Relying on Telemetry for Mission Critical Decisions: Lessons Learned from NASA' Reusable Launch Vehicle for use on the Air Force's Next Generation Reusable Launch Vehicle

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Failure Analysis

ABSTRACT

The U.S. Air Force's next generation reusable booster (NGRSB) offers the opportunity for the Space Command to use intelligent equipment for decision making replacing personnel, increasing safety and mission assurance by removing decisions from program management personnel who may not have had any flight-test experience. Adding intelligence to launch vehicle and spacecraft equipment may include requiring the builder to use a prognostic and health management (PHM) program. The PHM was added to NASA's aircraft programs in 2009 and we have requested NASA HQ and NASA Marshal Space Flight Center adopt the NASA PHM in the procurement contracts used on the new Space Launch Systems, NASA's congressionally mandated replacement for the Space Shuttle. Space Vehicle Program managers often make decisions for on-orbit spacecraft without ever having on-orbit space flight experience. Intelligent equipment would have eliminated the catastrophic failures on the NASA Space Shuttle Challenger and Columbia. These accidents occurred due to the lack of space vehicle subsystem engineering personnel analyzing real-time equipment telemetry presented on strip chart and video data prior to lift off during pre-launch checkout for the Space Shuttle Challenger and the lack of space vehicle real-time equipment telemetry for Columbia. The PHM requires all equipment to include analog telemetry for measuring the equipment performance and usable life determination in real-time and a prognostic analysis completed manually will identify the equipment that will fail prematurely for replacement before launch preventing catastrophic equipment failures that may cause loss of life.

KEY WORDS: Telemetry Analysis, Failure Analysis, Prognostic Analysis, Prognostic Science, Telemetry, Diagnostics, Predictive Diagnostics, Prognostic Technology, Reliability Analysis

INTRODUCTION

The Air Force is planning to develop a reusable space booster (RSB) to replace the expendable Atlas and Delta launch vehicles known as the EELV. The RSB will 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. 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 DOD 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.

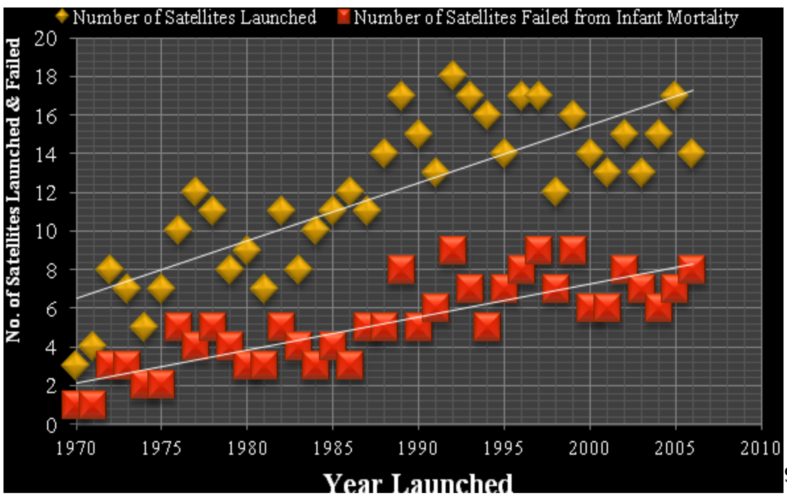
FIGURE 1 A CONCEPT FOR THE AIR FORCE'S NEXT GENERATION REUSABLE SPACE BOOSTER

Autonomic Logistics (AL): The CBM autonomic logistics system monitors the health of the aircraft/Launch vehicle 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. Through prognostics and health management, computers use accumulated data to track when a part will fail. With this aid, maintainers can fix or replace a part *before* it fails and keep the vehicle flying or ready to fly.

FIGURE 2 THE AIR FORCE $130M F-35 JSF INTELLIGENT-EQUIPMENT-BASED EMPLOYS EMBEDDED PREDICTIVE ALGORITHMS THROUGHOUT ALL ELECTRICAL AND MECHANICAL EQUIPMENT

The procurement contracts used to purchase launch vehicles, launch vehicle services and spacecraft do not require companies to identify the equipment that will fail prematurely for replacement before launch. The space vehicle procurement contract require companies to measure and confirm equipment performance, and for many decades it was believed that equipment that passes performance testing are more likely to meet mission life requirements even though there is no relationship between performance and usable life.

Figure 3 illustrates the premature failure rates for commercial satellites starting in 1970. The rate varies indicating that the cause is a systemic one and not related to personnel. The suppliers of electrical and mechanical parts used in spacecraft and launch vehicles promise that a few of their parts will fail prematurely.[7] This information is available to space vehicle builders in the form of proprietary normal and cumulative distribution curves. The dynamic environmental acceptance testing program (ATP) which is used to measure and confirm contractual equipment performance requirements was added to the manufacturing process of launch vehicles and spacecraft specifically to increase the likelihood that the parts that were promised to fail prematurely by the suppliers would fail prematurely would fail during ATP.[3]



[9]

FIGURE 3 THE PREMATURE FAILURE RATE OF MILITARY, COMMERCIAL AND NASA SATELLITES FROM 1970 THROUGH 2005 (FROST & SULLIVAN)[5]

The mission life of space and launch vehicles is determined contractually by using predefined stochastic equations in a probability reliability analysis (PRA) in references such as Mil STD 217. A PRA defines no behavior. PRA is a substitute often a poor substitute, used to quantify behavior only when the real behavior cannot be quantified for many reasons such as cost effectiveness or insufficient time. Once the U.S. government adopted probability reliability analysis (PRA) in 1960 to quantify equipment and vehicle reliability in probabilistic terms, the government contractors simply stopped looking for the causes of premature equipment failures and developed production processes that matched with the failure rates that the government stated was contractually acceptable. According to Aerospace Corporation; Air Force space missions fail prematurely within the first year at about 25% and NASA, commercial and military spacecraft all continue to suffer from catastrophic infant mortality failures at rates up to a 70% within the 45 days of launch.[1]

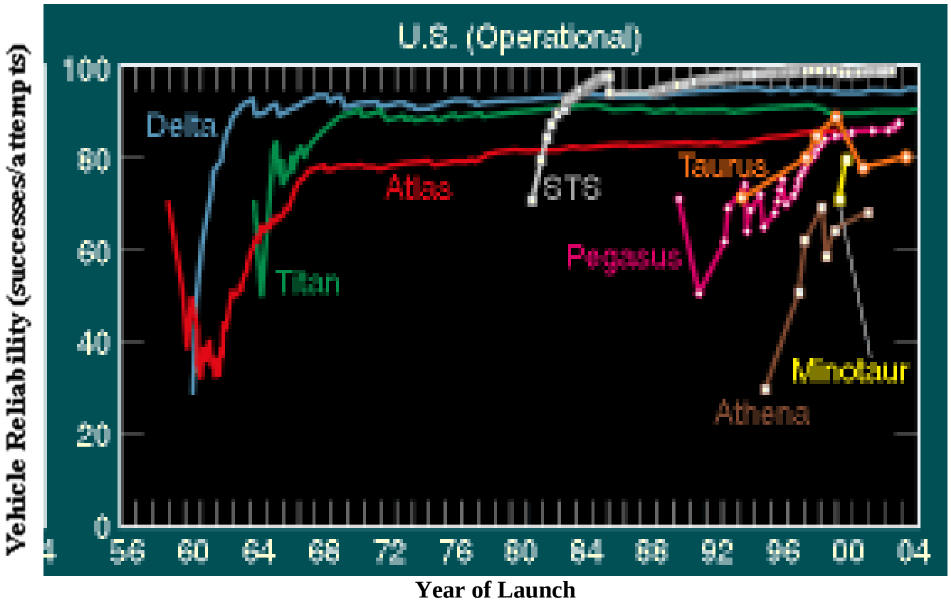


FIGURE 4 THE RELIABILITY OF U.S. LAUNCH VEHICLES FROM 1957 TO 2004

Figure 4 is from the Aerospace Corporation study published in 2001, which also identified the premature failure rates of most U.S. and Air Force launch vehicles and the subsystems that the premature equipment failures occurred. [2] Figure 4 illustrates that getting to space using rockets is unsafe. [8]

WHY CAN TELEMETRY BE CRITICAL TO MISSION SUCCESS?

[4] An analog telemetry interface is embedded in circuits and mechanisms and so the information from a telemetry circuit is equipment performance related information. Performance information is information about how well equipment is functioning only. For equipment that passes performance testing, how well equipment is operating is unrelated to how long the equipment will operate because performance is unrelated to usable life.

[6] Because spacecraft manufacturers do not measure and confirm spacecraft equipment usable life before launch, spacecraft reliability is dominated by infant mortality failures caused from parts with accelerated aging that go undetected during performance testing. [9] Premature equipment failures occur after the spacecraft equipment has been exhaustively and comprehensively performance tested twice in factory equipment-level and vehicle-level acceptance-testing programs (ATP) demonstrating that performance testing of equipment is inadequate for producing equipment that won't fail prematurely.

Spacecraft equipment remaining usable life is measured by using the equipment analog telemetry (equipment performance data) generated during factory ATP to measure and confirm contractual equipment performance. The measurement of equipment usable life is done by using proprietary predictive algorithms to process the SAME equipment analog telemetry behavior to measure and confirm equipment usable life. These measurements identify the equipment that will fail prematurely for replacement before launch ensuring that every launch is a success.

THE GAME CHANGING TECHNOLOGY THAT USES PROPRIETARY DYNAMIC MODEL-BASED OR DATA-DRIVEN PREDICTIVE ALGORITHMS TO MEASURE REMAINING USABLE LIFE

A predictive algorithm includes a series of actions, including a scientific analysis, made by personnel trained to prevent surprise failures from occurring. Using diagnostic technology, personnel are trained to react with a diagnostic analysis after a failure occurs. Changing the paradigm from one of reaction to prevention requires training in completing a scientific analysis. Proprietary predictive algorithms simply relate past equipment, non-repeatable transient events that is identifiable in equipment engineering test data with equipment end of life.

Proprietary predictive algorithms demodulate telemetry behavior and illustrate the presence of accelerated aging that may be present in normal appearing telemetry from fully functional equipment. Accelerated aging in equipment test data is caused from at least one piece-part (electrical or mechanical) aging in performance must faster than all other parts in a circuit or mechanism. Equipment with accelerated aging in its performance test data will fail prematurely with 100% certainty.

RESULTS OF THE PROGNOSTIC ANALYSIS COMPLETED ON THE 1986 NASA SPACE SHUTTLE CHALLENGER ACCIDENT

In 2006, the CBS television show called 60 minutes released the information about the NASA Challenger Space Shuttle failure that the manager for the Challenger solid rocket motors had predicted the failure and that both his management and NASA management ignored the prediction from the very person that they should have listen to.

FIGURE 5 THE SPACE SHUTTLE CHALLENGER SRM O-RING FAILURE OF THE SPACE SHUTTLE CHALLENGER "O" RING WAS RECORDED ON VIDEO BEFORE LIFT-OFF ON THE LAUNCH PAD

In 1986, on the evening prior to the Challenger launch, the Space Shuttle Challenger manager of the solid rocket motors at Morton-Thiokol predicted to both his management and Space Shuttle management the failure was going to occur in the cold temperature that the Challenger was going to launch in. This prediction was based on previous Space Shuttle single O-ring failure that had occurred on the previous Space Shuttle launch only during a little warmer weather.

The outside temperature at the Kennedy launch pad for the Challenger was even colder that the previous coldest launch temperature and the Morton-Thiokol engineering manager knew the Challenger's O-rings would be even stiffer than previous launches and thus would allows some thrust leakage to occur. The early signs of premature failure were present on the retrieved Challenger SRM "O" rings confirmed the total failure predicted by the Morton Thiokol engineering manager. The Morton-Thiokol SRM engineering manager predicted the "O" ring failure to both Morton-Thiokol management and NASA management, but equipment failures were believed to be instantaneous and random (and thus unpredictable and unpreventable) and so both Morton-Thiokol and NASA Space Shuttle management ignored the SRM engineering manager's prediction.

The focus of the Challenger failure analysis was on the parts that failed during launch rather than on the technical and management decisions that occurred that would have prevented the equipment to fail. In 1986, Space Shuttle mission control and flight team technical and management personnel were trained to react to surprise Space Shuttle equipment failures after they occurred. Technical and management personnel were not trained to identify the information that would have prevented a failure from occurring because theoretically, equipment failures are instantaneous and random and so cannot be predicted nor prevented. Today, with the dismissal of probability reliability analysis (PRA) as a viable tool to quantify equipment usable life, the Challenger failure can be understood so that it will not be repeated.

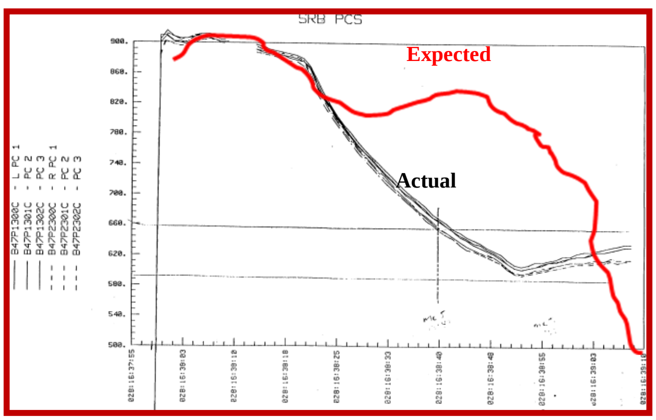


FIGURE 6 THE NASA SPACE SHUTTLE CHALLENGER SRM TANK PRESSURE TELEMETRY BEHAVIOR WHEN O-RINGS FAILED

The available real-time launch vehicle telemetry and real-time video available from the NASA Challenger launch in 1986 during the launch pad checkout and launch operations identified the failure of the "O" rings at lift-off. This video and the subsequent drop in solid booster tank pressure telemetry at the instant the hole was made in the solid motor caused the lateral movement of the Challenger 73 seconds after lift-off indicating that the Challenger had been shoved hundreds of yards horizontally.

This caused the failed solid booster segments with the failed "O" ring to flex and separate enough so that the leaking field joint that had been closed at lift off due to vertical forces would open allowing the propellant thrust to escape and burn into the center tank. There were no less than four prognostic markers/identifiers present for the Challenger launch data that was included in the failure analysis report, collected and recorded, anyone of which should have been recognized that a catastrophic failure was going to occur. The prognostic markers that could have been used to stop the Challenger launch present include:

- The damaged "O" ring data from previous Space Shuttle launches at a cold temperature launch provided by Morton-Thiokol SRM engineering manager
- The burn-through of the solid booster "O" rings at lift-off clearly visible at solid rocket motor ignition on available video data. This burn through would have been identified by engineers trained in prognostic analysis if present during launch evaluating real-time telemetry. The Challenger flight director would have been instructed to terminate the launch at burn-through, dousing the solid rocket motors with water.

- The significant drop in solid rocket motor fuel tank pressure in telemetry after the hole in the side of the solid motor tank occurred (see SRM tank pressure telemetry figure below) but no engineers were monitoring the data in real-time

- The Space Shuttle mission control room did not have any subsystem personnel stationed at the strip chart recorders, evaluating real-time analog telemetry from the Challenger prior to lift-off. The lack of engineering analysts to evaluate all Shuttle telemetry/information searching for prognostic identifiers were not used to save cost, because NASA believes that failures are instantaneous and random (Markov property) and so cannot be predicted nor prevented and so the engineering personnel were not necessary.

- All the Space Shuttle telemetry/data was recorded and displayed on strip chart recorders for use in the event of a failure to be used in a failure analysis.

FIGURE 7 AN EMPTY CHALLENGER MISSION CONTROL AT JSC PRIOR TO LAUNCH OF THE SPACE SHUTTLE CHALLENGER

There was abort actions available that would have been taken in the event that a failure in the solid rocket motor were detected in the video and telemetry. The Space Shuttle main engine was to be ignited using fuel from the central tank early, while the Space Shuttle was going at a high enough speed, the solid rocket motors could have been be jettisoned early. Because the engineering personnel were removed from mission control room strip chart recorders, no one was evaluating the telemetry real-time to identify a launch abort was necessary.

It is our hope that when the technical and management personnel recognize the extreme value of the information provided to make decisions with in equipment telemetry related to equipment reliability, space vehicle program management will be forced to use the information made available to them from telemetry. In the past, decisions were made using program management experience for manned space flight operations, which is the wrong experience to use.

RESULTS IN THE PROGNOSTIC ANALYSIS COMPLETED ON THE 2003 NASA SPACE SHUTTLE COLUMBIA ACCIDENT

In 2007, the author submitted a prognostic analysis of the Space shuttle Columbia accident to NASA HQ, Safety and Mission Assurance Office. Unlike the engineering analysis that was completed that uses past equipment information to determine past equipment behavior with certainty, a prognostic analysis uses the very same past equipment information about behavior to predict future equipment behavior with certainty.

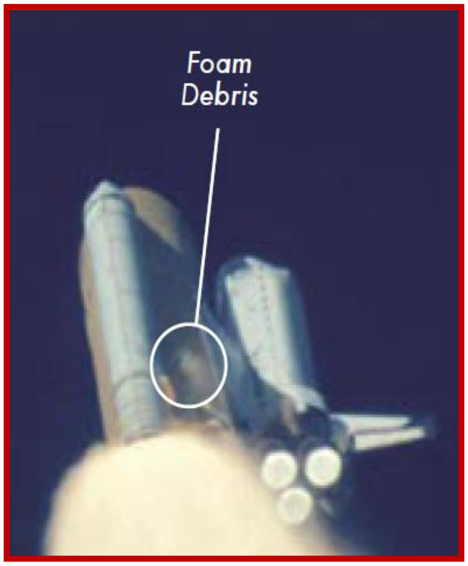


FIGURE 8 VIDEO OF SPACE SHUTTLE COLUMBIA CENTER TANK FOAM INSULATION FALLING CAUSING DAMAGE TO COLUMBIA DURING LAUNCH

The available Space Shuttle real-time data/telemetry from the NASA Columbia during launch showed the debris that damaged wing and subsequent accident in 2003 was not evaluated until long after the accident occurred during failure analysis/data review. This engineering analysis determined an impact had occurred to the wing, causing internal damage to the Shuttle wing.

A prognostic analysis would have required personnel to look at the available telemetry to determine if damage to the Shuttle wing occurred during launch. A person trained in prognostic analysis would have enforced the management to at least, look at all the information that was available before making decision to reenter earth atmosphere. Columbia Space Shuttle wing telemetry sensor data confirmed the significant wing damage occurred. This information was found long after the accident. The sensor data was not analyzed after arriving on-orbit due to the magnitude of the effort, until after the failure already occurred in the failure investigation.

This action is consistent with traditional diagnostics practices/techniques used throughout the space industry to ignore information when it is both time consuming and labor intensive and the risk appears extremely low. The Space Shuttle was the most instrumented vehicle with equipment telemetry ever produced. When management personnel do not or cannot evaluate available information that was made available, a prognostician will ensure that the data would be at least looked at and factored in the decision making before making decisions. The prognostic markers/prognostic for the Columbia failure includes:

- The previous/known problem of Shuttle insulation foam falling off all previous Shuttle external tanks during ascent
- The real-time video data showing slabs of insulation falling from the external tank onto the Shuttle during ascent
- The potential for external tank insulation foam striking the Shuttle during ascent causing damage
- The availability of internal Space Shuttle wing telemetry to analyze whether damage had occurred

There is one major similarity between the Space Shuttle Challenger failure and the failure of the Space Shuttle Columbia. In both the Challenger and Columbia accidents, NASA personnel consciously decided to ignore the technical information provided and available from Space Shuttle telemetry. For the Challenger, NASA eliminated the subsystem engineering team that evaluated real-time telemetry during launch readiness and launch to save money. There had been no problems in the past with the Space shuttle during the many successful launches that could be used to justify the engineering team and so management decided to eliminate the engineering positions. All the Space Shuttle Challenger telemetry was still recorded and archived, but the value of the knowledge from telemetry was ignored. For the Columbia failure, again NASA management chose to ignore the telemetry that was available from the Space Shuttle to determine if damage had occurred prior to authorizing the Columbia reentry.

CONCLUSION

Intelligent equipment capable of deciding whether the actions requested from it can be accomplished using common analog equipment telemetry are superior to some program management personnel decisions made on the NASA reusable space boosters who may not have acquired the flight experience to make flight related decisions have proved to be invaluable in increasing safety and mission assurance. Adopting a PHM program on the NGRSB will provide the technical justification for the Air Force’s next generation reusable launch vehicle be fully instrumented with equipment analog telemetry and launch teams be fully manned during all pre-launch, launch operations. A PHM will ensure that the Air Force’s NGRSB program managers will rely on engineering data and engineering and prognostic analysis for mission critical decisions. A PHM will provide on-board equipment that will not fail prematurely for achieving

100% mission success. The acceptance of prognostic technology and the use of a prognostic analysis by the Air Force Space and Missiles systems Center will stop program management ignoring the data generated specifically for use in decision-making. Although the decisions by NASA management may remain unchanged, having the engineering data available for decision-making before conclusions are made will increase the likelihood that a correct action will result. Prognostic analysis removes decision making from personnel who may not be experienced in data reduction and analysis techniques and forces the use of all data to be accumulated, analyzed and the results provided to personnel to make decisions based on all available, relevant data.

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