USING ANALOG TELEMETRY TO MEASURE USABLE LIFE INVASIVELY ON THE AIR FORCE'S NEXT GENERATION REUSABLE SPACE BOOSTER EQUIPMENT

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ABSTRACT

Measuring and confirming equipment usable life that passes dynamic environmental factory acceptance testing (ATP) will ensure no equipment will fail prematurely increasing safety and mission assurance on the Air Force's Next Generation Reusable Space Booster (NGRSB). The same analog telemetry generated and analyzed during ATP used to measure and confirm equipment performance per the procurement contract can serve both purposes. Since the NGRSB payload lift requirement is the same as the EELV, the need for exotic combinations of reusable and throwaway components is unnecessary unless they yield new level of reliability, maintainability and supportability. A prognostics and health management (PHM) program exploits the presence of non-repeatable transient events (NRTE) (a.k.a. accelerated aging) that is missed during any engineering analysis in equipment analog telemetry to calculate equipment remaining usable life/mission life. Without an invasive physical measurement of equipment usable life, satellite and launch vehicle equipment reliability is dominated by premature equipment failures. If the Air Force continues to calculate NGRSB equipment mission life on paper, the NGRSB equipment reliability will also be dominated by infant mortality failures just as all expendable launch vehicle equipment is. The Air Force's, Markov-based reliability paradigm used to procure Air Force satellites and launch vehicles, results in space mission infant mortality failure rate as high as 25%/year. According to the Aerospace Corporation, Air Force space vehicle equipment that passes both equipment level and vehicle level ATP has a 70% likelihood of failing prematurely within 45 days after arriving in space. If a PHM is used on the NGRSB, it stops premature failures and lowers life overall cycle cost providing superior reliability, maintainability, supportability and availability for future Air Force space missions that are too important and too expensive to fail prematurely.

INTRODUCTION

Current procurement contracts for launch vehicles and satellites do not require contracts to produce equipment that will not fail prematurely. The procurement contracts specify that some equipment can fail prematurely without penalty and so contractors supply equipment to the Air Force that will fail prematurely. Premature space mission failures occur because spacecraft equipment testing is used to identify the equipment that fails performance testing for replacement but does not measure equipment usable life. Since spacecraft equipment mission life is not measured before launch, but calculated on paper as part of the reliability analysis predictions using stochastic equations, spacecraft equipment should be failing prematurely. Using a PHM program similar to the one adopted by NASA[12] and the Air Force on the NGRSB may win DoD funding from the lower life-cycle cost, demonstrating that the Air Force will adopt the necessary advanced technologies, policies and practices for lowering NGRSB life-cycle cost while increasing spacecraft reliability, supportability and availability.

[14] The current space vehicle program reliability paradigm for success is that safety, maintainability and supportability are a function of reliability and redundancy. [3,4,5, 13] This paradigm produced many successful space missions but also produced the greatest catastrophic space vehicle failures and the premature failures of over 25% of all military, NASA and commercial space missions making getting to space and working in space highly unsafe. The new paradigm for mission success developed by the Air Force for the F-35 Joint Strike Fighter is that safety, maintainability and supportability are a function of reliability, redundancy and prognostics and health management (PHM) capabilities. [14] After educating NASA HQ on the benefits of the PHM program in 2009, NASA adopted this paradigm for all future aircraft. Failure Analysis has requested NASA HQ and MSFC Space Launch System Program Management personnel to adopt the same non-Markov paradigm on all future NASA space vehicles.

FIGURE 1 AN ARTIST CONCEPT FOR THE HIGHLY SUPPORTABLE AND MAINTAINABLE NEXT GENERATION AIR FORCE REUSABLE BOOSTER

The reason that the Air Force F-35 won DOD funding was the incorporation of the PHM and the same PHM can be leveraged to upgrade the logistics and supportability paradigm used in today's space systems. [15]The F-35 vehicle design drivers were reliability, supportability & maintainability, which all defined in its autonomic logistics system (ALS) that lowered the life-cycle cost of the F-35 JSF by 50% over existing fighter programs. This same cost savings would occur on the Air Force's proposed NGRSB.

Since the premature failure of spacecraft and launch vehicle subsystem equipment is proprietary information, it is not available to the public from the space systems builders. However, it may be available from official sources that do have contractual access to it. Based on industry sources such as Aerospace Corporation, Futron Corporation and Frost & Sullivan, the reliability of space systems is dominated by premature equipment failures, failures that occur weeks or months after beginning of life. When the reliability of equipment is dominated by premature failures, it demonstrates that the cause of premature failures is not understood, nor can they be stopped. The high number of premature space systems equipment failures and failures that occur during the normal lifetime and end of life requires an extensive and expensive logistics program and spares.

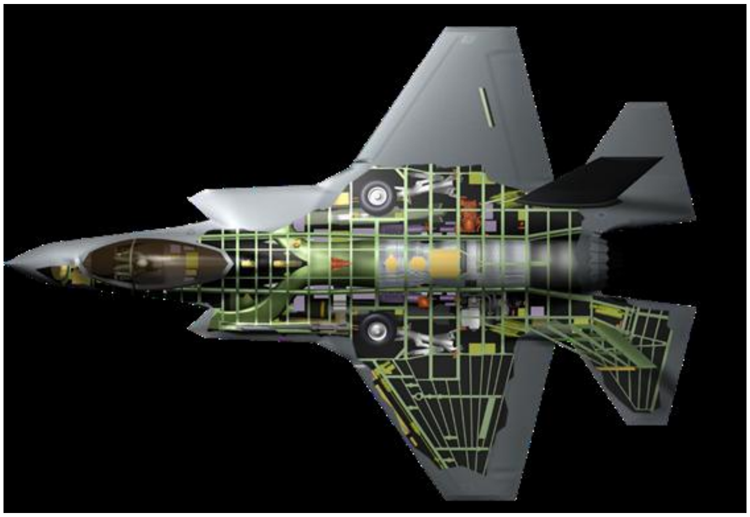


FIGURE 2 THE SYSTEMS ON THE AIR FORCE F-35 JOINT STRIKE FIGHTER SUPPORTED WITH A CONDITION-BASED MAINTENANCE (CBM) PROGRAM.

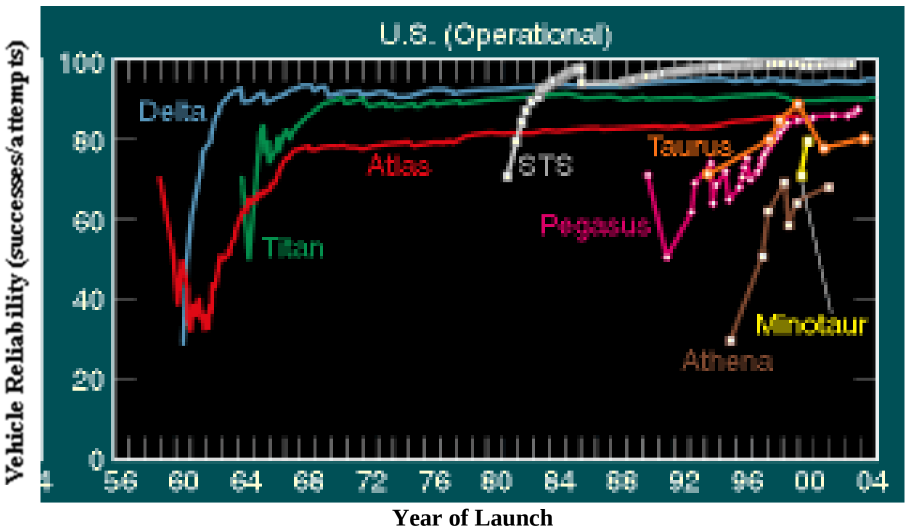
[9] To identify the cause of premature failures, the research was completed that identified equipment with parts suffering from accelerated aging caused when at least one part is aging prematurely. As a part ages prematurely, it causes non-repeatable transient event (NRTE) in its performance data including analog telemetry. [1] The use of telemetry is an important design requirement on all military satellites and launch vehicles. Although telemetry is not separated out as a single cost, its use impacts all major design drivers and system cost in many ways.

In the past, an NRTE was misdiagnosed as systemic noise and overlooked. Today, a prognostic analysis is used to illustrate and identify the presence of an NRTE in equipment performance data or telemetry. A prognostic analysis is an engineering analysis that uses past performance data to predict equipment remaining usable life. A prognostic analysis cannot use speculation to identify the cause of an NRTE that is present.

The heart of the condition-based maintenance program is the prognostic (scientific) analysis that is completed either automatically by the equipment with embedded, model-based or data-driven predictive algorithms. [11]Equipment with embedded predictive algorithms are considered intelligent equipment because they measure remaining usable life continuously and alert the right personnel through the on-board telemetry system which equipment will be failing in the near future and when. Intelligent equipment will improve the logistics of space systems and raise the reliability of space systems to a level never before achieved.

Predictive algorithms measure the equipment remaining usable life invasively using equipment analog telemetry or the measurement is completed manually by engineering personnel trained in completing scientific analysis of the data. For existing systems or equipment without embedded algorithms, the prognostic analysis is done manually by personnel trained in completing a scientific analysis of the engineering data from equipment. [6]A scientific analysis is necessary due to the addition of probability reliability analysis (PRA) in procurement contracts to quantify equipment mission life. PRA was added not because it was the right action to use, but because it was the best idea at the time. After adopting PRA in the space industry, an engineering analysis was allowed to use speculation to explain the behavior in test data used to measure equipment remaining usable life and/or guess at the sources of non-repeatable transient events that are used to measure remaining usable life. The current procurement contracts for military and NASA space systems only require equipment performance to be measured and confirmed by the contractor. The usable life is not measured but calculated as the reliability using stochastic equations in a PRA.

FIGURE 3 THE ACTUAL ACHIEVED RELIABILITY OF U.S. AND AIR FORCE ICBMS AND LAUNCH VEHICLES FROM 1957 THROUGH 2004 (AEROSPACE



CORPORATION, 2005).

[10] Predictive algorithms demodulate the telemetry or any equipment performance data in time, amplitude, frequency and phase to identify non-repeatable transient events that are tied to equipment end of life. The method that is used to determine remaining usable life is usually proprietary as are the predictive algorithms.

The demodulation of the data includes generating a baseline behavior profile, authenticating the data by identifying and eliminating any data from noise, expansion or contraction of the data, generating virtual data in the event insufficient data is available to generate a baseline. The prognostic analysis can be completed at the space vehicle factory, launch pad and so the algorithms are used to ensure the prognostic analysis is completed using only authenticated data.

[7] Today, the reliability of space vehicle equipment and space vehicles continues to be specified to contractors as a probability and so allows space vehicle suppliers to deliver some space vehicles that fail prematurely without financial penalty. If the space vehicle supplier misses the contractually agreed to delivery date, a financial penalty is levied on the supplier, thus motivating company test personnel to overlook test data that will slow down testing and increase risk of missing the delivery date.

Average Number of Mission Degrading Equipment Failures Occurring in Vehicle Level ATP After Equipment-Level ATP for 60 Air Force Satellite

Program	No. of satellites tested	Test failures/satellite						No. of satellites flown	Flight failures/ satellite
		Acoustic	TC	Acoustic	TV	TC	Acoustic		Early flight (first 45 days)
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	—	—	3.0	9.0	—	2	0.5
C	8	1.1	—	—	3.0	—	—	7	0.4
Total: 60								Total: 47	
Weighted averages		4.0							0.7

*Spacecraft only.
**Pre-environmental functional part of TC.

TABLE 1 RESULTS FROM AN AEROSPACE CORPORATION STUDY PROVING THAT DYNAMIC ENVIRONMENTAL FACTORY ACCEPTANCE TESTING PRODUCES SPACE VEHICLES WITH RELIABILITY DOMINATED BY PREMATURE FAILURES. [2]

USING A CBM WITH THE AIR FORCE REUSABLE SPACE BOOSTER

As a reusable aircraft, the RSB can benefit using the same logistical program adopted by the Air Force's F-35 Joint Strike Fighter in which the life-cycle cost was decreased by 50% by using a condition-based maintenance (CBM) program, also known as predictive maintenance program (PMP), over all previous jet fighter aircraft. The CBM program is being back-fitted on existing Navy and Air Force fighters that use a routine based maintenance program to lower the life-cycle cost. The F-35 won funding during peacetime with no super power enemy defined. It did so due to the inexpensive life cycle cost from the CBM. All future manned and unmanned fighter aircraft will use the CBM.

The NGRSB can benefit from a CBM by exploiting the key elements of the CBM, affordability, survivability, maintainability and supportability. This is done to enhance flight safety, increase system availability, eliminate false alarms such as CND's and RTOK's during maintenance and reduce life cycle costs.

Autonomic Logistics (AL): The CBM autonomic logistics system monitors the health of the aircraft systems in flight; downlinks the information to the ground. The data trigger personnel, equipment and parts to be pre-positioned for quick turnaround of the aircraft. [8] The AL is a natural evolution of legacy diagnostic capabilities coupled with the added functions, capabilities, and benefits offered by new space flight proven technologies.

FIGURE 4 AN ARTIST'S CONCEPT FOR THE AIR FORCE'S REUSABLE SPACE BOOSTER TO REPLACE THE EELV SHOULD BE MAINTAINED AS THE F-35 JSF

Ultimately, this automated approach results in higher launch rates necessary to support planned scheduled flight rates and increases in military space missions without any improvements. Autonomic logistics is also something of a mind reader. Through a system called prognostics and health management, computers use accumulated data to keep track of when a part is predicted to fail. With this aid, maintainers can fix or replace a part *before* it fails and keep the aircraft ready to fly. Like the rest of the program, the autonomic logistics system is on a fast track. It has to be available to support the air vehicle during operational test and evaluation.

Because logistics support accounts for two-thirds of a reusable booster's life cycle cost, a reusable space booster will achieve unprecedented levels of reliability and maintainability, combined with a highly responsive support and training system linked with the latest in information logistical information and technology. The spacecraft will be ready for flight anytime and anywhere. Autonomic Logistics (AL) is a seamless, embedded solution that integrates current performance, operational parameters, current configuration, scheduled upgrades and maintenance, component history, predictive diagnostics (prognostics) and health management, and service support based on the CBM program used on the Air Force's F-35. Essentially, AL does invaluable and efficient behind-the-scenes monitoring, maintenance and prognostics to support the aircraft and ensure its continued good health.

GOALS OF A PHM PROGRAM

- Enhance Space Vehicle Safety, Reliability and Availability – The engineering and management decisions are different for preventing a failure rather than reacting to a failure after one occurs.
- Reduce Maintenance Manpower, Spares & Repair Costs – A 50% reduction in cost can be expected when adopting a CBM over a routine maintenance program as achieved on the Air Force's F-35 JSF.
- Maximize Lead Time For Maintenance & Parts Procurement – The equipment informs operational personnel when it needs replacing and when it will fail.
- Eliminate Scheduled Inspections and Enable CBM – Actions are needed only when the equipment informs personnel.

  - Opportunistic maintenance reduces A/C down time
- Provide Real Time Notification& Health Reporting
  - Only informs ground personnel what NEEDS to be known immediately
  - Downlink info & "answers" in-flight
  - Informs maintenance & auto-log of the rest
- Aids in Decision Making & Resource Management – The equipment is the source of information for determining what equipment needs to be replaced and when rather than a schedule for replacement, replacing only equipment that needs to be replaced.
- Reduce Life Cycle Costs - Personnel are deployed and actions taken only when needed based on the intelligent equipment.
- Eliminate CNDs & RTOKs – Non-repeatable transient events are tied to equipment end of life and not systemic noise.
- Detect Incipient Faults & Monitor until Just Prior to Failure – Equipment change out can be conducted at the time of failure or prior to the failure to manage failures to a positive conclusion.
- Identify Potentially Catastrophic Failures Weeks/Months Before They Occur – Allows time for contingency procedures to be developed and rehearsed before execution/implementation, stopping surprise equipment failures that may increase risk of total mission failure due to surprise unexpected equipment responses that may be hidden during recovery procedures implementation.
- Uses Limited Specialized Sensors – Uses existing telemetry system sensors and data links.
- Take Max Advantage of the "Smart" Digital Spacecraft – Allows leveraging the digital data communications systems.

PHM CONSTITUENT FUNCTIONS AND PROCESSES

- Fault Detection – Identifies that equipment will experience a disruption of service sometime in the near future.
- Fault Isolation – Identifies what equipment will experience a disruption of service in the near future.
- Advanced Diagnostics – Identifies the equipment with at least one part suffering from accelerated aging.
- Predictive Diagnostics/ Remaining Useful Life Predictions – Predicts remaining usable life of equipment with at least one part suffering from accelerated aging.
- Component Life Tracking – Allows the parts that experience accelerated aging to be identified and tracked.
- Performance Degradation Trending – Trend equipment analog telemetry to ensure normal aging occurs.
- False Alarm Mitigation – Using only flight proven predictive algorithms means that there will be no false alarms.
- Warranty Guarantee Tracking – Provides the data enabling new business practices such as eliminating product/equipment warranty.
- Selective Fault Reporting
  - Only tells ground personnel what needs to be known and action to be taken immediately

- Aids in Decision Making & Resource Management
- Fault Accommodation and Possible Reconfiguration – Automatic redundancy switching when necessary.
- Information Management
  – Right info to right people at right time

MAINTENANCE PROGRAMS

Reactive Maintenance Program - Maintenance is performed only after a machine fails or experiences problems.

Preventive Maintenance Program - Preventive maintenance can be described as the maintenance of equipment or systems before faults occur. It can be divided into planned maintenance and condition-based maintenance. The main difference is determination of maintenance time, or determination of moment when maintenance should be performed. While preventive maintenance is generally considered worthwhile, there are risks such as equipment failure or human error involved when performing preventive maintenance, just as in any maintenance operation. Preventive maintenance as scheduled overhaul or scheduled replacement provides two of the three proactive failure management policies available. Preventive maintenance is conducted to keep equipment working and/or extend the life of the equipment while corrective maintenance, sometimes called "repair," is conducted to get equipment working again.

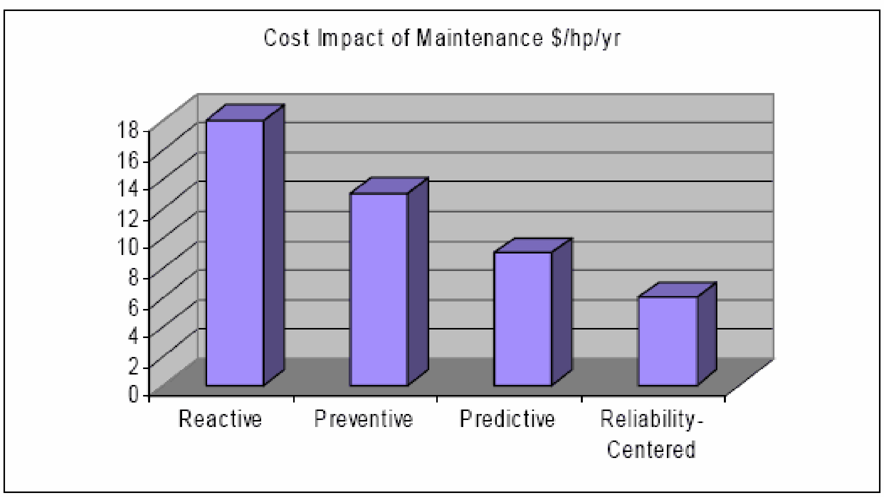


FIGURE 5 THE RELATIVE COST OF DIFFERENT MAINTENANCE PROGRAMS. (APPLEBY RELIABILITY, 2012) [16]

The goal of maintenance is to avoid or mitigate the consequences of failure of equipment. This may be done by preventing the failure before it occurs. It is designed to preserve and restore equipment reliability by replacing worn components before they fail. Preventive maintenance activities include partial or complete overhauls at specified periods, oil changes, lubrication and so on. In addition, workers can record equipment deterioration so they know to replace or repair worn parts before they cause system failure. The ideal preventive maintenance program would prevent all equipment failure before it occurs.

Predictive Maintenance Program - Predictive maintenance techniques help determine the condition of in-service equipment to predict when maintenance should be performed. This approach offers cost savings over routine or time-based preventive maintenance, because tasks are performed only when warranted. The main value of predicted maintenance is to allow convenient scheduling of corrective maintenance, and to prevent unexpected equipment failures. The key is "the right information in the right time." By knowing which equipment needs maintenance, maintenance work can be better planned (spare parts, people etc.) and what would have been "unplanned stops" are transformed to shorter and fewer "planned stops," thus increasing plant availability. Other advantages include increased equipment lifetime, increased safety, fewer surprise accidents with negative impact, and optimized spare parts handling.

Condition-based maintenance, attempts to evaluate the condition of equipment by performing periodic or continuous (online) equipment condition monitoring. The ultimate goal of predictive maintenance is to perform maintenance at a scheduled point in time when the maintenance activity is most cost-effective and before the equipment loses performance within a threshold. This is in contrast to time- and/or operation count-based maintenance, where a piece of equipment is maintained whether it needs it or not. Time-based maintenance is labor intensive, ineffective in identifying problems that develop between scheduled inspections, and is not cost-effective. The "predictive" component of predictive maintenance stems from the goal of predicting the future trend of the equipment's condition. This approach uses principles of statistical process control to determine at what point in the future maintenance activities will be appropriate. Most predictive analysis is performed while equipment is in service, thereby minimizing disruption of normal system operations.

Reliability-Centered Maintenance Program - Emphasizes the use of predictive maintenance techniques in addition to traditional preventive measures. When properly implemented, RCM provides the tools for achieving lowest asset Net Present Costs (NPC) for a given level of performance and risk. One area that many times is overlooked is how to, in an efficient way, transfer the predictive maintenance data to a Computerized Maintenance Management System (CMMS) system so that the equipment condition data is sent to the right equipment object in the CMMS system in order to trigger maintenance planning, execution and reporting. Unless this is achieved, the solution is of limited value, at least if the predictive maintenance solution is implemented on a medium to large system with tens of thousands of pieces of equipment.

CONCLUSION

Predictive algorithms allow a scientific analysis to be completed using existing equipment performance data including telemetry to measure remaining usable life, allowing a condition-based maintenance program to be employed, which identifies the right equipment needed at the right time, thus stopping equipment replacement based on a schedule rather than actual wear-out. The Air Force F-35 JSF program decreased the life cycle cost by 50% over existing fighter programs winning DOD funding for a jet fighter during peacetime with no identified super power enemy. Using the CBM on existing space systems by back fitting equipment with predictive algorithms or by completing a prognostic analysis manually will improve space logistics reliability, maintainability and supportability and decrease space systems life cycle cost by as much as 50% just as the F-35 JSF life cycle cost was decreased by 50%.

Using a CBM on new space systems such as the Air Force RSB will allow the Air Force to procure space systems and space systems equipment that will not fail prematurely and will exceed mission life, allowing fewer spacecraft to be procured, lowering overall space program cost and decreased the demands on space systems budgets.

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