



Los Angeles Section and
Space Systems Technical Committee

Responsive Space Launch with the Scorpius Family of Low-Cost, Expendable Launch Vehicles

Dr. James R. Wertz
Microcosm, Inc.
El Segundo, CA



1st Responsive Space Conference

April 1-3, 2003
Redondo Beach, CA

LESSONS LEARNED FROM PAST REUSABLE LAUNCH SYSTEM DESIGNS

Gregory Peralta, Lockheed Martin Technical Operations
Stephen T. Black, Lockheed Martin Technical Operations

ABSTRACT

The X-33 single-stage-to-orbit (SSTO) technology demonstrator funded by the United States Government and industry provided significant data to support SSTO design. The system focused on developing a highly responsive, operational efficient SSTO that could validate the basic technology and proof-of-concept. Recent endeavors, such as the NASA Space Launch Initiative Two-Stage-to-Orbit and SOV programs have utilized the methodology taken on the X-33. The X-33 enjoyed many design successes. Although, several set backs resulted in the premature termination of the X-33 program. In hopes of benefiting future designers of responsive, reusable launch systems, this paper will discuss the design philosophy and testing approach of the X-33 by emphasizing the lessons learned.

This paper will also review past programs and illustrate why future operational programs need distinctly separate developmental and operational programs. This separation must be accomplished by completely qualifying components and procedures during the development phase of a program.

Flight and mission performance as well as ground system operations efficiencies can be achieved through a "design to operations" systems approach with correct implementation of updated technologies where appropriate. Government investment must be directed toward operations certification of new system technologies as much as it is on traditional flight performance qualifications. Tremendous improvements can be made in system operations, which will translate into program efficiencies and lower overall system cost from the first launch and continuing through the life of the program.

SPACE TRANSPORTATION SYSTEM

The Space Transportation System (STS) is an example of the costly effects of not separating the design development test and evaluation (DDT&E) phase from the operational phase. The original goals of STS included 160 hour processing time and a total 14-day turnaround time.

These goals proved to be unachievable. In reality, the processing time was on the order of 90 days. The first 5 flights of the shuttle were designated as the development flight test. After these flights, the system was declared operational. During the flight test phase, large support infrastructures were established resulting in significant overhead which were later impossible to eliminate. As the program progressed, technology, performance, safety, cost, schedule and political limitations resulted in constraints, budget overruns, increased processing time and excessive manpower. In 1985, in an attempt to control costs, the program consolidated the processing operations contracts at KSC and JSC. The goal was to reduce turnaround time and increase annual flight rate. Before any benefits could be realized, the Challenger accident occurred in January 1986. The Master Verification Plan was modified adding more checks and balances between the design agencies and the operations organizations. All operations and maintenance procedures were rewritten to emphasize safety requirements and closed loop tracking. This setback added additional personnel and organizations to the existing overhead at all levels of the program.

In 1993, due to declining budgets and obsolescence it became apparent that a change was needed. Congress directed the Access to Space Study be performed. This study identified technology upgrades across all elements of the STS which could improve operability. The

outcome of this and other similar studies led to the National Space Policy in 1994 calling for SSTO/RLV development while maintaining the STS fleet with safety and operability improvements.

STS initiated many “in-house” efficiency improvements through several programs and initiatives. Examples included:

- Reliability Centered Maintenance (RCM) and predictive maintenance programs.
- Procedure streamlining
- Requirement reductions
- Automated Integrated Work Control and Scheduling System (IWCS)
- Frozen vehicle design eliminating discretionary hardware and software changes.

These, along with other changes, significantly reduced overhead costs and turnaround time. However, the original program goals were never realized.

In 1996, NASA restructured the STS with further consolidations by forming the Space Flight Operations Contract (SFOC). Additionally, NASA reinitiated Space Shuttle Program technology upgrade studies. The goals of the SFOC were to eventually reduce the costs of payload to orbit on STS from the current \$7500/Lb to \$3000/Lb through limited commercialization, increased flight rate, technology upgrades and by replacing the Reusable Solid Rocket Boosters with Liquid Fly Back Boosters.

X-33 ADVANCED TECHNOLOGY DEMONSTRATOR PROJECT ORIGINAL PROGRAM GOALS

The X-33 Phase II Cooperative Agreement Contract includes;

- X-33 advanced technology demonstrator flight test vehicle
- several ground technology articles
- full scale vehicle design definition

The absolute requirements of the combined projects were to produce data to enable business and government decisions to proceed with a privately funded reusable launch system (RLV) to replace the Space Shuttle.

At the beginning of the design phase of the X-33 program, the vehicle had the following performance goals:

- Aerodynamics under real gas effects
- Lifting body flight dynamics validation
- Structural load paths with an internal payload bay
- Reusable TPS thermal performance
- Reusable composite multilobe liquid hydrogen tanks
- Linear Aerospike engine performance
- Thrust vector control via differential engine thrusting
- Subsystem performance in a flight environment
- Flight at speeds exceeding mach 15 (connected to a monetary award)

In addition to the vehicle performance goals, the X-33 aimed to demonstrate RLV technologies to meet several operations performance goals. These goals included:

- 50 personnel touch labor
- 3 consecutive 7-day turn-arounds
- A 2-day turn-around

These contractual requirements were not derived by analysis but were declared. Operations capability criteria for future launch systems will be derived from end user specified requirements.

X-33 VEHICLE PERFORMANCE

As the fast track design phase of the program progressed, flight dynamics problems were solved and the outer mold line of the vehicle frozen. It then became apparent that the weight and program cost would not permit meeting all of the original contractual goals. To reduce weight, costs and schedule risks, subsystems were redesigned and several non-RLV traceable subsystems were eliminated.

Among the subsystems to be removed was the oxygen/hydrogen gasifier along with the turbo alternator. The gasifier was designed to convert liquid hydrogen to gaseous hydrogen for use in the reaction control system and hydrogen rich steam to power the turbo alternator. The reaction control system was redesigned to utilize gaseous methane and oxygen in a much simpler blow down system. The turbo alternators were replaced by rechargeable battery packs, which also substituted for ballast weight. This was not an impact to the full scale vehicle since the gasifier was not RLV traceable and the turbo alternator was going to be developed by a ground based program if necessary. Electrical power

and Reaction Control subsystems remained subjects of trade for *VentureStar*.

The removable payload bay container being designed to gather payload bay flight environment data and allow operations demonstrations was eliminated as non critical to the decision criteria for *VentureStar*. This also could be accomplished through a ground test program.

There were, however cases where systems were added which resulted in a net weight reduction. The pneumatic load assist device was added to the body flaps in lieu of additional electromechanical actuators and saved weight. The pneumatic load assist device is a relatively simple system consisting of a pressurized storage bottle, a pair of solenoid valves and pneumatic actuator. When the current draw of the associated electromechanical actuator exceeded a preset limit, the pneumatic actuator was pressurized or vented. This reduced the load on the electromechanical actuator.

The outcome of the weight/cost realignment was the deletion of items that were not required for the safe flight of the X-33, non-RLV traceable technologies, and those which did not support the critical decision criteria. The realignment would have allowed the X-33 flight tests to proceed. The outcome of the flight test would have determined the viability of *VentureStar*. When the X-33 program was terminated, the only performance criterion that was not going to meet the original requirements was the Mach 15 speed. It was determined that this speed requirement could be met if propellant densification were utilized. Therefore densification was the subject of further cost/benefit trades.

X-33 OPERATIONS PERFORMANCE

One of the original concepts for the X-33 Phase II project was to showcase operations technologies demonstrating minimum ground crew support, automation, and safe land/population over flight. Reality however, with a fast paced development program which must produce a quantum leap technology vehicle with performance and mass fraction to demonstrate single stage to orbit capability, is that the vehicle performance design (and budget) tends to take priority over operations demonstration development. This performance

driven approach has traditionally been one of the fundamental errors in program development for all previous operational launchers and some high performance aircraft, i.e., design the vehicle to meet performance requirements and the operations requirements is then driven to support that design. The Lockheed-Martin F-117 is a very good example of this. The primary design goal for the F-117 was stealth. To this end the aircraft was covered in radar absorbent material which requires excessive between flight rework thus impacting operability. Additionally, because the X-33 ground system and operations planning was to support a short-term 1 year, 15 flight program, it was purposely designed to maximize the use of existing GFE and other sources of acceptable existing hardware while minimizing "extras" that would be in an "operational system".

The X-33 operations team selected the launch and landing sites and the flight corridor, and developed a rocket range. They also designed and built the launch and flight test infrastructure. An operations and maintenance plan to support the objectives of the program had to be developed on a very limited budget and in a very short period of time. A rapid prototyping SkunkWorks approach was applied and integrated product development teams were formed with some of the best expertise in the country from a wide range of aerospace operations backgrounds.

Lessons learned from all previous launch systems programs were applied using aircraft philosophy to the greatest extent possible in developing the operations, flight test and integrated ground systems plans. An aircraft Reliability, Maintainability and Supportability approach was applied to the vehicle design to force incorporating operability and reliability into the vehicle design. This was crucial to enable the operability goals and government approval for over-population flight corridors.

A design to operations approach was applied to the ground launch systems utilizing very experienced personnel in all areas of expertise. This allowed sufficient automation and operability to be incorporated while keeping the investment costs to a minimum. To meet the operations goal of launching and monitoring the flight with only two computer work stations, state of the art commercial off the shelf hardware and software proved instrumental by providing

the degree of automation required. The Launch and Mission Control and Monitor System (LMCMS) contained additional work stations to enable off-line trouble shooting and parallel maintenance activities. A state of the art and low cost Independent Safing System (ISS) was embedded within the consoles to provide for emergency launch system safing/recovery should the single string primary LMCMS system fail during hazardous operations.

The original scope of the integrated health monitoring system (IVHMS) was significantly reduced to only monitor the TPS, engines and main propellant tanks. The original plan was to employ algorithms and techniques developed from previous RLV Phase I and NRA's to applicable X-33 systems for evaluation in an operational environment. The *VentureStar* operational system would then utilize these lessons learned in the design. Another system that was eliminated due to budgetary and schedule considerations, which would have added greatly to the operability demonstrations of the X-33, was the integrated operations maintenance system (IOMS). This system would have integrated data and information from the LMCMS/IVHMS with maintenance and logistics information to allow for automated maintenance scheduling and logistics notification immediately from time of fault detection. The logistics portion of the system would have produced procedures, staged hardware and indicated personnel requirements.

The Integration Test Facility (ITF) was created to provide a ground test facility for brassboard and flight hardware integrated ground/vehicle avionics and software validation. The X-33 avionics suite utilized state of the art subsystems including vehicle mission computers (VMC), vehicle health manager (VHM), flush air data system, GPS/differential GPS, inertial navigation units with ring laser gyros, and an advanced technology micro miniature avionics suite (Avionics Flight Experiment). The AFE was incorporated to ghost the actual avionics for evaluation. The X-33 in-flight management was completely autonomous with the only exception being several possible ground issued mission abort mode commands available for contingency situations.

Because of funding constraints and the fast track nature of this program many operability solutions were not incorporated such as the

development and qualification of maintenance free quick disconnects and automated umbilicals.

X-33 LESSONS LEARNED

As the design of X-33 matured and the vehicle and support systems were constructed, many lessons learned were being realized. It was determined volumetric efficiency and performance could be significantly increased with conformal propellant tanks. Weight reduction and improved design would be achieved by utilizing composite monocoque structure versus titanium tubular trusses. These are examples of improvements that were being incorporated into the SOV and RLV designs.

Ground test subscale composite LH2 tanks were utilized to perfect joint bonding techniques and evaluate advanced technology sensors for VHM. The resolution of the test LH2 tank leaks is a good example of solving problems during a development program as opposed to during an operational program. These ground test tanks uncovered many problems and in turn, validated new design solutions, which were incorporated, into the full size tanks.

The Integrated Test Facility was proving indispensable for all systems level validation of software/avionics operations; LMCMS to vehicle interface verification operations, ground procedure validations and launch/mission crew training.

FUTURE LAUNCH SYSTEMS

Future reusable launch programs must utilize the lessons learned from the STS program and build on knowledge gained through the X-33 Phase II projects. Because of the investment commitments required, vehicle and ground systems should be fully qualified prior to initiating the operational systems. SOV and *VentureStar* were begun on the correct path via the X-33 program, however the X-33 did not fully develop all of the technologies required to achieve the operability goals set forth by these programs. The remaining requirement is to bridge the developmental gap prior to reaching the operational phase. This should be accomplished by employing a combination of proven COTS, developmental technologies, automation and efficient procedures. These should be proven fully and qualified prior to incorporation into an operational system. For a

system to be effective in tomorrow's environment the vehicle and ground systems performance must be optimized for operability.

ISSUES & CANDIDATE DESIGN SOLUTIONS

Challenges that future programs face can be met by targeting specific issues for vehicle, ground and facility systems. Operations cost drivers are primarily due to complex systems that are maintenance intensive with a great deal infrastructure. The following table summarizes typical launch systems cost drivers that are applicable to current systems upgrades as well as new systems.

COMMAND, CONTROL AND MONITORING ISSUES

An enabling technology to support robust and efficient spaceflight operations is the

development of a ground based computer infrastructure. Today, each launch system (X-33, Shuttle, Ariane, Titan, Atlas and Delta) builds their own support structure to meet their perceived needs. Unfortunately for many, it is the development of "the system" that becomes the focus, and not what the system must accomplish. Often the end product is in direct conflict with operational efficiency (although a masterpiece of complex computer architecture).

Future space launch information systems must integrate key services, with as little custom developed system software as possible. While command and monitor software tends to be the focal point of most efforts, the desired system must provide command & monitor (for ground and mission operations), maintenance, planning (both ground and mission), and health analysis as a complete package. Through the use of interfaces, each component can operate independently, although the power and the

<u>Vehicle/Ground System Issues</u>	<u>Solutions</u>
High Maintenance Components	<ul style="list-style-type: none"> • <i>Robust TPS (eliminate re-water proofing and normal debris damage and thermal barrier checks)</i> • <i>Low Maintenance Engines (eliminate between flight intrusive inspections, increase design margins, eliminate post flight bearing drying and residual propellant purging).</i> • <i>Minimize wiring</i>
System Level Complexity	<ul style="list-style-type: none"> • <i>Self Contained Reusable Propulsion</i> • <i>Minimize electrical power and cooling requirements</i> • <i>Simplified Fluid Systems (minimum number/types of fluids, eliminate hazardous fluids.)</i> • <i>Maximize health management/BIT to the component level</i> • <i>Maximize commonality of hardware (i.e. Universal Signal Conditioners)</i>
Operational Complexity	<ul style="list-style-type: none"> • <i>Single Level Access of components</i> • <i>Standardization of Payload Interfaces</i> • <i>Payload containerization</i> • <i>Automated integrated work control</i> • <i>Eliminate unique/hazardous systems (pyrotechnics, ablatives, high pressure fluids, etc.)</i>
Labor Intensive Operations	<ul style="list-style-type: none"> • <i>Automated Interfaces and umbilicals</i> • <i>Self -Verifying Interfaces (Mechanical, fluid & Electrical)</i> • <i>Autonomous interface systems retest capability</i> • <i>Quick release mechanical fasteners for easy access.</i>

system's operability is a direct result of the pieces working as an integrated package. At present, there is no single system that fulfills these needs in an operable manner.

Next generation systems need to support the interfaces to a variety of end-items and vehicles. The typical solution is a system design with front end processors, telemetry processors, or the like, that transform acquired input into digital information. Ideally, a front end change should accommodate any new interface. The structure of contemporary system design is such that under the best circumstances there is at least some system impact to accommodate the new interface, and at worse the inability to support the interface. Solutions are available, but are often overlooked because of preconceived design solutions, or directives that force the use of custom solutions, instead of off-the-shelf.

Automation of the ground system (to reduce maintenance personnel) can be accomplished. A trade is required between the cost of automation and the magnitude of the workforce reduction. As programs mature and more operational knowledge is gained (which can be programmed into software), the number of active support people can decrease. The key for automation is to maximize the return on investment, and to realize that the investment may be spread over a period of time.

Platform flexibility and portability goals often impede the ability to deliver a ground system that supports the system requirements. By choosing any design, even a "portable" one, a baseline is established and there is often a high cost to upgrade hardware to a different vendor or design. Airlines accept these limitations on "portability" because their concern is life cycle cost. Thus an airplane placed in service 20-30 years ago, may have the same electronics suite, because it is more economical than upgrading to current technology. Even within the last 5 years, the ground industry "standard" has changed. So a large investment in designing portability in the past few years is mostly unrecoverable today. Thus it is life cycle cost, which may have little to do with portability, which should be the main focus in ground design.

VEHICLE HEALTH SUPPORT SYSTEMS

The requirements of space flight and the limitations of vehicle performance often limit

vehicle operational margin. When systems are operated "at the limit", reliability is reduced. This reduced reliability drives the development of systems capable of automatic fault recovery. The benefits of such a system must be weighed against its developmental costs. While it is quite beneficial to have health monitoring on a complex system that fails every 100 hours, it is impractical to spend money for health monitoring on a system that fails every 100,000 hours or to spend many automation dollars to monitor for a simple switch failure. There are some key decisions that affect health monitoring decisions: failure frequency, consequence, complexity, and the ability to describe all the failure modes / operating characteristics during system design. Determining the balance between vehicle resident health monitoring versus ground health monitoring of vehicle systems and the optimum "pay-back" requires analysis for the given system. These decisions are best made prior to entering into an operational phase.

MISSION PLANNING SYSTEMS

There are few commercially viable space mission-planning systems. There are, however, a number of commercial and DOD aircraft planning systems that may provide most of the functionality required. More research is necessary to determine the correct set of commercially available tools, which require a minimum amount of custom development.

INFORMATION, MAINTENANCE AND PLANNING SYSTEMS

Virtually all launch and mission systems use custom code, largely because the solution must adapt to the corporate culture model (e.g., it's always done *this* way). In the free market most business enterprises use commercial maintenance and planning solutions. Businesses adapt to a tool and can eliminate the cost of maintenance software development. The corporate culture for existing systems is firmly fixed, and there may be little benefit in a commercial maintenance and planning solution. Providing an integrated package with health, mission planning and command / monitor capabilities would complete the package required to solve the operational need.

Ground computer infrastructure development is impacted by the simple fact that there are few funds allocated to research. Typical R&D

focuses on the Flight Vehicle, with ground systems and operations relegated to necessary evils. Ground based computer systems that support flight programs are often under-funded, must meet unrealistic schedules, and deliver less than optimum performance. Computer organizations that develop these systems tend to miss the operational targets, because they are unaware of the system operations requirements, and often degrade into a large computer science project.

The most appropriate design team includes the end-user (i.e., the operations person) that relies on the system to meet their particular needs. Since the end-user knows the system requirements and understands both good engineering, and business practices, but is typically not a computer expert, the preconceived notions, and corporate culture influences can be factored out. With appropriate oversight (but not direction), the operable system can be developed.

CONCLUSIONS

Historically, launch systems development programs had ground system operability goals, which were compromised to meet mission performance requirements. Additionally, DDT&E infrastructures were put in place which became integral parts of the program operations and were never shed from the system over the life of the program. The combination of “design to performance” and developmental program operations infrastructure have resulted in the expensive launch delivery systems today. If future programs are to meet overall life cycle cost goals, total system (ground, mission and programmatic) performance must be optimized.

Flight and mission performance as well as ground system operations efficiencies can be achieved through a “design to operations” systems approach with correct implementation of updated technologies where appropriate. However, major technology infusion into a new system without turnkey enabling operations (certification & validation) leads to fundamental DDT&E infrastructure which once in place is very difficult to remove. Part of aircraft-like operability is to adopt the qualification approach used on commercial and military aircraft. A dedicated initial operations test and evaluation (or similar) program is executed before handing the system over to the operator who expects everything to work. Because of the typical

limited fleet size and high vehicle cost of space launch systems, a carefully crafted surrogate system validation is required to avoid debugging a system when it is “operational”. The development phase of a program must be distinctly separated from the operational phase of a program. Failure to maintain this separation burdens the operational program with continuous incremental improvements, validations and qualifications as opposed to incorporating fully qualified block upgrades.

Therefore government investment must be directed toward operations certification of new system technologies as much as it is on traditional flight performance qualifications. Tremendous improvements can be made in system operations, which will translate into program efficiencies and lower overall system cost from the first launch and continuing through the life of the program.