USING TELEMETRY TO CONFIRM EQUIPMENT PERFORMANCE AND MISSION LIFE REQUIREMENTS

Len Losik, Ph.D
Failure Analysis

ABSTRACT

The tools, technologies, practices, policies, procedures and procurement process developed and implemented over 50 years to produce highly reliable spacecraft and spacecraft subsystem equipment have yielded spacecraft and launch vehicles whose reliability is dominated by premature equipment failures and surprise equipment failures at yearly rates as high as 25% that increase risk and decrease safety, mission assurance and effectiveness. Large, complex aerospace systems such as aircraft, launch vehicle and satellites are subjected to most exhaustive and comprehensive acceptance-testing program at the factory that is also used in other industries and that also suffer from the high premature failure rates. Desired/required spacecraft equipment performance is measured confirmed during factory testing, however equipment usable/mission life requirement is not measured but calculated manually and so the spacecraft and launch vehicle equipment that will fail prematurely are not identified and replaced before use. Spacecraft equipment mission-life is 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 to identify the equipment that will fail prematurely include using a prognostic and health management (PHM) program. The PHM includes using predictive algorithms to convert equipment analog telemetry of any type into a measurement of equipment usable life by demodulating the telemetry behavior in time, amplitude, frequency and phase. The conversion of equipment analog telemetry from performance data to a measurement of usable life is done in a prognostic analysis. A prognostic analysis includes an engineering analysis that is shared with manufacturing and test, but results in premature equipment failures at rates as high as 70% once the equipment gets to space in space, but also includes a scientific analysis of the analog telemetry so that conjecture and speculation is not used to identify the presence as systemic noise.

INTRODUCTION

The systems engineering process was developed many decades ago after the development of the fleet of U.S. intercontinental ballistic missiles (ICBM) suffered from premature failure rates as high as 60%. [1,3] The U.S. government personnel that adopted the systems engineering method hoped the systems engineering method would allow the development and production of small, medium and large complex aerospace and defense systems that met all the requirements of the end user of the system. These included requirements for equipment and vehicle performance, reliability, serviceability and usable/mission life. The systems engineering method provides a process for the documentation for the concept development, requirements definition, identification and traceability, the traceability 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.

Today, spacecraft may have a mission life of 15 years and so identifying any equipment that will fail prematurely will increase the likelihood of meeting the 15-year mission life using a minimum of redundant equipment. [3] 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.

Table 1 Summary of Premature Equipment Failures on 60 Air Force Satellites during Dynamic Environmental Factory ATP and After Launch, On Orbit [11]

Air Force Satellite Program Name	No. of Satellites Tested per Program	Number of Equipment Failures/Test						No. of Satellites in Followed to Space	No. of Equipment Failure within 45 Days On-Orbit
		Acoustic	Thermal Cycling	Acoustic	Thermal Vacuum	Thermal Cycling	Acoustic		
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

The exact amount of expendable equipment is required to be known by all contract bidders because the cost of expendables greatly affects the final price, so knowing the exact amount to bid "levels the playing field" for the procurement of large complex systems.

Table 1 identifies the very high premature failure rate of spacecraft equipment procured by the Air Force that passed equipment-level ATP, integrated into a spacecraft, then failed during vehicle-level ATP, and then failed after arriving in space. The data in Table 1 was created to justify paying the high price of dynamic environmental ATP claiming that the large number of

failures that occurred before launch would occur in space decreasing spacecraft reliability substantially. The authors of the study that generated the data in Table 1 failed to note that the spacecraft equipment probability of failure after passing factory ATP twice was an unacceptable rate of 70% after 45 days. System and equipment usable/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. Figure 1 and Figure 2 identify the ~25% premature failure rate that have occurred on military, NASA and commercial space missions since the start of the space programs.
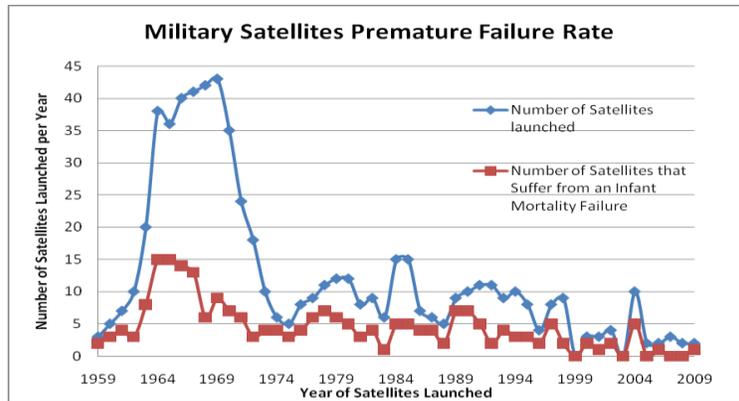

Figure 1 The Number Of Unclassified Military Satellites Launched And The Number Of Unclassified Military Satellites That Failed Prematurely From 1959 (Futron Corp. [13]).
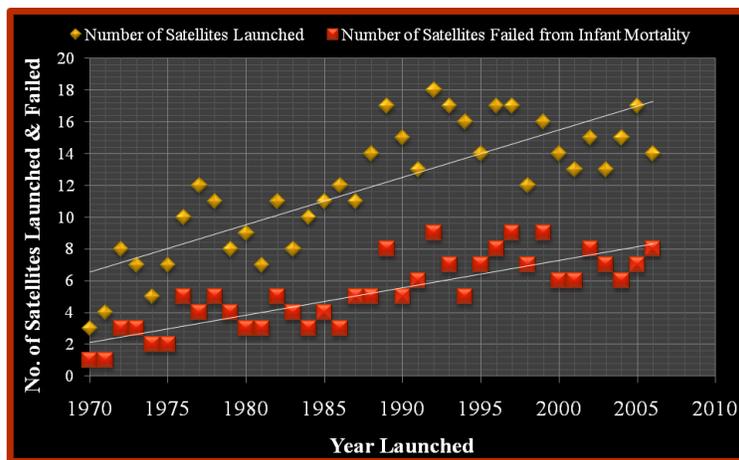

Figure 2 The Number Of Civil And Commercial Satellites Launched Per Year (Gold) And The Number That Failed Prematurely (Red). (Frost & Sullivan [12]).

EQUIPMENT PERFORMANCE MEASURING AND CONFIRMATION

Equipment and vehicle performance requirements are included in the procurement contract for all aerospace and defense equipment. [2] Equipment performance requirements will define how well equipment must function. When equipment is designed, it is designed to meet specific

performance requirements. [5]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. [4] If equipment fails five or more times, material control personnel will scrap the equipment and replace it, saying that its reliability is too low. When the same unit fails several times during manufacturing and test, it demonstrates that equipment failures are not random and thus do not have the Markov property (random and instantaneous) and should not be quantified using probability reliability analysis. [6]

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. Reliability when defined as a probability of failure and usable/mission life 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.
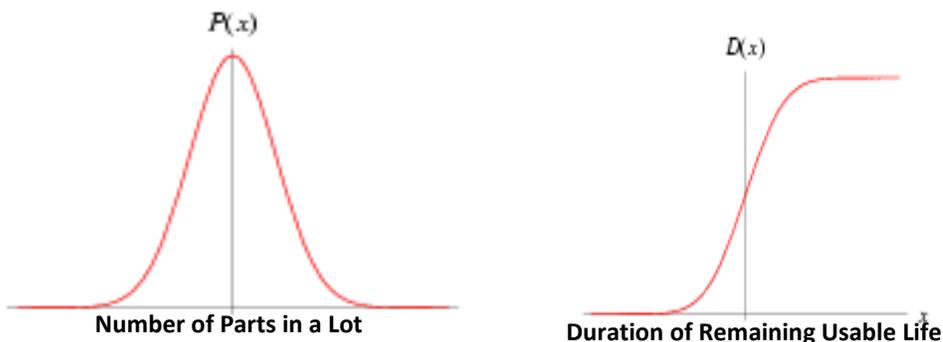

Figure 3 An Example of Proprietary Piece-Part Probability Distribution Function and Cumulative Distribution Generated By Parts Suppliers

Figure 3 are examples of proprietary probability distribution and cumulative 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 quantified by Aerospace Corporation, who publishes actual military spacecraft and launch vehicle reliability performance data infrequently. [3, 5, 11]

Figure 4 illustrates normal and parts with accelerated aging and why accelerated aging is visible in analog telemetry as a non-repeatable transient event (NRTE). [10] During the dynamic environmental factory acceptance test program (ATP), equipment performance is measured using a variety of methods including the evaluation of equipment analog telemetry. 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 during factory testing uses equipment telemetry. During testing, the equipment telemetry must remain within expected ranges. If it exceeds expected behavior, the equipment is repaired or replaced. This same telemetry can be used to measure equipment usable life using a prognostic analysis.
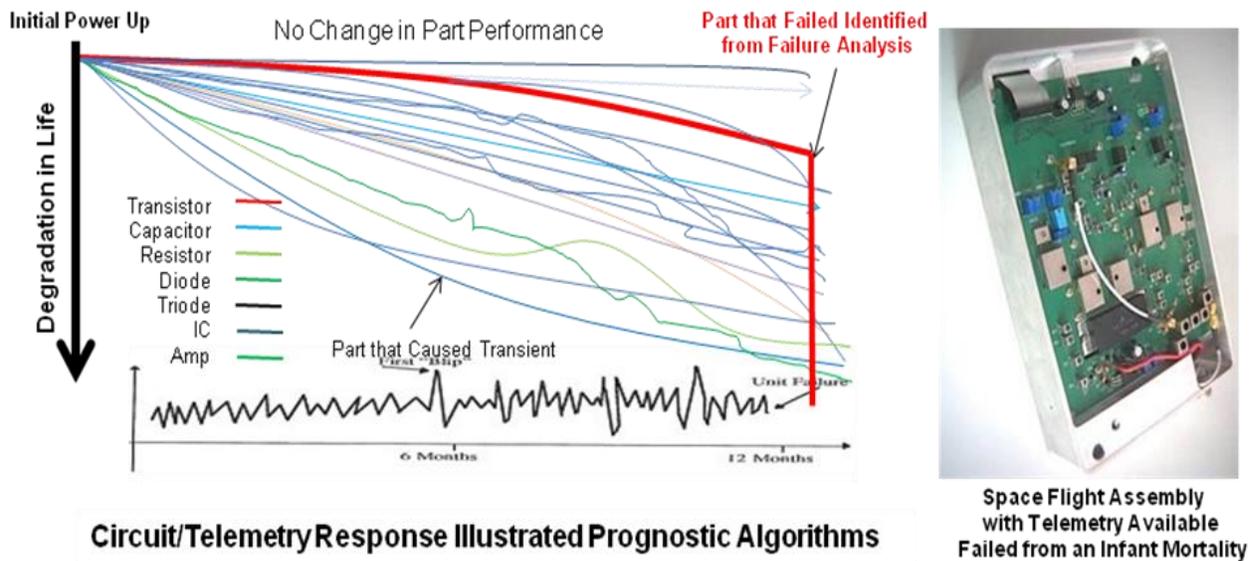

Figure 4 Why Predictive Algorithms Illustrate Accelerated Aging From A Part That Is Aging Prematurely In Functional Performance Missed in an Engineering Analysis

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 of analog 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.
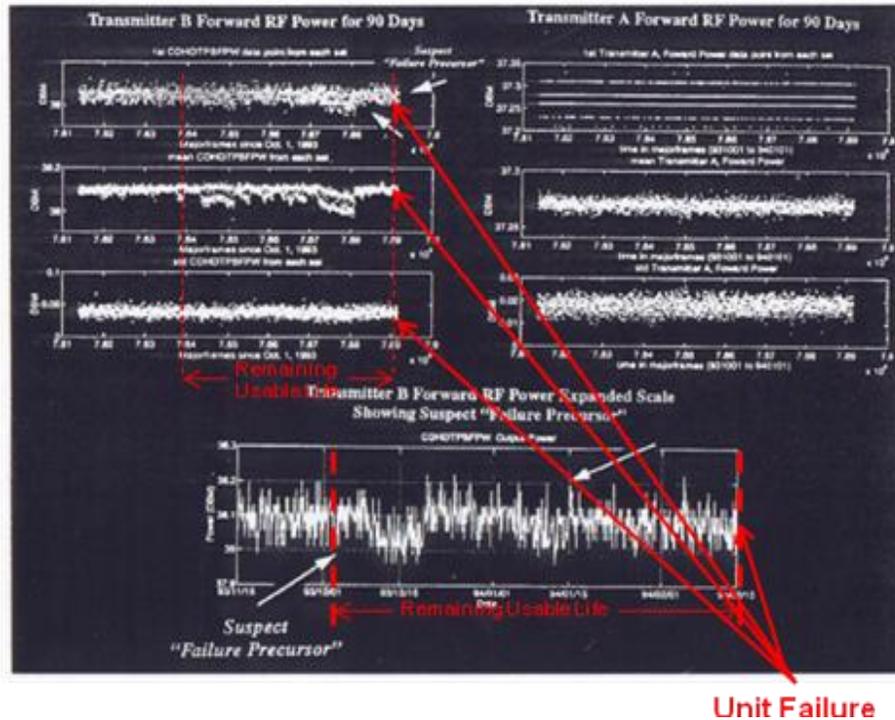

Figure 5 Results from the Prognostic Analysis Completed on the NASA EUVE LEO Science Satellite Motorola TDRSS RF Transmitter Unit A and Unit B Analog Telemetry

Figure 5 are the results from the prognostic analysis completed on the 2 Motorola TT&C RF Transmitters on the NASA EUVE LEO science satellite completed in 1995. Both EUVE Satellite TT&C transmitters were operated with a 100% duty cycle until TDRSS Transmitter B failed. [7] The transmitter RF Output measurement analog telemetry was available from both transmitters during the same period. A comparison of the telemetry behavior between Transmitter A and Transmitter B shows that there was no transient behavior present in the telemetry from the RF Transmitter unit A when a series of NRTEs was present in Transmitter B RF Output telemetry. The determination of the Transmitter B remaining usable life predicted using our proprietary cumulative distribution in Figure 6 was 5.1 months. The actual remaining usable life was 4.5 months.

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 from sources such as RF and electrical noise and accelerated aging.
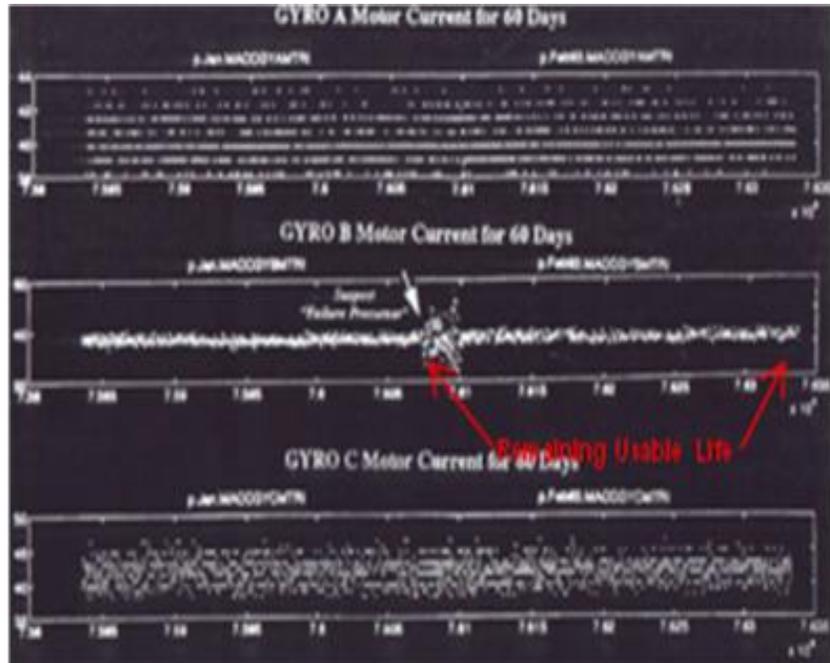

Figure 5 Results from the Prognostic Analysis Completed on the NASA EUVE Gyro A, B & C Motor Current Telemetry Illustrating the Presence of Accelerated Aging in Unit B Motor Current Telemetry Measurement.

Figure 5 is the results from the prognostic analysis completed on the 3 rate gyros used for attitude control and pointing on the NASA EUVE LEO space science satellite. The prognostic analysis illustrated the presence of accelerated aging in Gyro B motor current telemetry. The remaining usable life was predicted to be 5.1 months. The gyro output data had exceeded performance specifications 5 months before unit failure.

WHAT IS A PREDICTIVE ALGORITHM?

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. [8] 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.
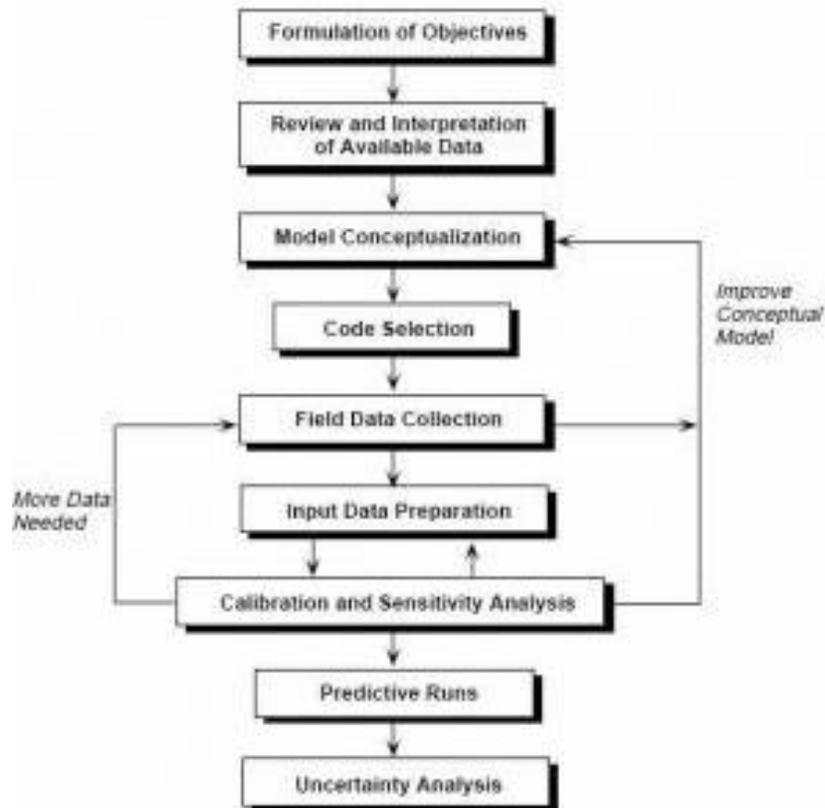

Figure 5 The Process for Developing a Predictive Algorithm

A diagnostic analysis uses analog telemetry to look backward in time to determine past equipment behavior. A prognostic analysis uses analog telemetry to look back in time to predict future equipment behavior with certainty. [12] 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 and so is a prognosis or a prediction of equipment behavior.

Predictive algorithms illustrate the presence of accelerated aging that is often identifiable in normal appearing data from fully functional equipment that will fail prematurely. [9] 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.

DETERMINING EQUIPMENT REMAINING USABLE LIFE (RUL) USING PREDICTIVE ALGORITHMS

Determining equipment 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]
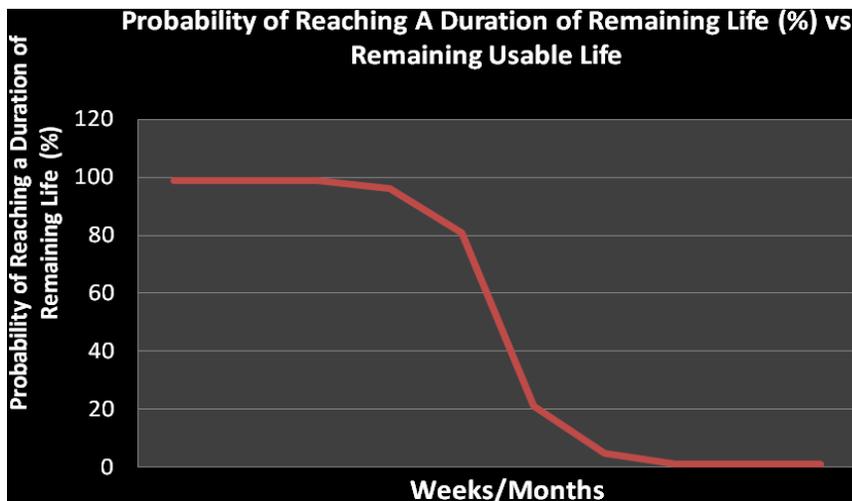
Figure 6 Our Proprietary Cumulative Distribution Used To Determine Equipment Time-To-Failure/Remaining-Usable-Life

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. "Military Satellite Reliability, from 1959 to Today," Futron Corporation, Bethesda, Maryland.