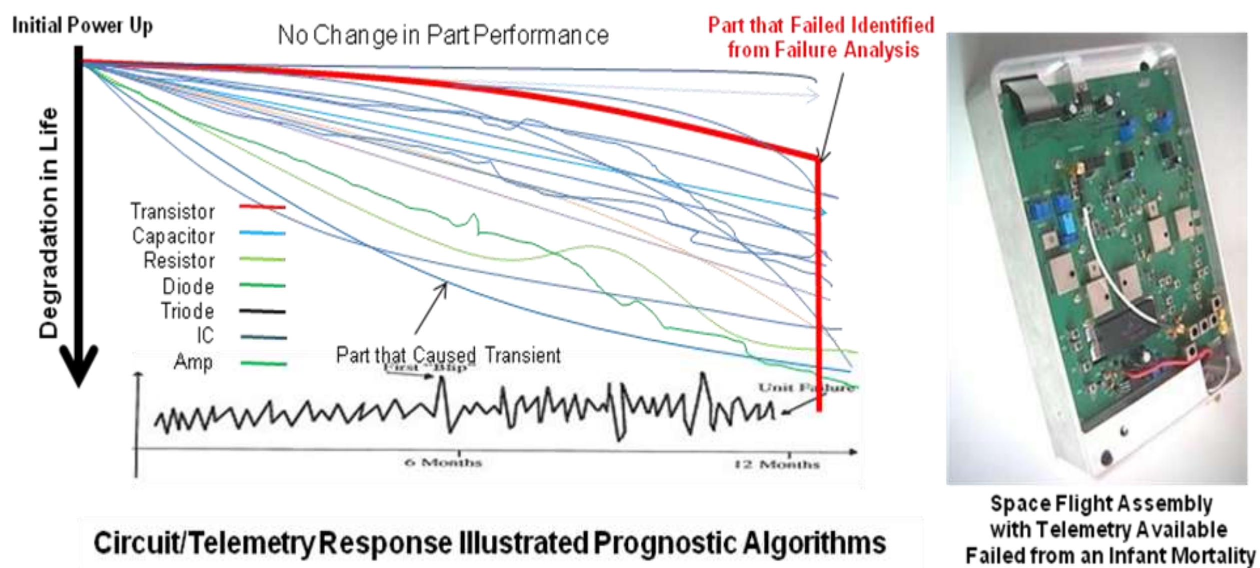


Figure 10. 1he Reason Predictive Algorithms can Measure Equipment Usable Life using Equipment Telemetry by Illustrating Accelerated Aging caused from a Part that is Aging Prematurely in Performance

When using PRA to quantify reliability, the behavior it is used to quantify is assumed to be instantaneous and random whether the behavior is or not. This means that the equipment test data must be memoryless, or that no behavior from before a failure is related to a failure. During many failure analysis that are completed after equipment fails, the equipment behavior during factory ATP is ignored for this reason. If past behavior is related to future behavior, then test data is deterministic and predictable.

When working with PRA, the likelihood of a single unit suffering from more than one failure is extremely low and yet, equipment that fails more than once is common in the production of large complex systems. When equipment is failing several times, it is an indication that it is not the fault of parts.

Parts suppliers provide well-documented proprietary probability distribution curves that quantify the likelihood of their parts going to fail prematurely and the number of parts that will fail prematurely in the parts sold. The low

reliability (and availability) of satellites (and launch vehicles) is well quantified by Aerospace Corporation, who publishes actual military spacecraft and launch vehicle reliability performance data infrequently.
The premature failure of spacecraft equipment will occur as long as the electrical and mechanical piece-parts/assembly suppliers, supply parts with a well-defined failure rate and equipment remaining usable life is not measured. The failure rate of parts is defined by proprietary probability distribution curves and the associated cumulative distribution curves (S-curve). As long as piece-parts suppliers provide parts with a well-known premature failure rate, and space vehicle suppliers are required to only measure and confirm equipment performance and calculate equipment reliability using PRA, spacecraft will continue to fail prematurely.

During the dynamic environmental factory acceptance test program (ATP), equipment performance is measured using a variety of methods. This is completed at the start, during and after the equipment is exposed to all the expected worst-case operational environments. [10] The most common method of measuring and confirming equipment performance uses equipment telemetry. During testing, the equipment telemetry must remain within expected ranges. If it exceeds expected behavior, the equipment is repaired or replaced.

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

TT&C Subsystem Test Plan	Fully Functional	Abbreviated Functional	Random Vibration	Pyro Shock	Thermal Cycling	Thermal Vacuum	EMI/EMC
Command Functional	X	X	X	X	X	X	X
Input Signal Reference	X	X					
Output Signal	X	X	X				
On/Off Telemetry	X	X	X	X	X	X	X
Ranging Loop Stress	X	X					
Output RF Power	X	X					
5 Volt Telemetry Calibration	X	X	X	X	X	X	X
15 Volt Telemetry Calibration	X	X	X	X	X	X	X
5 Volt telemetry Calibration	X	X	X	X	X	X	X
10 Volt Telemetry Calibration	X	X	X	X	X	X	X
IF Carrier Frequency	X						
Phase Noise	X						
Bit Error Rate	X	X	X	X	X	X	X
RF Output Power	X	X					
Spurious and Harmonic Output	X						
Output Power	X						
Inrush Power	X						
Input Voltage	X	X	X	X	X	X	X
Under voltage	X						
Overvoltage	X						

Table 5. Example of a Satellite TT&C Subsystem Dynamic Environmental ATP Test Plan and Subsystem Equipment Performance Measurements to be Measured and Confirmed Before, During and After Each Test

VI. Prognostic Analysis

The scientific analysis, training and tools used to conduct a prognostic analysis that will illustrate and identify the early signs of premature aging/failure (a.k.a. accelerated aging) are used in a prognostic analysis. Prognostic technology accepts that equipment failures do not have the Markov property and that accelerated aging exists and will identify the equipment that will fail prematurely within one year of use.

Key to predicting equipment remaining usable life is the availability telemetry or any other performance data. Telemetry was adopted for use on spacecraft from the jet-aircraft flight test community in the late 1950's at Edwards Air Force Base. Equipment analog telemetry was developed to retrieve jet aircraft equipment performance information from aircraft equipment in the event the pilot died in a crash before a debriefing occurred.

A prognostic analysis is a forensic analysis, which includes the illustration of accelerated aging that is often available in plain sight of test personnel 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 would identify when other units were going to fail. The thrust of prognostic technology is the production of perfect performing and perfectly reliable equipment and products while they are still at the factory.

The definition of the duration between equipment beginning-of-life (BOL) and end-of- life (EOL) can now be redefined. Using just diagnostic analysis, the duration is defined as 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.

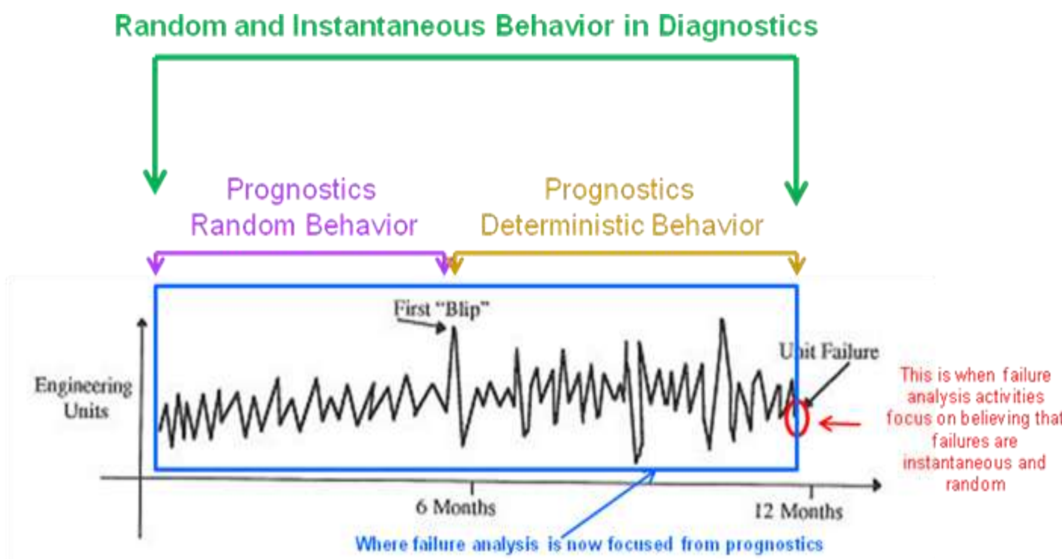


Figure 12. Comparisons between Definitions of Duration between Equipment Beginning-of-Life and End-of-Life Based on Diagnostic Analysis and Prognostic Analysis.

A prognostic analysis is a forensic analysis, which includes but is not limited to using 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 satellite/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. Satellite/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.

Satellite/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.

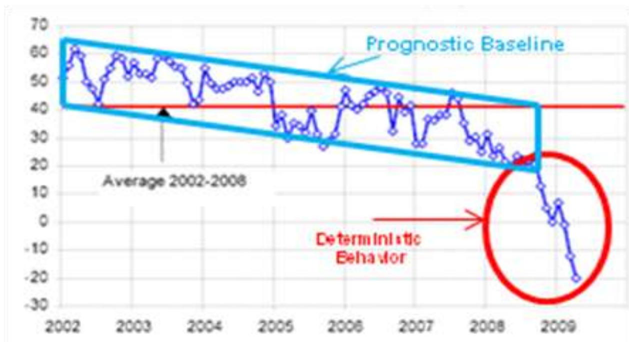


Figure 13. Example of a Prognostic Analysis Illustrating Non-Repeatable Transient Behavior/Early Signs of Premature Aging//Prognostic Markers/Prognostic Identifiers in Equipment Telemetry Caused from Accelerated Aging.

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

Accelerated aging occurs when at least one part in a circuit or mechanical assembly degrades in performance faster and causes non-repeatable, unique transient events.[11] When telemetry is available from either electrical or mechanical equipment, the non-repeatable transients are visible when the behavior is processed using predictive algorithms. Telemetry provides performance information. Data-driven predictive algorithms convert equipment performance information (e.g. volts, amps) into a measurement of remaining usable life.

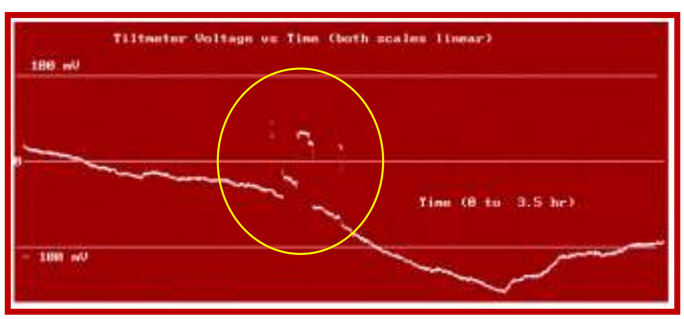


Figure 4. Example of the Transient Behavior in Equipment Telemetry caused from Accelerated Aging that's often Present in Normal Appearing Data from Fully Functional Equipment, Misdiagnosed as Noise

There is no performance analysis completed by the design engineer in the design and test phase of equipment that evaluates circuit/assembly performance/behavior as parts degrade in performance. The worst-case circuit analysis (WCCA) is a cost-effective means of screening a design to ensure with a high degree of confidence that potential defects and deficiencies are identified and eliminated prior to and during test, production, and delivery. [12] It is a quantitative assessment of the equipment performance,. It only accounts for manufacturing, environmental and aging effects and does not consider circuit/assembly behavior as parts age. It is inadequate for assessing the likelihood of transient behavior occurring as equipment is in use. In addition to a circuit analysis, a WCCA often includes stress and de-rating analysis and failure modes and effects criticality analysis (FMECA) and reliability prediction. The WCCA also does not evaluate equipment behavior as parts degrade in performance over use.

VII. Prognostic Technology

Prognostic technology includes pro-active diagnostics, active reasoning and model-based and data-driven prognostic algorithms. The algorithms can work in a full noise environment for illustrating accelerated aging and explain equipment failures are a combination of random and deterministic behavior. Prognostic technology includes the use of predictive algorithms for illustrating the deterministic information, often present in normal appearing data from equipment that is operating normally 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 satellite/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.

VIII. What is a Predictive Algorithm?

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.

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

A diagnostic analysis looks backward in time to determine past equipment behavior. A prognostic analysis looks back in time to predict future equipment behavior. A scientific analysis is necessary because the results from an engineering analysis only provide diagnostic information. The results from a diagnostic analysis cannot be used to measure equipment remaining usable life. A scientific (prognostic) analysis is completed on the results from diagnostic analysis.

Predictive algorithms illustrate the presence of accelerated aging that is often identifiable in normal appearing data from fully functional equipment that will fail prematurely. Predictive algorithms offer spacecraft purchasers and spacecraft builders the tools necessary to purchase satellites and launch vehicle services that will not fail prematurely and suffer from surprise on-orbit failures. Using predictive algorithms and prognostic analysis, contractors and mission control personnel will identify the equipment that will fail prematurely (and predict when satellite subsystem equipment will fail).

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

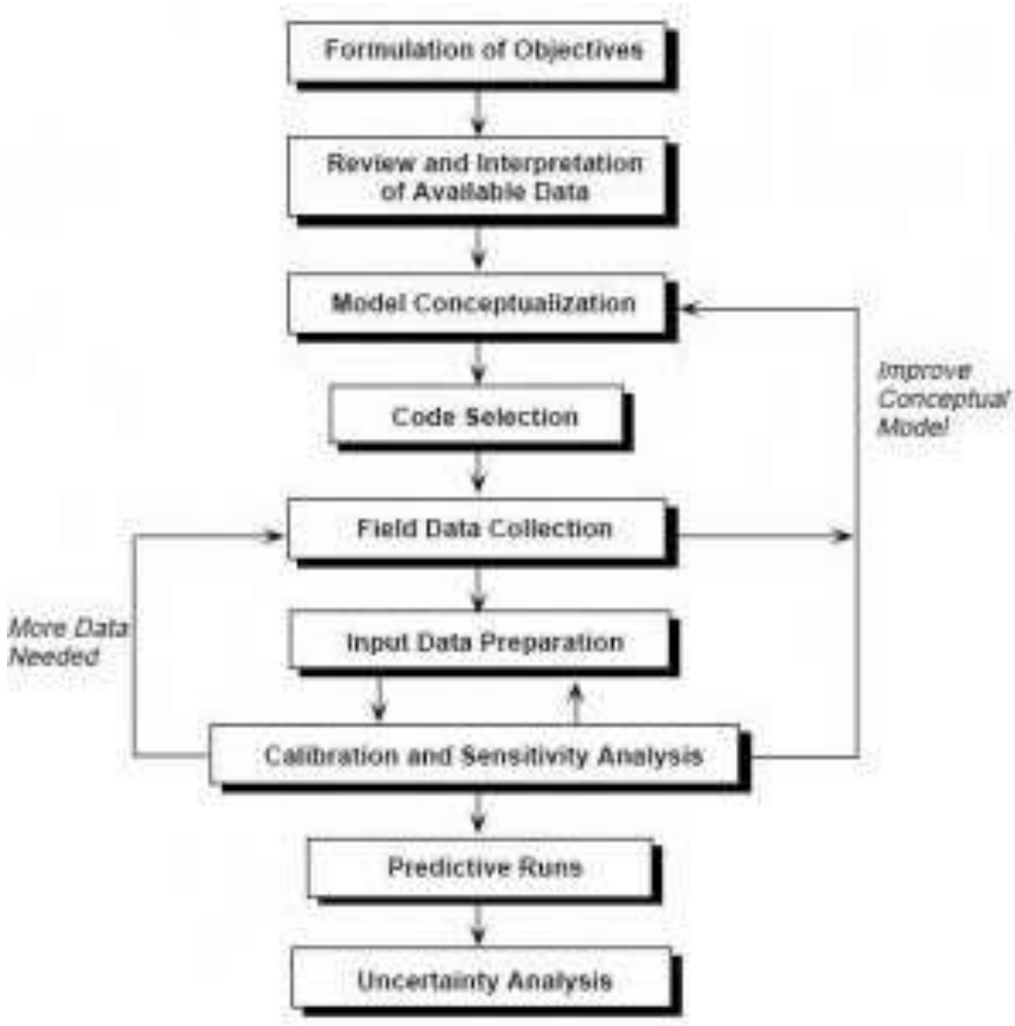


Figure 14. The Process Used to Develop a Proprietary Predictive Algorithm.

Prognostic technology uses almost any analog measurement available today on flight equipment and in satellite/launch vehicle telemetry systems. However, instrumentation with at least a single analog measurement integrated into equipment is necessary to illustrate accelerated aging.

The number and types of analog measurements per unit often includes voltage, current and temperature. Although prognostic analysis is insensitive to measurement sampling frequency, very low sampling frequency can affect the accuracy of the of remaining-usable-life calculation.

During the multi-service testing of the GPS system used to validate that GPS performance was superior to both the existing Navy TIMATION and TRANSIT satellite-based navigation systems, the performance and reliability of each on-orbit GPS satellite atomic frequency standards were critical to mission success. Spike in GPS Kalman filter results and simultaneous changes in satellite analog telemetry from the on-board atomic frequency standards were correlated with end of life. The atomic frequency standard supplier had not associated end-of life with behavior. This is because of the complexity of the GPS space and ground systems. The ground support personnel blamed the satellite for out-of-specification behavior and the satellite support personnel blamed the ground support equipment so that financial penalties would occur. Both systems received financial incentives for meeting established criteria and out-of-specification behavior resulted in lost financial incentives making correlations difficult and unreliable.

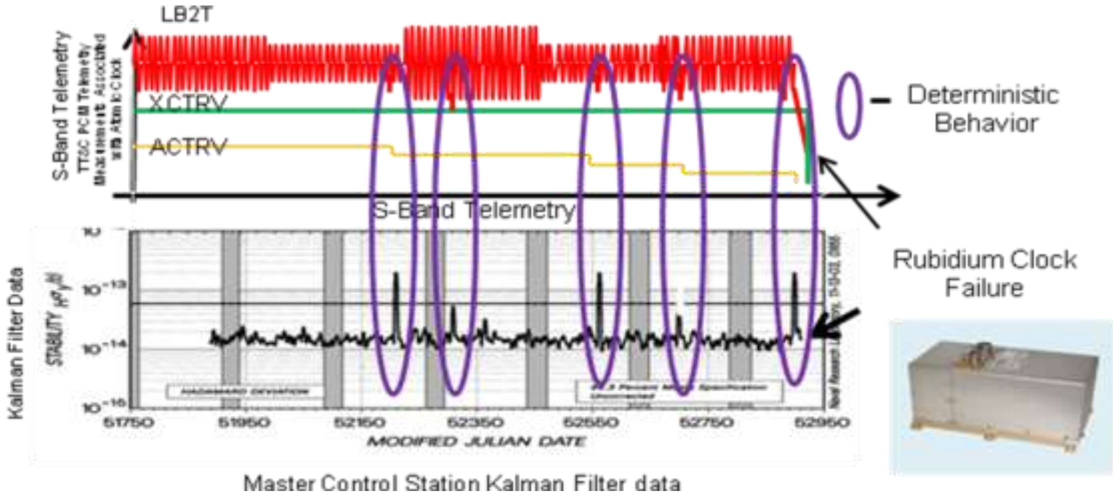


Figure 15. The Prognostic Analysis Completed on a GPS On-Orbit Satellite Rubidium Atomic Frequency Standard Illustrating Transient/Deterministic Behavior caused from Accelerated Aging (circa 1983).

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

Calculating remaining usable is a proprietary process and may be unique for each company/organization. The remaining-usable-life or the time-to-failure (TTF) for equipment can be calculated once accelerated aging has been identified by using the piece-part failure characteristics in equipment telemetry generated under test.[8]

Failure Analysis maintains a database of previous flight equipment failures that were analyzed over a 30-year period to generate a cumulative distribution curve to predict equipment remaining-usable-life for equipment that has been predicted to fail. This information is used to determine the probability of success (Ps) of a circuit with a failure precursor/accelerated aging identified reaching its predicted remaining-usable-life. This information is in the form of a cumulative distribution derived from actual remaining life that occurred on the many failures analyzed over a 30-year period.

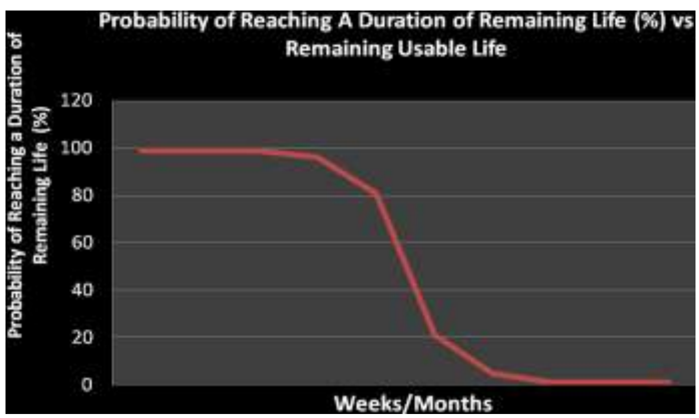


Figure 16: Proprietary Cumulative Distribution used to Determine Equipment Time-to-Failure/Remaining-Usable-Life for Equipment with the Early Signs of Premature Aging/Failure/Accelerated Aging.

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

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

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 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.

X. Measuring Satellite Equipment Remaining Usable Life on the NASA/U.C. Berkeley Extreme Ultra-Violet Explorer, Low-Earth-Orbiting Astrophysics Satellite [9]

The NASA/U.C. Berkeley Extreme Ultra Violet Explorer LEO astrophysics science satellite was launched in 1992. By 1995, there had been several premature failures of the Bus equipment. [13] Between 1994 and 1995, the NASA/U.C. Berkeley EUVE low earth orbiting satellite was utilized to demonstrate the feasibility of predicting on-orbit spacecraft equipment failures using data-driven prognostic algorithms. The NASA EUVE satellite Bus was produced by Fairchild Aerospace (now Orbital) as one in a group of 10 common-core, multi-mission spacecraft used for many GSFC science missions. It was designed to be serviceable by astronauts. The EUV telescope was to be replaced in space by astronauts at the end of the EUV telescope mission life.

Figure 17. NASA/U.C. Berkeley Extreme Ultra Violt Explorer Telescope Payload Designed and Built by U.C. Berkeley Space Sciences Laboratory to Function 10 Years On-Orbit and be Replaced by an Astronaut

To lengthen the science portion of the EUVE satellite mission, the Director of the U.C. Berkeley Center for EUV Astrophysics ordered the engineering staff to complete a prognostic analysis on the EUVE hoping to reduce mission control team support cost by paying for engineering resources only on the day EUV satellite equipment was predicted to fail. The results of the prognostic analysis allowed the CEA to close its mission control center, eliminate staffing and apply the remaining funding to the science portion of the mission,

Unit Failures Analyzed	FP Expected?"	FP Detected?	Date of FP	Date of Failure	Time from FP and EOL	RUL
Transmitter A	No	No	None	None	None	> 6 mos
Transmitter B	Yes	Yes	12/93	4/94	4.5 mos.	< 6 mos
Rate Gyro A	No	No	None	N/A	N/A	> 6 mos
Rate Gyro B	Yes	Yes	1/93	Unknown	Unknown	< 6 mos
Rate Gyro C	No	Yes	6/92	note 1	note 1	> 6 mos
T/R A	Yes	Yes	3/94	12/94	9 mos.	< 6 mos
T/R B	Yes	Yes	4/94	9/94	5 mos.	< 6 mos

Table 6. Summary of the Results from Measuring the Remaining Usable Life on the NASA EUVE LEO Astrophysics Satellite Completed at the Center for EUV Astrophysics, Berkeley CA. [7]

EUVE Telescope Payload Monitors	Date Telemetry Processed	Suspect "Failure Precursor" Expected?	Suspect "Failure Precursor" Found?	Remaining Service Life Estimate	Accuracy of FPP
DET1HVLT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET2HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET3HVLT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET4HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET5HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET6HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET7HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET1HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET2HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET3HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET4HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET5HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%

Table 7. Summary of the Results from Measuring Equipment Remaining Usable Life on the NASA EUVE LEO Astrophysics Satellite Telescope Photon Detectors Completed at the Center for EUV Astrophysics, Berkeley CA. [7]

EUVE Telescope Payload Monitors	Date Telemetry Processed	Suspect "Failure Precursor" Expected?	Suspect "Failure Precursor" Found?	Remaining Service Life Estimate	Accuracy of FPP
DET6HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET7HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET1HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET2HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET3HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET4HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET5HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET6HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET7HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET1HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET2HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET3HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET4HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET5HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET6HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET7HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%

Table 8. Summary of Results from Measuring NASA EUVE Astrophysics Satellite EUV Telescope Photon Detectors Remaining Usable Life using Detector Analog Telemetry. [7]

To lower engineering support cost further, the CEA took over EUV Bus mission operations from Goddard Space Flight Center, extending the science mission until 2002, when the EUVE satellite reentered the earth's atmosphere and crashed in an Egyptian desert.

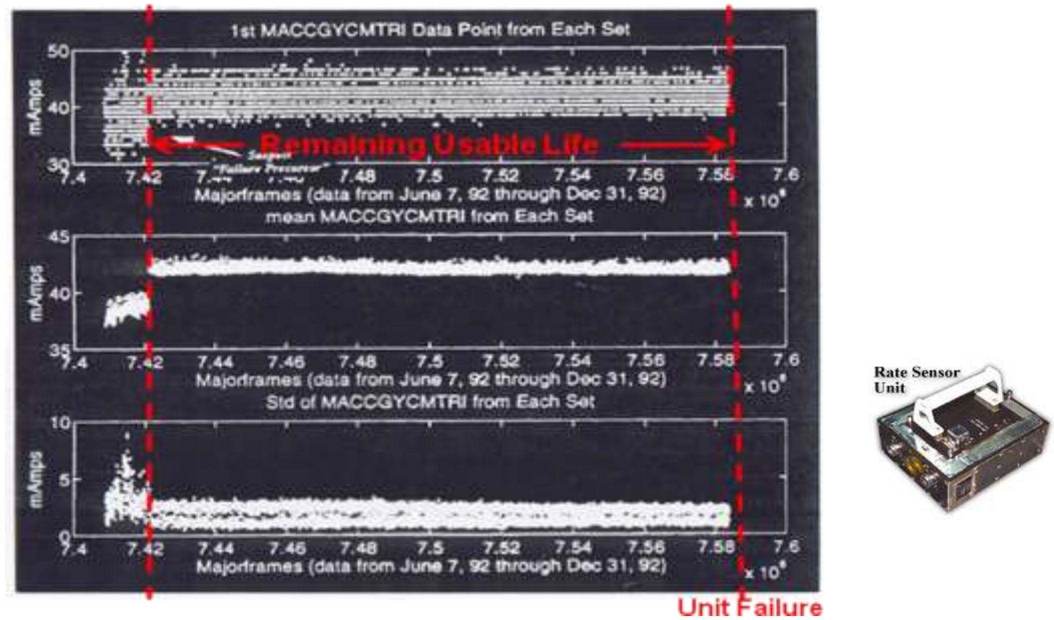


Figure 18. Results from Measuring Rate Gyro Remaining Usable Life using Rate Gyro Motor Current Telemetry Transducer Output (Post Processing Results). [9]

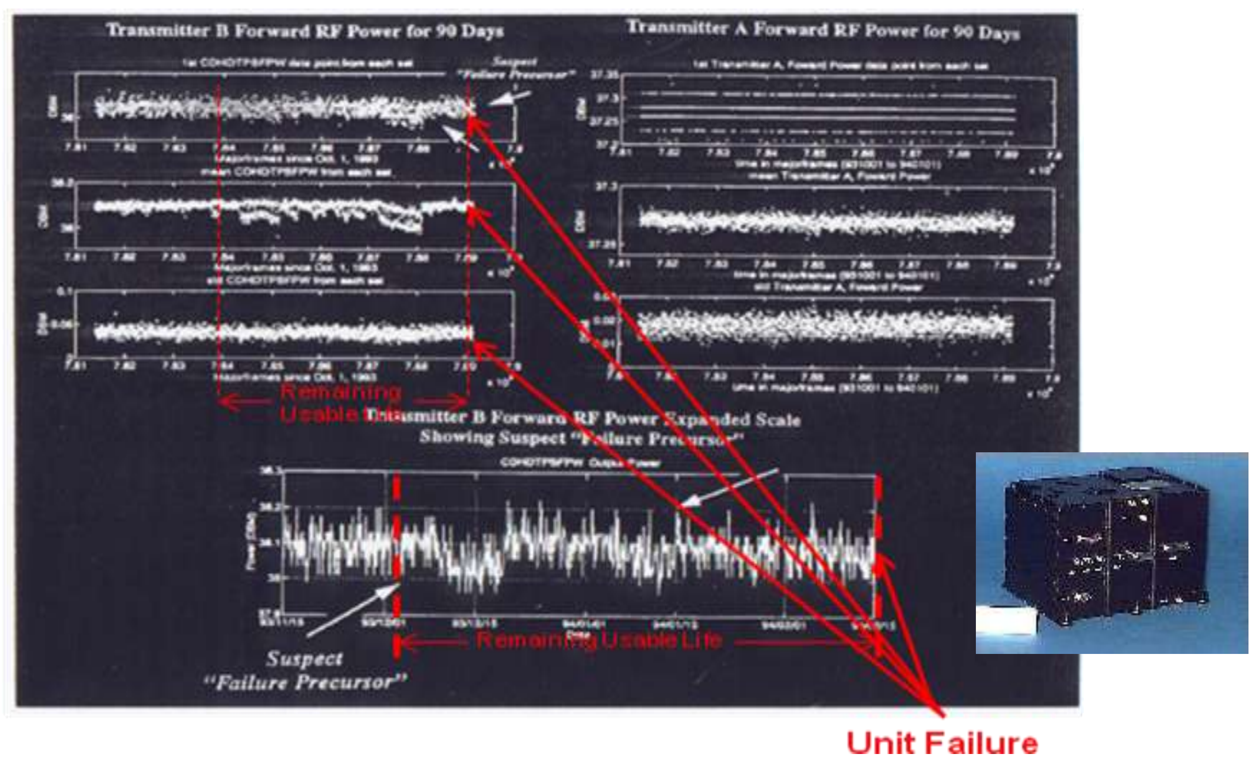


Figure 19. Results from Measuring Transmitter remaining Usable Life on the EUVE Satellite TDRSS RF Transmitter using the Forward RF Power Telemetry Transducer Output (Post Processing Results using Predictive algorithms). [9]

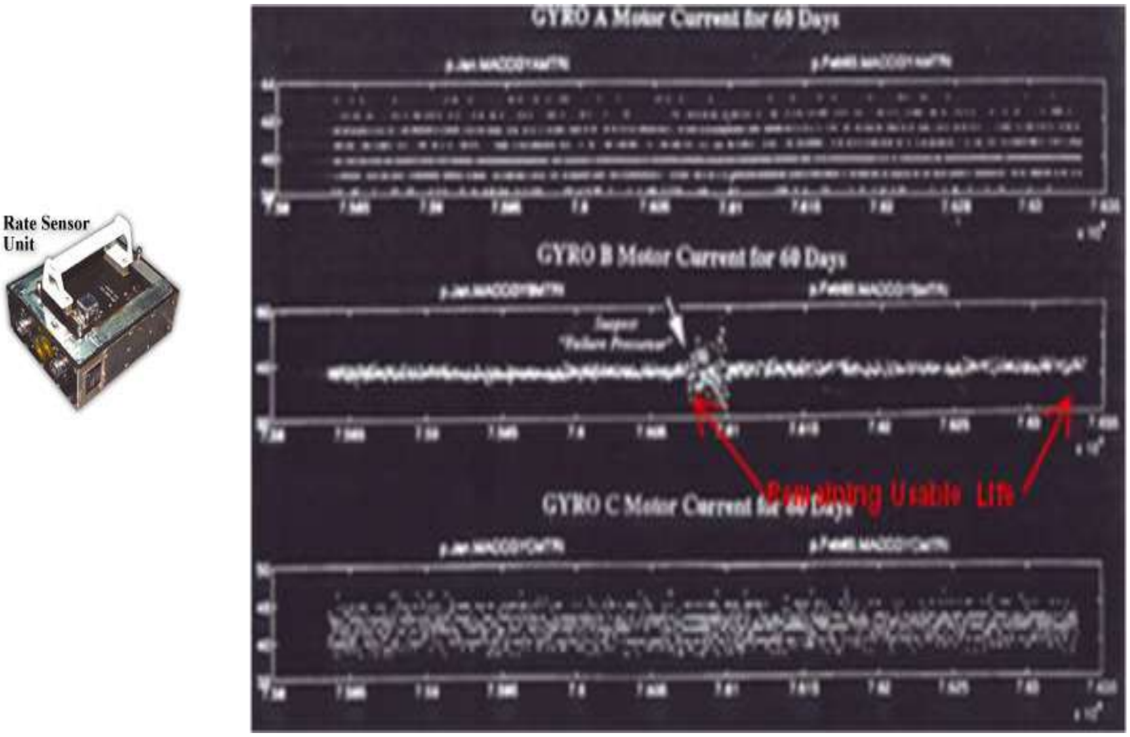


Figure 20. Results from Measuring the NASA EUVE Satellite Rate Gyro using Rate Gyro Motor Current Telemetry Transducer Output (Post Processing Results using Predictive Algorithms).

XI. Conclusion

The premature failures of ICBM’s in the 1950’s drove the adoption of tools, technologies and practices that result in producing equipment with reliability dominated by premature and surprise equipment failures in all operational environments. In the rush to produce vast quantities of weapons systems, the presence of accelerated aging preceding equipment failure was overlooked due to the many potential sources of transient and deterministic behavior. With procurement contracts including a financial penalty only for late delivery, it became highly advantageous to overlook all equipment transient behavior for equipment under test to minimize risk in missing the contractual delivery date. With the advancement of processor speed and stable test equipment and software, the transient behavior in test data can be associated with equipment end of life. The engineering practices necessary for meeting equipment performance and mission life require each to be measured and confirmed before use. The equipment remaining usable life can be measured after dynamic environmental acceptance testing is completed that measures and confirms equipment performance using predictive algorithms to measure equipment life. Equipment life can be measured by converting equipment analog telemetry into a measurement of mission life by identifying the presence of accelerated aging using predictive algorithms. A prognostic analysis uses predictive algorithms to convert analog equipment telemetry of any type to a measurement of equipment remaining usable life. Equipment with accelerated aging will fail prematurely with 100% certainty. Measuring equipment remaining usable life after confirming performance will allow the production of equipment that will not fail prematurely.

REFERENCES

1. Martin, James N, “Systems Engineering Guidebook: A Process for Developing Systems and Products”, CRC Press, Boca Raton FL, ISBN 0849378370.

2. Maral, Gerard, Bousquet, “Satellite Communications Systems,” John Wiley & Sons, West Sussex, England, ISBN 0471496545.
3. I-S Ching, “Crosslink, Aerospace Corporation’s Magazine of Advances in Aerospace Technology,” fall 2001, Aerospace Corporation, El Segundo, CA. pages 4-11.
4. Losik, Len, “Upgrading the Space Flight Factory Acceptance Testing for Equipment and Space Vehicle Design, Manufacture, Test and Integration,” AIAA Space 2009 Conference proceedings.
5. Tosney, William, Pavlica, Steven, “Crosslink, Aerospace Corporation’s Magazine of Advances in Aerospace Technology” "A Successful Strategy for Satellite Development and Testing” fall, 2005 issue, pages 6-10.
6. ”Markov Modeling for Reliability”, www.mathpages.com/home/kmath232/part 1/part 1.htm
7. Losik, Len, “Predicting Hardware Failures and Estimating Remaining-Usable-life from Telemetry,” SanLen Publishing, Sacramento, CA, 2004, ISBN 978-0-9767491-9-6
8. Failure Analysis, “Satellite and Launch Vehicle Prognostic Algorithms Users Guide”, V2.9
9. Losik, Len, Wahl, Sheila, Lewis, Owen, “Predicting Hardware Failures and Estimating Remaining-Usable Life from Telemetry”, Lockheed Martin Space Systems Company, Proceedings from the International Telemetry Conference, Las Vegas, NV, October, 1996
10. Cheng, Shunfeng and Pecht, Michael, “Multivariate State Estimation Technique for Remaining Usable Life Prediction of Electronic Products,” Association for the Advancement of Artificial Intelligence, CALCE, 2007.
11. Hamberg, Otto and Tosney, William, “The Effectiveness of Satellite Environmental Acceptance Tests” Aerospace Corporation. 1989.
12. Losik, Len, “Upgrading the Space Flight Factory Acceptance Testing for Equipment and Space Vehicle Design, Manufacture, Test and Integration,” AIAA Space 2009 Conference proceedings.
13. Tosney, William, Pavlica, Steven, “Crosslink, Aerospace Corporation’s Magazine of Advances in Aerospace Technology” "A Successful Strategy for Satellite Development and Testing” fall, 2005, pages 6-10.
14. Losik, Len, “Stopping Launch Pad Delays, Launch Failures, Satellite Infant Mortalities and On-Orbit Satellite Failures Using Telemetry Prognostic Technology,” Proceedings from the International Telemetry Conference, October 2007.
15. “Military Satellite Reliability, from 1959 to Today,” Futron Corporation, Bethesda, Maryland.