Benefits to Space Logistics and Supportability Using Intelligent, Decision-Making Self-Prognostic Equipment

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Abstract -- **To improve logistics and supportability for existing and future space systems, the key design driver needs to be changed from equipment and system performance to equipment usable life as is done on Air Force fighter aircraft and the new Boeing commercial passenger aircraft. Today, all space system procurement contracts require equipment performance to be measured and confirmed before purchase and delivery, but the same procurement contracts do not require the usable life of the equipment to be measured and confirmed resulting in equipment whose reliability/usable life is dominated by premature (infant mortality) failures. Premature failures drive space system logistics and supportability, increasing cost and decreasing serviceability and availability. However, reliability-centered systems measure equipment usable life to identify any equipment that suffer from an infant mortality for replacement before delivery, offer superior system availability, maintainability, reliability and supportability along with meeting or exceeding equipment and system performance requirements. Today, the expensive and outdated routine maintenance programs can be replaced by the cost-saving, condition-based maintenance (CBM) program. The CBM includes using intelligent, decision-making self-prognostic equipment that decrease increases availability while lowering the life cycle cost. The CBM is ideal for improving the logistics, availability and supportability for existing and tomorrow's space exploration programs that benefit financially from having the right equipment and supplies available at the right time.**

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I. INTRODUCTION

The Air Force is developing a reusable space booster (RSB) to replace the Air Force's EELV that is supplied by ULA hoping to decrease the cost per launch by 50%. After the two companies that originally supplied the EELV was allowed to merge, recent cost quoted to the customer for an EELV launch has exceeded all worse case cost projections. The original pricing proposed by the suppliers of the EELV was based on sharing the non-recurring engineering costs with commercial satellite launches that did not materialize and so the Air Force has had to pay almost all of these costs.

The initial cost to launch an EELV in 1998 was set at $72M. Recent prices to launch military satellites using the EELV have been as high as $475M justifying the Air Force development of an alternative space booster and motivating several companies to offer alternative launch vehicles to the Air Force and NASA at much lower prices than the EELV. .

The RSB payload lift capability requirement has been defined as that of the EELV. The only other RSB requirements that have been identified are the availability and the reliability offering the Air Force an opportunity to employ a reliability-centered program using CBM rather

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than exotic performance-based RSB using a 1950's era routine maintenance program..

Figure 1. The Air Force/Boeing Reusable Spacecraft Procured from NASA.

Figure 1 is the reusable spacecraft the Air Force purchased from NASA to obtain operational experience on a reusable launch vehicle. This experience will allow the Air Force to define the design requirements for its new reusable space booster that will replace the EELV.

However, recent published papers by Aerospace Corporation detailed exotic rocket engine combinations for extreme Isp performance rather than meeting the identified reliability or availability requirements. This is because space systems design engineers do not need to be conversant in reliability engineering since reliability engineers are used to calculate the system reliability, using customer provided stochastic equations. Thus, space system drivers usually include performance related items such as weight, power, lift capability, growth potential and cost.

The Air Force proposed reusable space booster (RSB) is being studied by several agencies within the Air Force hoping to use vehicle Isp performance as the RSB design driver rather than reliability, maintainability, serviceability and supportability. Figure 1 is the Air Force's classified, Boeing/NASA X-37, manned spacecraft launched several times to obtain flight and handling characteristics performance data for the future reusable space booster traveling at mach 25-reentry velocity hoping to obtain information that will allow the Air Force to quantify flight behavior to include in the contractor procurement documents for the RSB.

Figure 2 is an artist concept for the Air Force's $25B unmanned reusable space booster maintained like the F-35 JSF employing intelligent, self-prognostic equipment throughout with a system availability and supportability exceeding the EELV, costing 75% less per launch than the EELV.

Only the RSB availability requirement has been defined by the Air Force with the payload lift capability to LEO defined as the same as the EELV and so studying extreme payload lift performance options is not necessary for the RSB but will probably be done because the design engineers are performance based and not reliability/availability based.

The RSB would function as an aircraft during a brief portion of its flight and as a space booster to get its payload to space. 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. [12]

Figure 2. An Artist Concept for the Air Force's Next Generation Reusable Space Booster.

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 much lower life cycle cost from the F-35 CBM.[13] All future manned and unmanned fighter aircraft will use the CBM.

Based on the cost savings the Air Force has predicted to occur on the F-35 program, the Air Force is back-fitting it older fighter aircraft with embedded predictive algorithms to measure equipment remaining usable life. The Air Force can back-fit its existing fleet of launch vehicles with the experience it will gain by adopting a CBM program on its RSB.

II. THE CBM PROGRAM USED ON THE AIR FORCE'S F-35 JOINT STRIKE FIGHTER FOR USE ON THE RSB

Figure 3 is the intelligent, decision-making prognostic-based; reliability centered $300M Air Force F-35 Joint Strike Fighter. It is designed to use a condition-based maintenance program employing embedded predictive algorithms in all electrical and mechanical equipment lowering with projected life cycle cost savings to be near by 50% by using equipment that does not fail prematurely. This same CBM and prognostic-based equipment can be employed on the Air Force's RSB to increase safety and mission assurance and lower launch costs since the RSB will be operated much as a fighter with quick turn-arounds that are better accomplished by personnel who have maintained deployed fighter aircraft.

Figure 3. The Intelligent, Prognostic-Based, Reliability Centered $300M Air Force F-35 Joint Strike Fighter Designed to use a Condition-Based Maintenance Program

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.

Commonality: Commonality is the key to affordability – on the assembly line; in shared platforms; in common space systems that enhance maintenance, field support and service interoperability; and in almost 100 percent commonality of the avionics suite. Component commonality across all three variants reduces unique spares requirements and the logistics footprint. In addition to reduced flyaway costs, the CBM is designed to integrate new technologies easily during its entire life cycle.

Autonomic Logistics (AL): The CBM autonomic logistics system monitors the health of the aircraft systems in flight; downlink that information to the ground; and trigger personnel, equipment and parts to be pre-positioned for quick turnaround of the aircraft. 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.

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 boosters 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 fight anytime and anywhere.

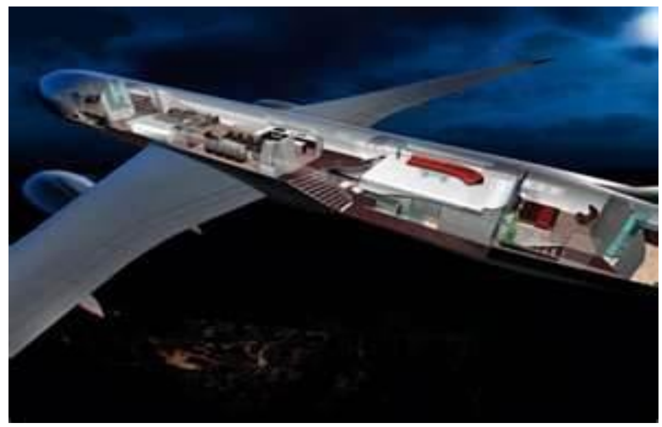

Figure 4. The New Boeing 787 Series of Commercial Aircraft Designed using a PHM Program and Employing a Condition-Based Maintenance Program to Increase Passenger Safety and Lower Aircraft Life Cycle Cost.

III. WHY LOGISTICS, SUPPORTABILITY, RELIABILITY, SERVICEABILITY AND AVAILABILITY SHOULD REPLACE EQUIPMENT AND SYSTEM PERFORMANCE AS DESIGN DRIVERS

Although rocket scientists and engineers can design performance-based systems, they are not trained to design reliability-centered systems. The design drivers for a space launch system generally include the maximum payload size and weight, and system reliability and availability through supportability. Increases in reliability using probability reliability analysis to quantify equipment reliability are made by the reliability engineer who selects more expensive, better screened parts (a.k.a. space qualified), more equipment for more redundancy. Better screen parts do not eliminate parts with accelerated aging. These parts are identified by completing a prognostic analysis, illustrating the accelerated aging in performance data exhibited by parts that age prematurely. [9]

At most large aerospace companies and organizations, design engineers are physically separated from the reliability and logistical engineers. The design engineer is responsible for the space systems physical design and performance while the reliability and logistic engineers calculate the reliability and logistics on paper almost independently from the design engineer, using stochastic equations provided by the procurement contract in a probability reliability analysis. All the technical information needed by the reliability and logistical engineers is provided in the procurement contract and so little technical interchange is necessary with the design engineers worried about performance.

Quantifying the turnaround time for the subsequent launch will be important to the RSB designers. The CBM allows the equipment to self-prognose and identify only the equipment that needs to be replaced be ordered and replaced and this information can be available to the maintenance personnel prior to the return of the RSB for landing using the on-board telemetry system [1][10]. Although the weight of the payload forces the RSB to be launched in a vertical position to minimize the weight and size of the RSB landing gear, much as the NASA Space Shuttle employed, the RSB will be able to utilize the CBM. A CBM allows the fastest turn around similar to the turnaround time for an Air Force F-35 JSF meeting the expected high availability requirement for the RSB.

Table 1. Results from an Aerospace Corporation Study Proving Satellite Reliability is Dominated by Premature Equipment Failures.

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.

[2] Table 1 includes the results from a 1989 Aerospace Corporation study that was used to justify the expensive factory acceptance-test program used on every Air Force satellite to increase spacecraft equipment reliability. Currently military and commercial satellites achieves a 75% mission success record.[3] The study included 60 Air Force procured satellites from a variety of suppliers that did not employ intelligent, self-prognostic equipment and showed that the reliability of Air Force procured spacecraft reliability is dominated by premature failures. Forty-seven of the sixty satellites in the study were launched and the premature equipment failures were included in Table 1.

Since the premature failure of spacecraft and launch vehicle subsystem equipment is company proprietary information, it is not generally 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 NASA, [5] Aerospace Corporation [4], Futron Corporation[3] and Frost & Sullivan,[11] 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.

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 make decisions related to replacement by continuously measuring remaining usable life and they alert the right personnel through the on-board telemetry system in the near future. Intelligent equipment will improve the logistics of space systems and raise the reliability of space systems to a level never before achieved.

IV. THE RELIABILITY-CENTERED SPACE SYSTEM

With a few exceptions, preventive maintenance has been considered the most advanced and effective maintenance available for use by many organizations. A Preventive Maintenance program (PMP) is based on the assumption of a "fundamental cause-and-effect relationship between scheduled maintenance and operating reliability. This assumption was based on the intuitive belief that as mechanical parts wear out, the reliability of any equipment is related to its operating age. It therefore follows that the more frequently equipment was repaired or overhauled, the better protected it was against the likelihood of failure. The problem that drove the cost was in determining what age was necessary to assure reliable operations.

Some experts reached the conclusion that, a maintenance policy based exclusively on a maximum operating duration would have little or no effect on the failure rate no matter what the limit. In separate independent studies, it was found that a difference existed between the perceived and the intrinsic design life for the majority of equipment and components. It was discovered that in many systems, equipment greatly exceeded the perceived or stated design life, while failed prematurely.

Figure 5. The Intelligent, Decision Making, Self-Prognostic, Reliability-Centered Army/Rockwell Collins Shadow UAV using Embedded Predictive Algorithms to Predict Equipment Failures.

Figure 4 is the intelligent, decision-making self-prognostic, reliability-centered army/Rockwell Collins Shadow UAV using embedded predictive algorithms from its PHM program to measure on-board equipment remaining usable life for down-linking in real-time to shadow ground crew.

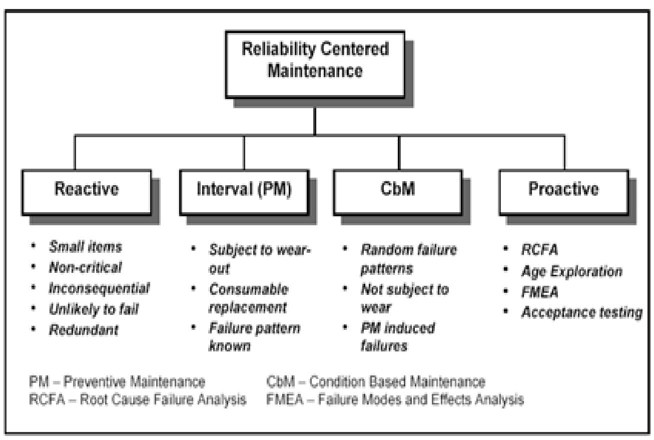

Figure 6. Components of a Reliability Centered Maintenance Program.

Reliability-Centered Maintenance (RCM) programs provide the optimum mix of reactive, time- or interval-based, condition-based and proactive maintenance practices. The application of each strategy is shown in Fig. 1. These principal maintenance strategies, rather than being applied independently, are integrated to take advantage of their respective strengths in order to maximize facility and equipment reliability while minimizing life-cycle costs.

RCM includes reactive, time-based, condition-based and proactive tasks. In addition, a user should quantify the system's boundaries and performance envelopes, system/equipment functions, functional failures, and failure modes, all of which are critical components of the RCM program.

Preventive Maintenance (PM) programs assumes that failure probabilities can be determined statistically for individual machines and components, which is not true, and parts can be replaced or adjustments can be performed in time to preclude failure. For example, a common practice has been to replace or renew bearings after so many operating hours assuming that bearing failure rate increases with time in service.

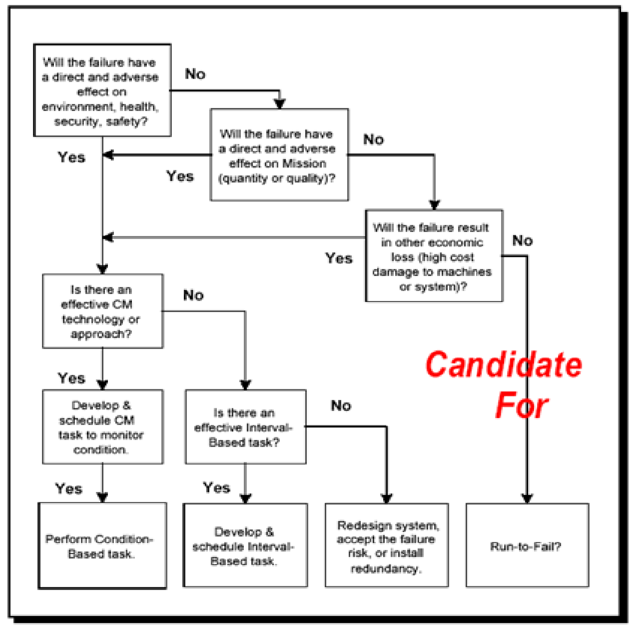

Figure 7. An Example of a Reliability Centered Maintenance (RCM) Logic Tree.

Fortunately, advances using a prognostic and health management (PHM) program have made it possible in many cases to identify the precursors of failure, quantify equipment condition and schedule the appropriate replacement with a higher degree of confidence than was possible when performing strictly interval-based maintenance relying upon usually erroneous estimates of when a component might fail. It has been discovered that there are many different equipment failure characteristics, only a small number of which are age- or use-related.

This new knowledge has increased the emphasis on Condition Monitoring (CM), often referred to as Condition-Based Maintenance (CBM), which has caused a reduction in the reliance upon time-based preventive maintenance.

It should not be inferred from the above that all interval-based maintenance should be replaced by condition-based maintenance. In fact, interval-based maintenance is appropriate for those instances where abrasive, erosive or corrosive wear takes place, material properties change due to fatigue, embrittlement, etc. and/or a clear correlation between age and functional reliability exists.

In addition, for those systems or components where no failure consequences in terms of mission, environment, safety, security or Life-Cycle Cost (LCC) exist, maintenance should not be performed, i.e., the equipment should be run to failure and replaced.

The concept of RCM has been adopted across many government and industry operations as a strategy for performing maintenance. RCM applies maintenance strategies based on consequence and cost of failure. In addition, RCM seeks to minimize maintenance and improve reliability throughout the life cycle by using proactive techniques such as improved design specifications, integration of condition monitoring in the commissioning process, and the Age Exploration (AE) process.

V. What is a Prognostic & Health Management Program?

PHM is an enhanced diagnostic process for determining the state of a component to perform its function(s), allows a high degree of fault detection and fault isolation capability with very low false alarm rate. It leverages the presence of accelerated aging in equipment performance data, including equipment analog telemetry, to identify the equipment that will pass ATP and fail prematurely after arriving in space.[6] A prognostic analysis measures actual material condition or state of health, which includes predicting failures, determining the remaining performance life remaining of components.[14] Health management systems make intelligent, informed, appropriate decisions about maintenance and logistics actions based on diagnostics/prognostics information, available resources and operational demand.

VI. Features of the PHM

- Enhance Space Vehicle Safety, Reliability and Availability – The engineering and management decisions are different for preventing a failure rather than react 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 Enables 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 is 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 in necessary, 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.

VII. 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

VIII. MAINTENANCE PROGRAMS

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.

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 fault 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.

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.

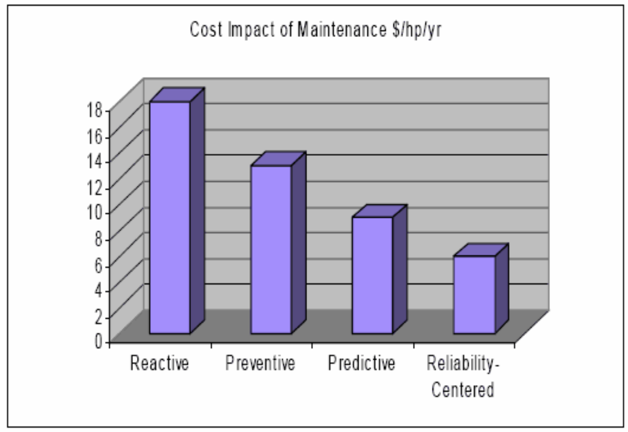

Figure 8. The Cost Comparison between Different Maintenance Programs. (Appleby Reliability, 2012) [16]

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 and so the results are unrelated to actual life. 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 pieces of equipment.

IX. SPACE VEHICLE DESIGN DRIVERS

Although rocket scientists and engineers can design performance-based systems, they are not trained to design reliability-centered systems. The design drivers for a space launch system generally include the maximum payload size and weight, and system reliability and availability through supportability. Increases in reliability using probability reliability analysis to quantify equipment reliability are made by the reliability engineer who selects more expensive, better screened parts (a.k.a. space qualified), more equipment for more redundancy. The only requirements defined for the Air Force RSB has been the payload capability to match the EELV, vehicle availability and reliability.

Quantifying the turnaround time for the subsequent launch will be important to the designers. The CBM allows the equipment to self-prognose and identify only the equipment that needs to be replaced be ordered and replaced and this information can be available to the maintenance personnel prior to the return of the RSB for landing using the on-board telemetry system. Although the weight of the payload forces the RSB to be launched in a vertical position to minimize the weight and size of the RSB landing gear, much as the NASA Space Shuttle employed, the RSB will be able to utilize the CBM. A CBM allows the fastest turn around similar to the turnaround time for an Air Force F-35 JSF meeting the expected high availability requirement for the RSB.

X. THE RELIABILITY-CENTERED MAINTENANCE PROGRAM PRINCIPLES

- RCM is Function Oriented—RCM preserves system or equipment function, not just operability for operability's sake. Redundancy of function, through multiple pieces of equipment, improves functional reliability but increases life cycle cost in terms of procurement and operating costs.

- RCM is System Focused—RCM is more concerned with maintaining system functionality than with individual component function.

- RCM treats failure statistics in an actuarial manner. The relationship between operating age and the failures experienced is important. RCM is not overly concerned with simple failure rate; it seeks to know the conditional probability of failure at specific ages (the probability that failure will occur in each given operating age bracket is ignored).

- RCM Acknowledges Design Limitations. One RCM objective is to maintain the inherent availability of the equipment, recognizing that changes in inherent reliability are the province of design rather than of maintenance. Maintenance only maintains the level of reliability for equipment that was provided for by design. However, RCM recognizes that feedback from the PHM improves on the original design life and safety. In addition, RCM recognizes that an increase often exists from the calculated design life and the actual design life.

- RCM is driven by safety, security and economics—not performance, safety and security must be ensured at any cost so cost-effectiveness becomes a criterion.

- RCM defines failure as "Any unsatisfactory condition"—Therefore, failure may be either a loss of function (operation ceases) or a loss of acceptable quality (operation continues but impacts quality).

- RCM addresses the failure mode and consider the failure mode characteristics.

- RCM reduces the number of failures while lowering the program cost.

- RCM Acknowledges Three Types of Maintenance Tasks: The time-directed (preventive maintenance), condition-directed (CM) and failure finding (one of several aspects of Proactive Maintenance). Time-directed tasks are scheduled when appropriate. Condition-directed tasks are performed when the equipment identifies a conditions indicate and actions are needed. Failure-finding tasks detect hidden functions that have failed without giving evidence of pending failure. Additionally, performing no maintenance, Run-to-Failure, is a conscious decision and is acceptable for some equipment.

- RCM is an intelligent, decision-making system, equipment generates and gathers and remembers data from the results achieved and feeds this data back to improve the design and future maintenance.

XI. SPACE PROGRAMS THAT USED PREDICTIVE ALGORITHMS TO MEASURE EQUIPMENT USABLE LIFE

[14] The current paradigm for space systems mission success is defined as space vehicle safety; maintainability and supportability are a function of reliability$_{act}$ (R_{act}) and

redundancy. R_{act} is the reliability based on the ratio of successes to attempts. Reliability$_{cal}$ (R_{cal}) is the reliability that is the result from using stochastic equations in a probability reliability analysis (PRA) to calculate reliability rather than measure usable life. This paradigm has been used for the past 50 years produced the greatest catastrophic failures ever experienced by the United States space program and a premature mission failures of over 25% of all military, NASA and commercial space missions making getting to space and working in space highly unsafe.

This new reliability paradigm puts safety, maintainability and supportability as a function of reliability, redundancy and the prognostics and health monitoring (PHM) program. This paradigm is well suited for the space and defense industries because aerospace telemetry is used in the PHM and is available on most aerospace equipment including spacecraft and launch vehicle equipment for a variety of reasons. Telemetry was borrowed from the jet aircraft flight-test community developed at Edwards Air Force Base over 50 years ago to collect jet aircraft test data before the pilot was killed. With our direction, NASA HQ has published this paradigm for all future NASA aircraft. We have also requested that NASA adopt the PHM paradigm on all future manned and manned space missions.

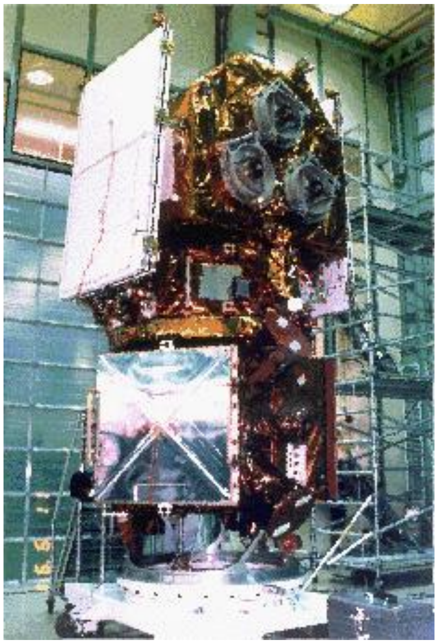

Figure 9. The NASA GSFC/U.C. Berkeley $300M Extreme Ultra-Violet Explorer LEO Space Science Satellite that Received a Prognostic Analysis in 1996.

Figure 9 is the NASA EUVE LEO Science satellite produced by Fairchild Space Systems and U.C. Berkeley Space Sciences Laboratory and launched in 1992 that received a prognostic analysis in 1996 with assistance from Lockheed Martin Advanced Development Center located in Sunnyvale CA. that confirmed the results using proprietary, pattern recognition software. [20] The results published by Lockheed Martin illustrated that satellite and launch vehicle equipment with accelerated aging could be identified during factory I&T for replacement before launch stopping the premature failures of Air Force procured spacecraft. [18]

Figure 10 is the INTELSAT 7 and 7A satellite designed by the author in 1987 that is the first satellite for use with predictive algorithms to identify the equipment that was going to fail prematurely for replacement prior to launch. The new Boeing 787 commercial aircraft will use embedded predictive algorithms as part of a PHM program to lower logistical cost by 50% while increasing passenger safety.

The Air Force F-35 JSF Autonomic Logistics System utilizes sustaining engineering, a 24/7 help desk with access to electronic joint-service technical data, intelligent maintenance management with global supply chain accessibility and new support equipment management.

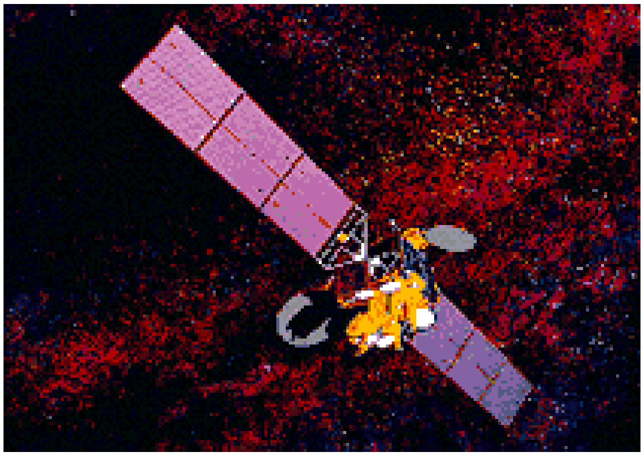

Figure 10. An Artist Concept of the INTELSAT 7 and 7A Commercial, Geostationary C & Ku-Band Communications Satellite Manufactured by Space Systems/LORAL and Launched in 1995.

Figure 11 is one of twelve Boeing/Air Force GPS Block 1 satellites that received a prognostic analysis on a regular basis between 1978 and 1983. The results were used to decode which atomic clock to be used to support multi-service system wide testing. [6][7][15]

Space systems logistical and supportability programs were originally developed for expendable ICBM and launch vehicle systems such as the Atlas, Titan and Delta (THOR) launch vehicles. These logistical systems are expensive and complex and must provide large quantities of unneeded equipment and goods due to the extremely high number of premature equipment failures that occur during all phases of the design, manufacturing, launch readiness and launch. Intelligent, decision-making self-prognostic equipment allows aircraft to stop requiring downtime for routine maintenance, reacting only when the equipment determines the actions necessary. For spacecraft, intelligent equipment stops premature failures that dominate spacecraft equipment and requires large numbers of redundant equipment for long life equipment, lower cost and shortening delivery schedules.

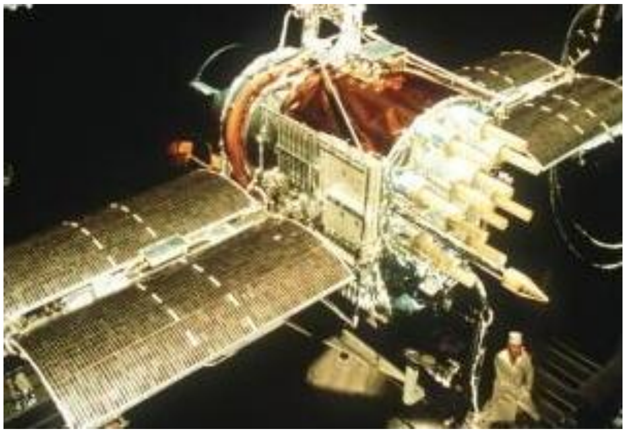

Figure 11. The Boeing/Air Force GPS Block 1 Satellite Qualification Vehicle with a NUDET Secondary Payload that Received a Prognostic Analysis in 1983 Following 3-Axis Stabilization Post Early Orbit Operations.

XII. CONCLUSION

Because (non-aerospace) companies suffer the financial losses associated with producing equipment and products that fail prematurely, these companies developed the prognostics and health management program to stop the manufacture of products and equipment that fail prematurely. The PHM improves space systems reliability, availability, serviceability and supportability greatly by eliminating premature equipment failures requiring far less equipment shipped and far less equipment needing to be replaced.

Using the condition-based maintenance program as a part of a prognostics and health management program, existing and future space systems mission life defined by the traditional bathtub reliability curve changes to the bathtub curve, increasing usable life with no change to the equipment design, while the cost to produce and maintain space systems greatly decreases.

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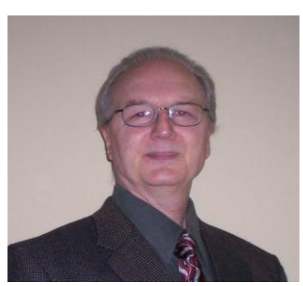
BIOGRAPHY



Dr. Losik is the President and Chief Technical Officer of Failure Analysis. Dr. Losik has over 30 years experience in the design, manufacture and test of military, NASA and commercial satellites, ground stations, missiles and launch vehicles.

Dr. Losik is an award winning spacecraft designer, winning awards from Boeing, the U.S. the Air Force GPS Program Office as the Boeing GPS Space and Ground Manager and INTELSAT, for the design of the INTELSAT 7 and 7A commercial geostationary communications satellites. As a spacecraft TC&R subsystem engineer, Dr. Losik led the design of the INTELSAT satellite microprocessor-based centralized command, control and telemetry centralized and distributed electronics. The INTELSAT 7 was the first commercial, geostationary communications satellite designed to use a microprocessor and have all its subsystem equipment usable life measured before launch using predictive algorithms.

As the Global Positioning System (GPS) TT&C subsystem engineer and the GPS Space and Ground Segment Manager, Dr. Losik pioneered the use of predictive algorithms on the Boeing/Air Force's GPS MEO satellites and the General Dynamics/Convair Atlas E/F launch vehicles beginning in 1980. Dr. Losik also led the integration of the GPS IONDS nuclear detonation detection subsystem (NDS) and the GPS L3 UHF crosslink link subsystem into the GPS Block 1 qualification vehicle that reworked and retested and launched in 1983 and the design of the follow-on 28 Boeing Block 2 and 12 Block 2A satellites.

Dr. Losik used predictive algorithms successfully on NASA, military and commercial satellites, missiles and launch vehicles to predict spacecraft equipment failures. Dr. Losik published the results of his research related to the source and tools for finding and processing the information that is available to predict equipment failures. He published the results of his research to NASA GSFC in 1996 and in 2 books and over 25 technical papers at a wide variety of technical conferences.

As the NASA/NOAA GOES Next Spacecraft Manager, he was responsible for the design, manufacture and test of 10 NASA/NOAA GOES Next 3-axis stabilized, geostationary weather satellites. Dr. Losik completed a prognostic analysis on the first GOES Next satellite (GOES 8) which did not suffer from premature equipment failures and portions of GOES Next J-M satellites that did.

As the Air Force Titan 34D and Boeing IUS solid rocket motor (SRM) Test Manager at United Technologies, he led the testing of the Titan thrust vector controlled SRM acceptance test program and the Titan SRM 5 to 7 segment upgrade.

As the Program Manager on the NASA GSFC Extreme Ultra-Violet Explorer (EUVE) low earth orbiting space science program, U.C. Berkeley Center for EUV Astrophysics at the Space Sciences Laboratory, Dr. Losik completed the first prognostic analysis on a NASA satellite in 1996. The results were published in conjunction with authors from Lockheed Martin Space Systems Company Advanced Development Center located in Sunnyvale CA.

Most recently, Dr. Losik worked at Force Computers and embedded predicted algorithms in telecommunications industry NEBS and ETSI high-availability public telephone switching network (PTSN) computer servers for companies such as Verizon, AT&T and Alcatel-Lucent.