QUALITY INITIATIVES

IN THE AIR FORCE DEVELOPMENT

OF REUSABLE LAUNCH VEHICLES

THESIS

Charles S. Galbreath, Captain, USAF
AFIT/GSO/ENY/01M-03

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

in Partial Fulfillment of the Requirements for the

Degree of Master of Science in Space Operations

Charles S. Galbreath, B.S.A.E., M.A.S.

Captain, USAF

March 2001

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Charles S. Galbreath, B.S.A.E., M.A.S.
Captain, USAF

Approved:

Milton E. Franke, PhD Thesis Advisor	5 Mar 2001 Date
E. Price Smith, Lt Col, USAF Committee Member	5 Mar 2001 Date
Curtis H. Spenny, PhD Committee Member	5 March 2001 Date

Acknowledgements

I would like to thank my faculty advisor, Dr. Milton Franke, for his guidance and support throughout the course of this thesis effort. Additionally, I would like to thank my AFRL sponsors Arthur Temmesfeld and Alan Taylor for the latitude afforded me in this endeavor and committee members, Lt. Col. Price Smith and Dr. Curtis Spenny, for their insightful guidance, wisdom, and feedback.

A researched based thesis of this type would not be possible without the support of numerous people providing their experience and insight. First, I would like to thank Maj. Nathan Titus, who pointed me in the right direction and volunteered invaluable information. Special thanks go to the Space Operations Vehicle Technology Office, especially William Gillard, for opening their office to me and providing direct and constructive input. I would, also, like to thank Robert Johnson for providing his analysis of shuttle operations and taking the time to discuss reusable launch vehicle development. I am also grateful for the experience of working with Jerry Carlin and Marcus Shaw and their continued support during the research of this thesis.

Last, but certainly not least, I'd like to thank my family for their patience and understanding during the entire AFIT experience, especially throughout the ordeal of thesis research and writing.

Charles S. Galbreath

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List of Acronyms

AFMC	Air Force Material Command
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
ACC	Air Combat Command
AIAA	American Institute of Aeronautics and Astronautics
APU	Auxiliary Power Unit
BIT	Built In Test
CONOPS	Concept of Operations
CRV	Crew Return Vehicle
DODSA	Department of Defense Space Architect
ELV	Expendable Launch Vehicle
ET	External Tanks
GPS	Global Positioning System
IMVP	International Motor Vehicle Program
INCOSE	International Council on Systems Engineering
IPT	Integrated Product Team
ISS	International Space Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
LAI	Lean Aerospace Initiative
LEM	Lean Enterprise Model

LESAT	Lean Enterprise Self Assessment Tool
LRU	Line Replaceable Unit
M&S	Modeling and Simulation
MASINT	Measurement and Signature Intelligence
MIS	Modular Insertion Stage
MIT	Massachusetts Institute of Technology
MSFC	Marshall Space Flight Center
MSP	Military Spaceplane
MTV	Multipurpose Transatmospheric Vehicle
MUA	Military Utility Analysis
NASA	National Aeronautics and Space Administration
NRO	National Reconnaissance Office
OPF	Orbiter Processing Center
PDVS	Product Development Value Stream
QFD	Quality Function Development
RLV	Reusable Launch Vehicle
SE	Systems Engineering
SEAS	System Effectiveness Analysis Simulation
SMC	Space and Missile Systems Center
SMC/XR	Developmental Planning Directorate, Space and Missile Systems Center
SMP	Strategic Master Plan
SMV	Space Maneuvering Vehicle
SOV	Space Operations Vehicle

SPST	Space Propulsion Synergy Team
SRB	Solid Rocket Booster
SSC	Stennis Space Flight Center
SSTO	Single Stage To Orbit
STS	Shuttle Transportation System
TAV	Transatmospheric Vehicle
TPS	Thermal Protection System
TRD	Technical Requirements Document
TSTO	Two Stage To Orbit
VAB	Vehicle Assembly

Abstract

This thesis identifies useful tools and techniques available to aid the Air Force development of a reusable launch vehicle (RLV). These tools are identified by comparing traits found within the Lean Aerospace Initiative, Six Sigma and systems engineering. While identified specifically for the RLV effort, these tools and techniques will be of use to many development programs. Historical perspectives of both RLV development efforts within the Air Force and origins of modern quality teachings are provided, to establish a common foundation of knowledge, upon which, further analysis can be conducted. This thesis, also, summarizes the current RLV effort within the Air Force and NASA. With the tool-set identified and the RLV effort enumerated, the tool-set and RLV effort are matched to determine the current level of integration. More importantly, the tools-set serves as the basis to form specific recommendations to aid the Air Force RLV effort.

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CHAPTER 1 INTRODUCTION

Throughout the distinctive history of military space operations, the paradigm of expendable launch vehicles has remained. Extensive launch lead times and delays are accepted and considered the norm. Additionally, with virtually no means of satellite retrieval, for repair or upgrade, satellites are designed with multiple redundancies to ensure reliability. This creates tremendous cost and weight penalties in satellite design. Within the Air Force there is a movement to change the expendable launch vehicle constraint. The development of a reusable launch vehicle (RLV) system will fundamentally change the nature of space operations. By shifting from a launch on schedule toward a launch on demand mindset, the Air Force will provide improved space support into any theater of operation and help to assure the United States' access to space. Furthermore, the ability to recover on-orbit assets will allow satellites to be designed with less expense and greater capabilities. While RLVs potentially offer great benefits, the development of such systems is technically complex and programmatically challenging.

The goal of this thesis is twofold. First, it identifies tools and techniques, found within modern quality approaches, available to aid the Air Force development of a reusable launch vehicle system. Second, the tools and techniques identified are applied to the RLV efforts within the Air Force. An assessment of current tool usage,

accompanied by examples, and identification for potential improvements is made. The objective is not to be prescriptive or to uncover some hidden truth that will suddenly make RLV development easy. Rather, the purpose is to provide a unique perspective on many issues facing RLV development, which may lead to innovative solutions to existing problems. In accomplishing these goals, this thesis will demonstrate the basic notion that there is a myriad of approaches to achieve quality and emphasizes the importance of examining multiple methods and not locking solely into one, oblivious of all others. For the purpose of this thesis, quality is taken to be activities intended to achieve improved products and processes and is not limited solely to the concept of quality popularized in the 1980s. In fact the later form of quality is a subset of the larger concept addressed in this thesis.

1.1 Scope

The goal of developing reusable launch vehicles is the modern "Holy Grail" within the aerospace community. This is illustrated in the many RLV activities currently under development. The X-Prize is one example of this worldwide effort to achieve a RLV system. Currently, 19 companies, from five countries, seek to win the $10 million prize for building a privately funded vehicle to fly three people into space, return and repeat within two weeks [9]. Within the Air Force and National Aeronautics and Space Administration (NASA), several X-Vehicle programs hope to advance the technology required to deploy RLVs [38]. Other private development is also ongoing within the companies building the X-Vehicles. While the component of the aerospace industry involved in RLV development is large, the scope of this thesis will be confined

exclusively within the Air Force and NASA efforts. Specific activities within industry and private development efforts such as Roton and Kistler will not be addressed [27][46]. This is not to say that potential benefits will not arise from these activities, but the assumption is that the preponderance of benefit will come from efforts within the government development programs. The scope, in terms of RLV development, of this thesis is pictorially represented in Figure 1-1, where the front pane represents the totality of the current RLV community: industry, private development, Air Force and NASA programs. As time progresses, the landscape of RLV activity will change and evolve in unpredictable ways. Within the current Air Force and NASA efforts include the development of various prototype vehicles, and therefore are included in the scope, represented by the inner box.

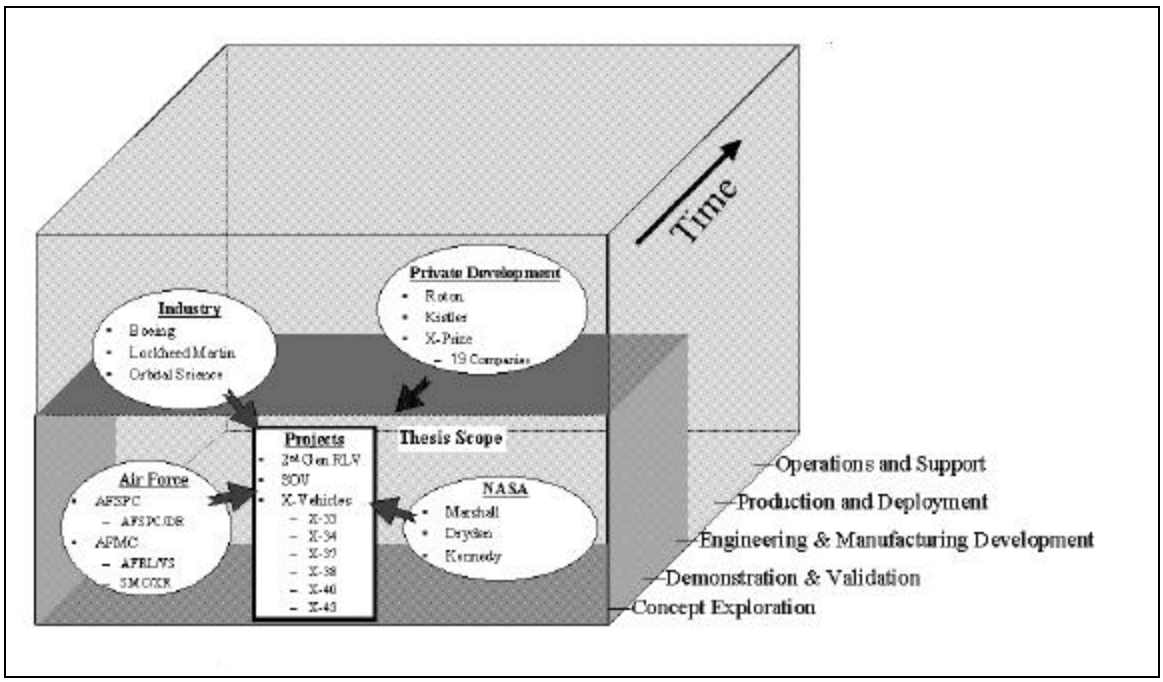


Figure 1-1 Thesis Scope of RLV Development

Also essential to this thesis is an examination of the various quality approaches available to aid RLV development. These quality approaches create the framework with which current RLV development efforts are analyzed. Initially, the research of this thesis focussed on the concepts found within the Lean Aerospace Initiative (LAI), continuing the efforts of previous AFIT thesis work by Endicott [13] and Matuzsack [34]. While their work concentrated on the applicability of lean to operational issues, here the emphasis is on developmental efforts. Other lean research, conducted at the Massachusetts Institute of Technology (MIT), also examines RLV development, with a greater emphasis on commercial systems and sole reliance upon LAI [35]. This thesis expands the analytic framework by including Six Sigma and systems engineering approaches to quality improvement in the early phases of development, which the Air Force and NASA are currently operating. The inclusion of the Six Sigma and systems engineering approaches came with the realization that in order to maximize the benefit to the Air Force RLV effort a broad-based approach must be used; because no single quality initiative possesses all possible techniques offering promise to the Air Force.

1.2 Methodology

The first step to determine what quality initiatives offer the RLV effort is to conduct a literature review of both quality and RLV topics. The examination of both historical attempts and current efforts in RLV development within the Air Force and NASA, followed by an introduction to modern quality, contained in Chapter 2, will provide the necessary background information required to conduct subsequent analysis and make recommendations for improvement. Step two, contained in Chapter 3,

identifies key traits and similarities between quality approaches to arrive at a set of unquestionably useful techniques and practices. These are then applied in Chapter 4 to the current RLV efforts to determine how quality techniques are already being used and how they can further benefit reusable launch vehicle development. Most of the issues discussed, particularly in Chapter 4, are of a programmatic nature, focussing more on managerial approaches to insure system success rather than on technology in and of itself. Certainly, technology represents one of the largest risk areas to RLV development and the various technology maturity efforts will, therefore, be discussed. Recognizing the difference between academic identification and practical employment of these techniques, Chapter 4 also discusses some of the potential issues associated with real-world application of the recommendations.

1.3 Limitations

Within the analysis of RLV efforts, one main limiting factor overshadows all others. Simply, the current RLV programs of NASA and the RLV efforts within the Air Force are still in the very early stages of development. The designs for finalized systems do not exist and therefore many of the operational issues have not matured to the point allowing detailed analysis. The influences of the lack of definition are minimized by the nature of this thesis. By focussing on the programmatic aspects of development, undefined operational issues are not of paramount concern. Rather, it is the development of those operational issues and the practices employed by the Air Force and NASA teams that are pertinent. While other limiting factors such as time and expense are present, their impacts do not play as significant role as the emergent nature of the RLV efforts

CHAPTER 2 BACKGROUND

The history of RLV development, insight into current thinking and a basic understanding of the prevailing RLV efforts provides the framework from which analysis may be thoughtfully undertaken. Similarly, an appreciation for the background of current quality initiatives will prove beneficial.

2.1 Air Force Reusable Launch Vehicle Development

2.1.1 *Historical Perspective*

The Air Force goal of a military spaceplane (MSP) is not a new one. The first major Air Force effort to build an MSP was the Dyna-Soar (for Dynamic Soaring) rocket plane. Also known as the X-20, this vehicle harbored the Air Force ambition to have a manned space program between 1958 and 1963. The vehicle design was a wedge shaped delta wing aircraft, launched into orbit by an expendable booster. Once in orbit, plans called for maneuvering capability, controlled by the vehicle's lone pilot. Finally, the Dyna-Soar would have the ability for controlled re-entry and the capability to land like an airplane. The original mission for this system was transcontinental bombing from orbit. After technical challenges rendered this mission impractical, a growing financial constraint led to its cancellation in December 1963, two years before its first scheduled orbital flight. While the Dyna-Soar never achieved operational status, the over 2,000 hours of wind tunnel tests (Figure 2-1), advancements in environmental controls and guidance subsystems proved invaluable in other space developments, including the Space Shuttle [28][53].

Figure 2-1 Dyna-Soar Wind Tunnel Model, 1960 [12]

The next Air Force project designed to advance military spaceplane technology was the X-24 series. This joint Air Force/NASA project investigated high altitude supersonic use of a lifting-body design. This approach used the body contours and aerodynamic control surfaces rather than wings to provide lift. While the X-24 was not intended to achieve operational status, plans called for a rocket booster to launch a similar vehicle into space where it could ferry crews and supplies to the planned military space stations, return through the atmosphere and land like a plane. The X-24A, depicted in Figure 2-2, performed 28 powered drop tests from a B-52, serving to validate the lifting body design, which in turn guided the development of Space Shuttle designs [40].

Figure 2-2 X-24A [63]

The national effort to build the Space Shuttle represented the next attempt by the Air Force to operate a military spaceplane. Unlike previous Air Force efforts, this was not a new design specific to the Air Force, but a modification of the already existing NASA Space Shuttle. The plan called for Space Shuttle systems fully launched, controlled and operated from within the Air Force. The *Challenger* tragedy in 1986, ended this plan, but served to organizationally solidify space within the Air Force [53].

2.1.2 *Vision and Policy*

Throughout the late 1980s and 1990s, the dream of a military spaceplane remained in the plans and visions of Air Force thinkers. In 1994, Air University published *SPACECAST 2020*, a collection of various operational research analysis white papers examining concepts for the future of the Air Force. Two systems clearly stood out in the minds of the analysts, a high-energy laser and a transatmospheric vehicle (TAV). "The TAV contributed to virtually all space missions because it made access to space easier" [52]. A rocket powered spaceplane, the TAV, also known as "Black Horse," was

envisioned as being slightly larger than an F-16 [52]. The particular design features of the TAV are not as important as the continued expression by the Air Force of the need for a MSP. Another Air University publications, 1996's *Air Force 2025*, reiterated the desire for a MSP [1]. The multipurpose transatmospheric vehicle (MTV) was to be a single platform capable of such missions as intelligence, surveillance, reconnaissance, global mobility, and strike. Additionally, the Global Area Strike System section of *Air Force 2025* further developed the concept of the TAV [1].

Thoughts about military spaceplanes were not confined to Air University. The joint National Reconnaissance Office (NRO) and Department of Defense Space Architect (DODSA) "Launch on Demand Impact Study" examined the far-reaching changes a RLV system would have on the nature of warfare [11]. Finally, Air Force Space Command's Strategic Master Plan (SMP) for fiscal years 2002 and beyond, explicitly calls for the Space Operations Vehicle and Space Maneuver Vehicle, currently advocated within the Air Force. This document clearly identifies the shortcomings of current spacelift system stating:

> "…complex, non-standard launch vehicle-to-payload interface designs and lengthy processing timelines lead to costly operations for both payload and launch vehicle. Future operations demand a reduction in preparation and integration timelines from months to hours and a substantial reduction in O&M costs" [6].

Of the over 60 Air Force Space Command (AFSPC) mid-term (2008-2013) prioritized needs, "On Demand Space Asset Operation Execution" ranked in the top 10. The SMP continues to lay out a course of action for the Air Force, stating that cooperation with the NASA RLV efforts will enable future AFSPC programs in the mid and far-term years. Additionally, the Air Force should closely follow the RLV developments made in the

commercial sector. The Strategic Master Plan, recommends the development of a two-stage-to-orbit (TSTO) SOV, followed by efforts for a single-stage-to-orbit (SSTO) version, if warranted.

While the vision within the Air Force clearly calls for a military spaceplane, current national space policy does not allow for such development. First stated in the 1994 *National Space Transportation Policy*, the Air Force has been restricted to expendable launch vehicle (ELV) development, while NASA is given the responsibility for RLV development [56]. This sentiment was again expressed two years later in the *National Space Policy* [55]. The pertinent directives from this policy are as follows:

> "NASA will work with the private sector to develop flight demonstrators that will support a decision by the end of the decade on development of a next-generation reusable launch system."
>
> and
>
> "DoD, as launch agent for both the defense and intelligence sectors, will maintain the capability to evolve and support those space transportation systems, infrastructure, and support activities necessary to meet national security requirements. DoD will be the lead agency for improvement and evolution of the current expendable launch vehicle fleet, including appropriate technology development" [55].

Clearly, with such guidelines, for the Air Force to retain any hope of ever operating a military spaceplane, it must work closely with and rely heavily upon NASA.

2.1.3 *Current Effort*

The most thorough military spaceplane initiative in decades emerged in 1998 with the release of the "Concept of Operations for the Phase I Space Operations Vehicle System" [4]. More than a single military spaceplane, the Space Operations Vehicles system not only calls for a highly flexible, lightweight space launch vehicle (SOV), but a

Modular Insertion Stage (MIS) and Space Maneuver Vehicle (SMV) as well. The role of the MIS is to support orbital payload delivery from a sub-orbital SOV flight. The SMV will provide larger payloads with extra on-orbit maneuverability. The CONOPS recognizes the current role of the Air Force in RLV development and the importance of leveraging with NASA efforts. This is exemplified by the Memorandum of Agreement signed between AFSPC, AFRL, and NASA in 1997, formalizing the relationship between the entities in the development of the SOV and NASA's RLVs [4].

A very comprehensive document, the CONOPS also identifies two key technical challenges. The first is the development of an advanced, efficient and highly operable propulsion system. The second is the development of lightweight structures including cryogenic tanks and thermal protection systems. Since these are the same key technologies being demonstrated by the X-33 program, the CONOPS states that with close working relationship with NASA the Air Force plans to leverage off the X-33 for the SOV development [4].

The CONOPS also addressed the operational issues of the Space Operations Vehicle System. One such facet, is the required level of reliability. Ideally, the reliability of the SOV would approach the levels achieved by commercial air traffic, allowing operations near populated areas [4]. This would allow the greatest level of operational flexibility. Another facet is the desired sortie rate of an SOV. With a peacetime rate of one flight every five days, the SOV is identified to have the capability, in wartime, to achieve a flight a day for a duration of four days. Additionally, the SOV is to be capable of multiple mission types, across all four AFSPC mission areas, Space Control, Force Enhancement, Force Support, and Force Application. Knowledge and

recommendations on mission capabilities are to come from modeling and simulation efforts (M&S), wargaming and military utility analysis [4].

Nearly a year after the Space Operations Vehicle System CONOPS, Air Force Space Command expanded the system definition with the release of the "Concept of Operations for the Space Maneuver Vehicle System". Originally intended as the primary payload of the SOV, the SMV's operations have been expanded to include delivery from expendable launch vehicles (ELVs). The SMV is envisioned to be an unmanned orbiting vehicle with an integral propulsion system, able to complete its orbital mission return to earth and be re-launched in a short period of time [5]. Figure 2-3 contains an artist conception of an SOV deploying an SMV.

Figure 2-3 Artist Concept of SOV with External SMV [50]

Like the SOV CONOPS earlier, the SMV CONOPS calls for a close relationship with NASA. Technologically speaking, the SMV is a much simpler system than the SOV. With only a few technical hurdles remaining, such as a reusable main propulsion system,

the largest technical challenges come from overall vehicle integration, required to achieve the goal of aircraft-like operation. Aircraft-like operation is an essential element of both the SOV and SMV systems. The turn around time for the SMV, in emergency situations, is anticipated to be only a few hours, a remarkable improvement over current capabilities. With another system providing the launch capabilities, the SMV is allowed to have a looser standard for accidental loss rates. The SMV objective is less than one failure per 100 sorties, a far cry from the objective SOV standard of airline reliability, with only one catastrophic failure in 2,000,000 flights [5][29].

With the concepts of operation for both the Space Operations Vehicle System and the SMV in place, groups within the Air Force are currently undertaking the task of system development. The primary center for SOV and SMV development is the Military Spaceplane Technology Office of the Air Force Research Laboratory. With a main branch overseeing all activity and concentrating on the SMV at Kirtland AFB and a branch responsible for the SOV system, the technology office views its primary responsibility as advocate for the military spaceplane. This includes maintaining a relationship with NASA, promoting the development of beneficial technologies and educating the Air Force on the capabilities and benefits of military spaceplane systems [58]. To this end, the program office, with engineering experience and technical insight have used the SOV and SMV CONOPS to create a Systems Requirements Document for the SOV and a Technical Requirements Document for the SMV. These documents provide quantifiable criteria for many of the operational and design features of each craft. They are used to support concept development, postulate performance requirements,

support development of mission needs statements, and provide a baseline for wargaming and other M&S activity [2][3].

2.2 NASA RLV Development

As identified above, the Air Force efforts are closely linked to the technology programs and RLV development efforts within NASA. With this dependency established it is important to understand the NASA history of RLVs and their current programs.

2.2.1 *Space Shuttle*

As the first reusable launch vehicle, the Space Shuttle represents a major leap in spacelift capabilities. Since its development in the 1970s, the Shuttle Transportation System (STS) has accomplished over 100 missions, placing more than 2.75 million pounds of cargo into orbit. Most people are aware of the success of the STS, deploying and repairing satellites, its instrumental role in building the International Space Station (ISS), and the many scientific studies conducted while in orbit. But few are fully aware of the infrastructure required and the operational practices involved in keeping this marvel of modern science flying. While the launch, on-orbit and recovery operations, illustrated in Figure 2-4, garner the public's attention, it is the ground operations that make it all possible. In four major centers, Kennedy Space Center (KSC), Johnson Space Center (JSC), Marshall Space Flight Center (MSFC), and Stennis Space Center (SSC), over 1000 civil servants are employed to ensure safe operations. Additionally, approximately 12,500 contractors are part of the United Space Alliance, responsible for ground processing and launch operations [24].

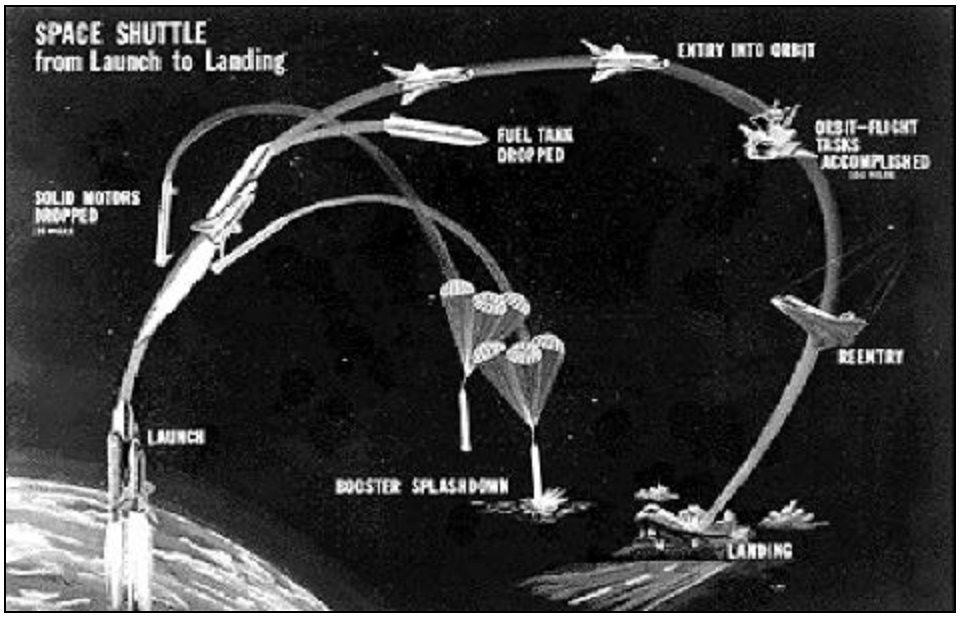


Figure 2-4 Generic Shuttle Mission Profile [24]

Not only do STS ground operations required thousands of people, but also considerable lengthy, demanding a massive supporting infrastructure. Upon return from a mission each orbiter must undergo a thorough refurbishment routine lasting approximately 10 weeks. Conducted at the Orbiter Processing Facility (OPF), mechanical, fluid, electrical and thermal control systems are inspected and prepared for another launch. Other activities include post-flight troubleshooting, payload bay removal and reconfiguration, and complete system checkout. The orbiters are not the only components of the STS to undergo refurbishment. The solid rocket boosters (SRB) are also recovered, using barges, and returned for refurbishment, as illustrated in Figures 2-5 [24].

Figure 2-5 Solid Rocket Booster Being Returned By Barge [24]

The SRBs are moved to a cleaning area, inspected, and disassembled. From there, the SRB motor segments are sent by rail to Utah, while the skirts are delivered to KSC to the Assembly and Refurbishment Facility. Once the motors are reloaded with propellant, they return to KSC, again by rail. The solid rocket boosters are then reassembled in the massive Vehicle Assembly Building (VAB). Figure 2-7 illustrates the solid rocket boosters being stacked, mated to the external tank, and finally mated with the orbiter, within the VAB. Typically, the entire stacking and mating procedure takes six weeks [24].

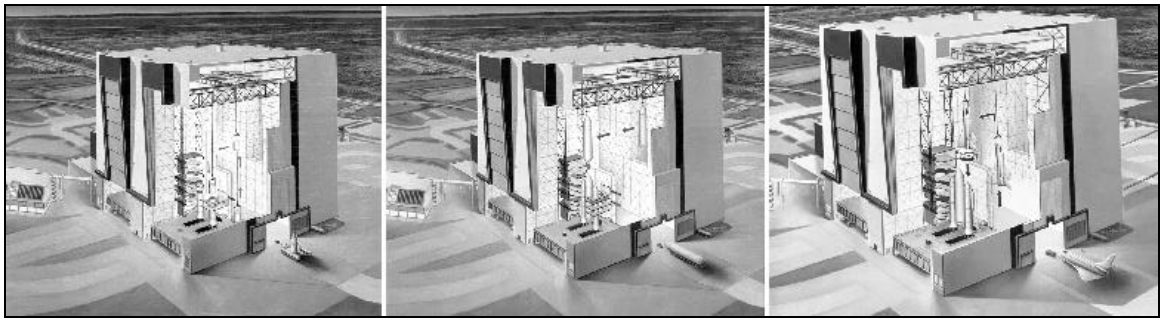


Figure 2-6 Shuttle Assembly at VAB [24]

Once the STS has been reassembled, it is rolled to the launch site, by one of two six million pound crawlers. An additional 21 days of processing may be required at the launch site. During this time, propellants and cryogenics are loaded, final checkouts performed and ordinances are connected. The infrastructure necessary to support ground operations is also considerable, as illustrated by some of the facilities at Kennedy Space Center, in Figure 2-8 [24]. The intent of this section was not to provide a detailed description of shuttle ground processing, but rather to provide some appreciation for the enormous amount of effort required in ground processing. While the Shuttle Transportation System is a remarkable achievement, to reach the Air Force objective of aircraft-like operation, improvements must be made.

2.2.2 *Second Generation Reusable Launch Vehicle*

NASA recognizes the need for improvement and has begun the necessary steps to develop a shuttle replacement system. The Second Generation Reusable Launch Vehicle Program plans to begin full-scale development after 2005, in order to operationally field a system by 2012. This system hopes to improve safety by a factor of 100 and reduce launch costs by a factor of 10. While set designs are not yet in place, various demonstration programs, in the form of X-Vehicles, are ongoing to mature the required technology and allow for smoother development of the Second Generation RLV in the coming years [48]. Descriptions of these X-Vehicle programs are contained in Chapter 3, with fact sheets available in Appendix B.

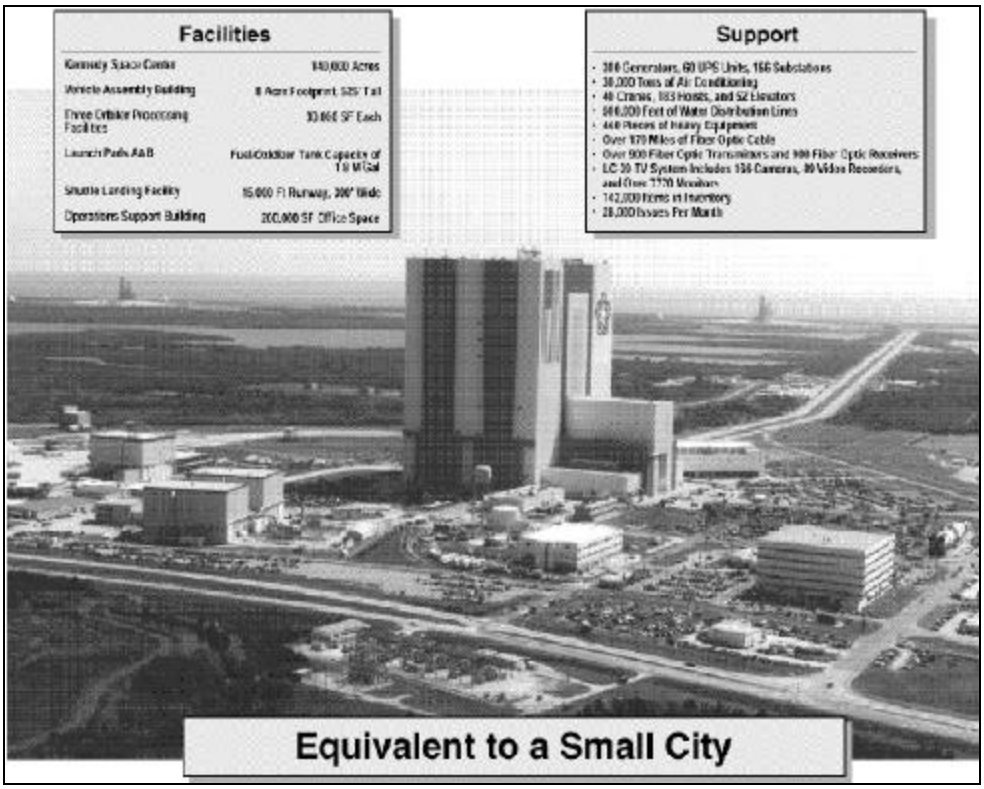


Figure 2-7 Kennedy Space Center [24]

2.3 Introduction to Quality Initiatives

Just as the concept of a reusable military spaceplane is not new to the Air Force, or RLV operations new to NASA, the concepts of quality are not new. As with RLVs, an appreciation of the fundamentals of quality is necessary before continuing with analysis or application.

2.3.1 *Origins of Modern Quality*

Not only are the concepts of quality not new, they are very old. An example of this is found in the Code of Hammurabi, dating from 2150 B.C. Contained within the many provisions is the following, "If a builder has built a house for a man, and his work is not strong, and the house falls in and kills the householder, that builder shall be slain" [18]. While such penalties are frowned on in modern times, certainly the accountability, conformance to requirements and fitness for use aspects of the code parallel modern thoughts on quality [47]. Today, quality implies more than this early example. "Quality is a judgment by customers or users of a product or service; it is the extent to which the customers or users believe the product or service surpasses their needs and expectations" [18]. The idea that the needs and expectations are not to be merely met, but surpassed, is an essential point to modern quality. But to get to this point took many years with multiple incarnations of quality. During the Renaissance period in Europe, apprenticeships and guilds were established to ensure the craftsmanship and quality of workmanship. This was sufficient in an isolated society with little choice in builders [18]. With the emergence of industrial society came freedom of choice for the consumer. Manufacturers now had to compete for business, and thus had to improve quality and lower costs.

In the United States, Scientific Management appeared as an early attempt to achieve new levels of quality and reduced cost. Created by Frederick Taylor, Scientific Management sought to improve worker performance through application of engineering practices and scientific methods. Taylor stated four foundations with which management should build their systems.

- Develop a science for each element of a man's work
- Scientifically select and then train, teach and develop workman
- Develop a healthy cooperation with workers
- Equally divide work between management and workers [62]

Even though the focus of Taylor's efforts were on manual labor, the improved management/worker relationship and analysis of activity he spoke of 100 years ago are very much a part of modern quality. Other facets of quality continued to emerge in the subsequent years. Included in this list of developments are Shewhart's statistical quality control, Deming's Plan-Do-Check-Act cycle, statistical analysis, Pareto analysis, and the works of Juran, Crosby, and Ishikawa [47][62]. Largely ignored within the United States, quality techniques emerged in the 1980s as a means to compete with the Japanese, who had successfully incorporated quality teachings.

Today quality has spread throughout the United States, spanning across all areas of business and gained unprecedented support. With this expansion, has come a boom in the number of names and approaches used to achieve quality. Some of these approaches are Total Quality Management, Zero Defects, Continuous Quality Improvement, "Faster, Better, Cheaper", and the ISO 9000 standards, just to name a few. With so many approaches attempting to achieve the same basic objective, a certain level of confusion on the part of potential users is understandable.

CHAPTER 3 ANALYSIS

There are many techniques found within the Lean Aerospace Initiative, Six Sigma and systems engineering which offer promise to the Air Force reusable launch vehicle effort. The techniques include modeling and simulation, value stream mapping, baselining and benchmarking current systems, statistical analysis, use of integrated product teams, requirement definition and incremental improvements. To identify those techniques most beneficial, an analysis of the Lean Aerospace Initiative, Six Sigma and systems engineering is conducted. Once identified, these tools are tailored for suggested use by the Air Force reusable launch vehicle effort.

3.1 Analysis of Lean Aerospace Initiative, Six Sigma and Systems Engineering

Over the course of modern management development, there remains the goal of achieving increased performance at reduced cost. Despite this common objective, each modern quality initiative approaches the solution in a slightly different manner. In order to determine how the three quality initiatives can contribute to the reusable launch vehicle effort, an analysis of their approaches is conducted. With this analysis both commonality and differences are identified. Those areas in common can be considered basic truths, with a foundation in modern common sense. Where the three approaches differ, does not suggest a falsehood, but rather an original method to achieving the continual objective of customer satisfaction. While these solutions will be tailored for application to the Air Force reusable launch vehicle effort, their basic methodology can be applied to virtually any program.

3.1.1 *Choosing Lean Aerospace Initiative, Six Sigma and Systems Engineering*

For this thesis, three modern quality initiatives were selected for a variety of reasons. The Lean Aerospace Initiative (LAI) was selected for its current role within the Air Force. A collaboration between industry, the Massachusetts Institute of Technology (MIT) and the Air Force, LAI represents the Air Force's plans to improve quality [54]. Jacques Gansler, Under Secretary of Defense for Acquisition and Technology, stated "I am counting on the Lean Aerospace Initiative to play a leading role in the Revolution in Military Affairs and the Revolution in Business Affairs" [15]. Next, the approach known as Six Sigma was selected for its statistical basis and reputation it has gained as one of the best-known American contributions to quality improvement [47]. The practice of systems engineering rounds out the list of quality initiatives analyzed in this thesis. Systems engineering was selected for its wide-spread use in technical development programs and its awareness of architectural interdependencies. While each of these approaches is unique, they are also bound by a common objective some of the tools and techniques will overlap. Furthermore, the common objective of customer satisfaction places each of them within the collective umbrella concept of quality. This idea is illustrated in Figure 3-1. While LAI, Six Sigma and systems engineering were selected for this thesis and thus represented in this figure, any of the modern quality initiatives and approaches discussed in Chapter 2 could be represented in a similar manner. It is also important to remember that the size of each initiative's domain and overlap among initiatives will vary from program to program.

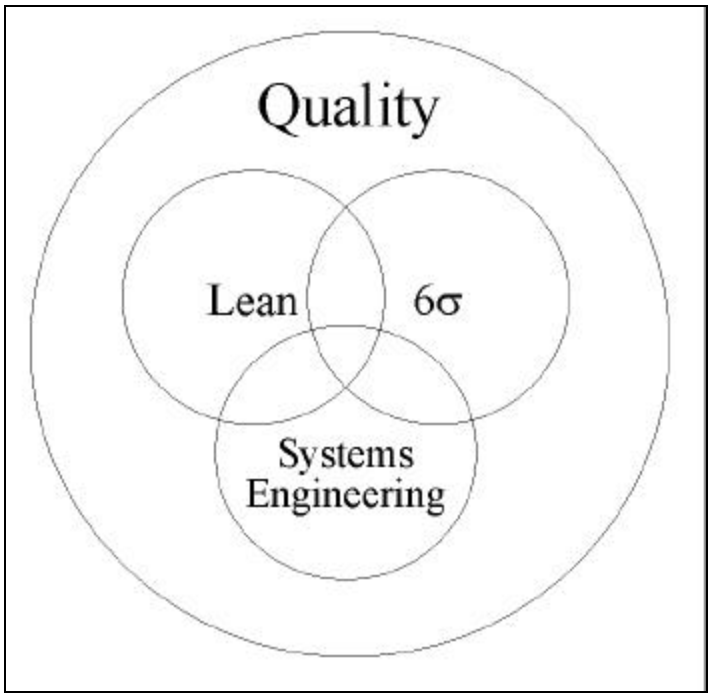


Figure 3-1 Notional Representation of Modern Quality Initiatives

3.1.2 *Lean Aerospace Initiative*

3.1.2.1 Foundation

The Lean Aerospace Initiative traces its roots to the automotive innovation of the Toyota Motor Company, whose remarkable production and management system was described in the book, *The Machine that Changed the World* [60]. This book served as one of the results of the International Motor Vehicle Program (IMVP) [33]. Conducted by the Massachusetts Institute of Technology (MIT) to study the automotive manufacturing techniques used worldwide, the IMVP sparked a quest for lean and a removal of wasteful practices in the United States. As the concepts of lean became better understood within the aerospace community, a consortium was formed among the Air Force, the aerospace defense industry and MIT. The Lean Aerospace Initiative (LAI)

was formed in 1993 to identify and implement lean principles and practices in Air Force acquisitions [33]. In a three phased approach, the LAI has conducted research, developed and deployed tools to support implementation across every sector of Air Force acquisition. Currently in phase three, the LAI is seeking to eliminate barriers to implementation, enhance the effectiveness of the national workforce, and emphasize education of LAI principles [54].

3.1.2.2 Basic Principles

Two of the original authors of *The Machine the Changed the World*, Womack and Jones, continued their advocacy of lean in the book *Lean Thinking* [61]. In this book they identify five general principles to lean thinking. The first of these principles is "value" which they defined in terms of "specific products and services having specific capabilities offered at the specific prices to specific customers" [33]. In other words, it is providing the right thing to the right place at the right time. The next principle is "value stream." The value stream for a product is all activities required to transform raw materials into a finished product in the hands of the user. Within the value stream, all activities are classified in one of three categories: creates value, does not create value but is unavoidable given constraints, and has no value and can be eliminated [33]. The third principle is "flow." Once the waste has been removed from the value stream, the remaining activities must work together to create a seamless flow. Small lot production is used with single unit batch sizes as the ultimate goal [33]. Throughout the value stream the effects of the fourth principle, "pull", are felt. The customers pull of the product at the end of the value stream cascades up the supply chain creating a just-in-time nature within the enterprise. Finally, there is the principle of "perfection." This is the

realization that continuous process improvements can be made. Therefore, product improvement, time savings and cost reductions are ongoing activities. With these basic principles, the Lean Aerospace Initiative has sought to improve Air Force acquisitions and has created many tools to help realize the this goal.

3.1.2.3 Tools and Techniques

One of the first tools available to organizations seeking lean was the Lean Enterprises Model (LEM). This systematic framework encompasses the above mentioned principles and was generated from research-based benchmarking. With over sixty identified enabling practices contained within twelve overarching practices; the LEM is designed to assess the leanness of an organization or process [32]. The overarching and enabling practices of the Lean Enterprise Model can be found in Appendix A. Another useful technique is found within the basic principles themselves. By mapping the value stream of a process, an organization can readily identify those areas of waste. This enhanced understanding is essential to process improvement. Recently the LAI has developed "Transitioning To A Lean Enterprise: A Guide for Leaders", a three volume set of information about lean that detail activities for implementation and outlines potential barriers [33]. The Lean Enterprise Self-Assessment Tool (LESAT) is currently in development. This assessment is designed for leadership to gain understanding of how effectively their organization is integrating the concepts of lean within their core and supporting processes. It must be stressed that the benefit of such a tool is not in the score received, but from the objective insight gained and the additional knowledge of how to achieve lean [31].

3.1.3 *Six Sigma*

3.1.3.1 Foundation

Six Sigma emerged as the management principle responsible for the dramatic change in Motorola in the 1980s. Through the use of Six Sigma, Motorola transformed itself from a company on the verge of requiring government support to a company receiving the first ever Malcolm Baldrige National Quality Award in 1988 [20]. In 1981, Motorola senior management committed to improve overall quality tenfold. They decided to track the single metric of "total defects" and through statistical analysis managed to reduce waste, increase profits and reshape their entire organization [47]. With the opening of the Six Sigma Academy in 1994, this initiative has improved the profit margins of many companies, including General Electric, Allied Signal, DuPont Chemical, and Polaroid. Originally only applied to the manufacturing sector, General Electric was the first to apply Six Sigma to services. The improvements at General Electric, since the introduction of Six Sigma, have been exceptional, including an 11% growth in revenue and a 13% growth in earnings [21].

3.1.3.2 Basic Principles

The meaning of Six Sigma comes from statistics and the incredibly small percentage found under a normal curve, beyond six standard deviations from the mean. Changes in the various level of standard deviation are depicted in Figure 3-1. If defects can be confined to this small percentage, less time and money will be consumed correcting problems, customers will be more satisfied and profits will increase. Achieving this level of production is not easy. Traditionally, companies accept three or

four sigma performance despite the fact that this creates between 63 to 2700 problems per million opportunities [44].

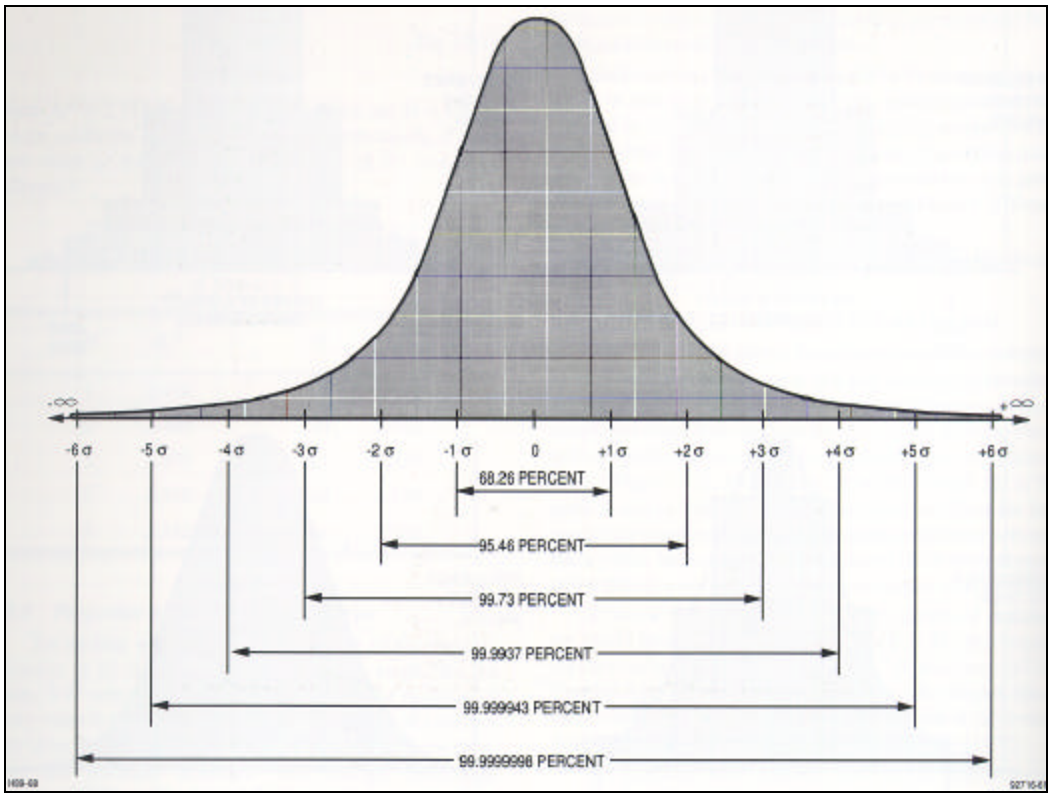


Figure 3-1 Typical Areas Under the Normal Curve [20]

Six Sigma is more than just statistical analysis. It is a long term, forward thinking initiative to fundamentally change the way a corporation does business. Additionally, it expands the normal scope of quality efforts to put the emphasis on economic value for the customer and the supplier [21].

3.1.3.3 Tools and Techniques

Naturally, with an initiative named for a statistical region under a curve, Six Sigma relies heavily on statistical analysis and measurement. But to accomplish this level of performance requires other tools and techniques. Pyzdek notes that the

techniques of Six Sigma are not new but rather are the tried and true methods proven over many decades [44]. Six Sigma trains a small group of change agents in a handful of proven quality methods and places them throughout the organization. These change agents are broken into different levels, based on their experience, skill with Six Sigma techniques, and level within the organization [21]. Some of the most important of these change agents are those in senior level leadership positions. Since the actions of Six Sigma will cut across typical organizational boundaries, only senior leadership can successfully implement this approach [44]. The tools that these change agents utilize are applied within the "Breakthrough Strategy." This strategy differs slightly for each segment of a corporation employing Six Sigma [21]. The business and operations perspectives on the "Breakthrough Strategy" are given in Table 3-1.

Table 3-1 Six Sigma Breakthrough Strategy [21]

	Business Perspective	**Operations Perspective**
R	Recognize the true states of your business	Recognize operational issues that link to key business systems
D	Define what plans must be in place to realize improvements	Define Six Sigma projects to resolve operational issues
M	Measure the business systems that support the plans	Measure performance on the Six Sigma projects
A	Analyze the gaps inn system performance benchmarks	Analyze project performance in relation to operational goals
I	Improve system elements to achieve performance goals	Improve Six Sigma project management system
C	Control system-level characteristics that are critical to value	Control inputs to project management system
S	Standardize the systems that prove to be best-in-class	Standardize best-in-class management system practices
I	Integrate best-in-class systems into the strategic planning framework	Integrate standardized Six Sigma practices into policies and procedures

One of the more understated techniques of Six Sigma is the realization that incremental steps must be used on the path toward achieving the desired level of performance. When

Motorola earned the Malcolm Baldridge Award in 1988, they had not yet achieved a six sigma level of performance. In fact their goal was to reach six sigma four years later in 1992 [47]. This approach is reiterated in the practice of focussing financial achievement in 12-month increments [21]. The final technique of Six Sigma introduced in this thesis is benchmarking. Through the use of benchmarking, companies can gain a competitive edge over competition. Companies utilizing Six Sigma view benchmarking as an essential tool and use it as a stepping stone for greater success. Six Sigma defines three types of benchmarking. First, internal benchmarking focuses on common practices among diverse functions within the same company. For example the supply practices of the accounting department may be compared with the supply practices of the engineering department. The second type of benchmarking is competitive and obviously focuses on the practices used by competitors within the same industry. Finally, there is functional benchmarking. Similar to internal benchmarking, functional expands the range of comparison to other companies, regardless of industry [21].

3.1.4 *Systems Engineering*

3.1.4.1 Foundation

Unlike LAI and Six Sigma, which emerged from private industry, systems engineering (SE) began within government projects [22]. Built on the best practices of the 1940s, 50s and early 60s, systems engineering was essential to the success of early national satellite systems of the 1960s. Additionally, systems engineering shares many common practices with the highly effective Lockheed Skunk Works, responsible for such aircraft as the U-2 and SR-71 in the late 1950s and early 60s [14]. While initiated for

large, complex, multidisciplinary government projects, use of systems engineering has spread throughout industry, to large and small businesses [22]. Today, the International Council on Systems Engineering (INCOSE) seeks to refine systems engineering and advocate its use [23].

3.1.4.2 Basic Principles

While there is ongoing discussion on what exactly constitutes systems engineering, a few key points are universally accepted [30]. INCOSE offers the following to the question "What is Systems Engineering".

> "Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem" [23].

It seems natural that an organization seeking to successfully complete a complex challenge would utilize both an interdisciplinary approach and early requirement definition. Martin simply states "systems engineering is really about common sense" [30]. Beyond direct application, systems engineering offers a way to see past individual components, to see their interactions and the system as a whole [22].

3.1.4.3 Tools and Techniques

With such a broad definition of systems engineering it is not surprising that within systems engineering there lies a wide variety of tools. The objective here is not to list all possible tools and techniques available to systems engineers, but rather to highlight a few of the key ones. Above all, the systems engineering processes are driven by requirements. That is, throughout the project cycle, requirements are kept in the

forefront, shaping all actions [14]. This is best illustrated by the "Vee" model of the project cycle in Figure 3-2.

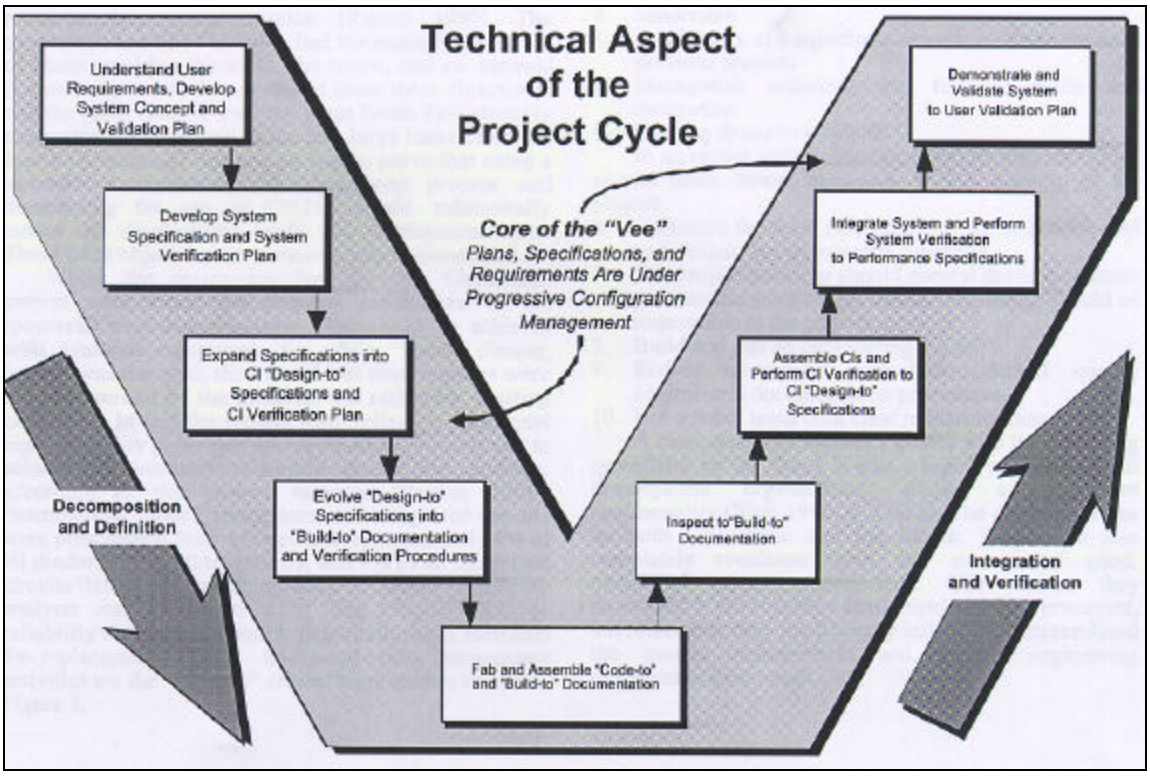


Figure 3-2 Systems Engineering "Vee" Diagram [14]

Once understood and agreed to, the requirements are placed under project control and subsequently serve to develop system ideas and specifications. Another model often used in systems engineering is the spiral model. In the spiral model, the basic methodologies of systems engineering are repeated throughout the life of a project. On successive iterations, design features are improved and defined from an initial concept to a final operational product. The spiral model is of particular use early in development to help determine what other models and techniques should be used for a given project [30]. Knowing that a system is complex, cutting across many disciplines, the use of integrated

teams is critical. Forsberg and Mooz cite the Clementine and Mars Pathfinder projects as two that effectively employed co-located integrated product teams. Their respective project managers deemed the use of these teams essential to project success [14]. Under the guidelines of the given constraints, each area must work with the other to balance their own requirements in order to obtain the most optimal design. Modeling and simulation are also frequently used in the systems engineering process and is useful in the identification and validation of requirements and the exploration of potential concepts. The tool-set available to systems engineering is virtually endless. Furthermore, it is the tailoring of existing tools and models, which makes systems engineering flexible and applicable to such a wide range of projects [14].

A summary of some of the salient features of the three quality initiatives discussed is provided in Table 3-2.

Table 3-2 Summary of Quality Initiatives

	Lean Aerospace Initiative	**Six Sigma**	**Systems Engineering**
Foundation	*The Machine that Changed the World*	Motorola Corporation	Government Projects
Basic Principles	Remove all wasteful operations and processes	Reduce defects and process variability	Examine the system in its larger context and achieve optimal balance between system elements
Tools, Techniques and Models	Lean Enterprise Model	"Breakthrough Strategy"	Process's are requirement driven
	Value Stream	Incremental Improvements	Spiral Development
	LESAT	Benchmarking	Co-located teams and IPTs
	Transitioning to a Lean Enterprise	Change Agents	Simulation Tools

3.1.5 *Similarities and Crossovers*

With the shared goal of improved quality, faster and cheaper development, it is not surprising that the three modern quality initiatives discussed have some commonality in the principles, tools and techniques to achieve this goal.

3.1.5.1 Top Level Leadership

All three initiatives state the importance of senior management leading the way. With the Lean Aerospace Initiative this fact is clearly spelled out in "Transitioning To a Lean Enterprise: A Guide for Leaders". In order for the transition to be successful it must be lead by top management, who fully embrace and commit to the ideas of lean and who are open minded to new concepts that may seem counter-intuitive [33]. This matches very well with the statements of Six Sigma on the importance of leadership. "Successful performance improvement must begin with senior leadership. Start by providing senior leadership with training in the principles and tools they need to prepare their organization for success" [44]. The role of the leader is to develop an infrastructure to support Six Sigma and remove barriers to experimentation and change. Leadership is also critical in systems engineering. As discussed earlier, since systems engineering calls for the use of integrated teams spanning beyond normal organizational boundaries, it is up to management to facilitate this activity. Additionally, the empowerment of project managers and subsystem managers was deemed one of the top five reasons for the success of the Clementine and Mars Pathfinder projects [14]. This level of empowerment can only come from executive management. Furthermore, within the context of systems engineering, part of the role of leadership is to clearly state and achieve consensus on requirements, which are critical to further system engineering efforts.

3.1.5.2 Spiral Development/Incremental Improvements

Another trait common among all three initiatives is the concept of incremental or spiral development. Previously identified under "Tools and Techniques" of both Six Sigma and systems engineering, incremental development is also an enabling practice with the Lean Enterprise Model [32]. Under the overarching practice of "Maximize Stability in a Changing Environment", the shorter timelines associated with an incremental approach allows for manageable improvements not as susceptible to unwanted outside influence. Simply put, to effect dramatic change within an organization takes time and if attempted all at once would be too large an undertaking. However, if the steps towards improvement are divided into more tangible and achievable objectives, success, albeit incremental, is more obtainable regardless of the quality approach being used.

3.1.5.3 Modeling and Simulation

Modeling and simulation plays an important role in both LAI and systems engineering. As discussed earlier, modeling and simulation is used in the system engineering process to validate requirements and explore potential concepts. Similarly in LAI, modeling and simulation is used to permit understanding and evaluation of the flow process [32]. This provides insight to the value stream and identifies critical linkages and areas of potential waste.

3.1.5.4 Integrated Product Teams

Also utilized by both LAI and systems engineering, integrated product teams provide the project manager with a balanced solution. The importance of integrated

teams was already discussed and is exemplified by the comments made by the project managers of the Clementine and Mars Pathfinder projects [14]. An overarching practice within the Lean Enterprise Model, "Implement Integrated Product and Process Development," calls for the use of people knowledgeable on all areas of the product's life cycle [32]. Perhaps the largest area of agreement between LAI and systems engineering, the first enabling practice identified under this overarching practice, is for those seeking lean to use a systems engineering approach in product design and development [32]. More than a mere overlap, the recognition of SE within the framework of LAI highlights a necessity to utilize multiple approaches to achieve improved quality. Here, LAI is stating the use of basic SE principles, such as requirement definition, problem solving techniques and big picture approach, can be of particular benefit. This obvious overlap is strengthened by the next enabling practice calling for the establishment of clear requirements. Recall that requirements shape the entire systems engineering process [14].

3.1.5.5 Value Stream Analysis

Although not specifically called out within Six Sigma, the concept of the value stream is applicable to all three of the modern quality initiatives discussed here. In order to reduce defects, Six Sigma identifies and attempts to remove costs that provide no value to the customer [44]. To identify these non-beneficial costs, some level of value stream mapping must be conducted. Recall from the previous discussion of the Lean Aerospace Initiative that the value stream is all activities required to transform raw materials into a finished product in the hands of the user [33]. Weiss and Warmkessel further break the product value stream into four component value streams as illustrated in Figure 3-3 [59].

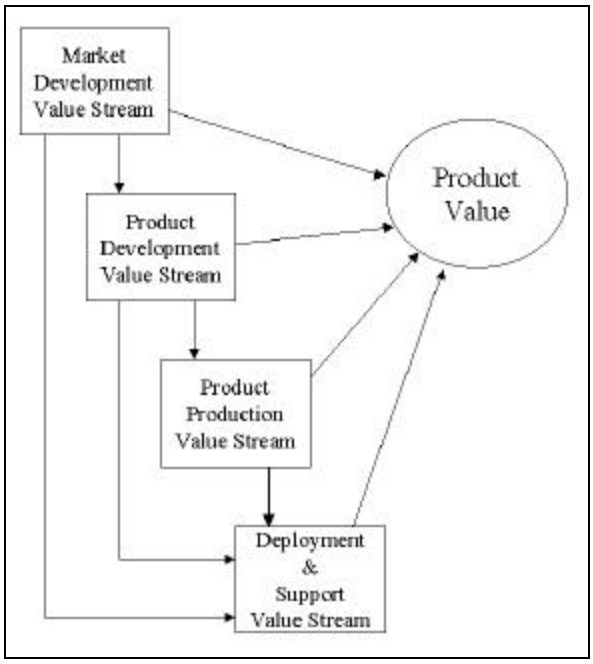


Figure 3-3 Components of Product Value Stream [59]

Focussing on the Product Development Value Stream (PDVS), they add that the systems engineering process provides a structured method for analysis.

> "The SE elements of requirements analysis and baseline validation are applied to developing the specification of the required value. Functional analysis is used to identify all the necessary activities and develop the optional sequence arrangements of these to achieve the end product. Synthesis trades those options against criteria generated to minimize interfaces and eliminate unnecessary activities. This step also trades the forms that will be used to communicate the tasks and their relationships within the value stream. Finally, verification and validation looks again at the PDVS to optimize flow and ensure that performing the specified tasks in the network will provide the specified value. Many times this involves an iterative process" [59].

The example of using the systems engineering process to aid in the definition of LAI concept of value stream mapping, effectively illustrates that the quality initiatives are not mutually exclusive, but rather operate very well together, each contributing to the others effectiveness. This cooperative approach is summarized in Table 3-3.

Table 3-3 Application of Systems Engineering Process to PDVS [59]

Systems Engineering Process Elements	LAI PDVS Application
1. Requirements Analysis	Establish specific product values. Include not only performance characteristics, but also broader aspect of value such as availability and appeal to user.
2. Requirements Baseline Validation	Assess product values against enterprise value expectations
3. Functional Analysis	Define the specific tasks necessary to provide the specified value. Develop the options for sequences of task execution.
4. Synthesis	Perform trades on options. Develop the full task network looking for ways to eliminate unnecessary activities and reduce number of interfaces and long feedback loops.
5. Verification/Validation	Review PDVS to optimize flow and ensure that it produces product value in an effective way that is consistent with enterprise constraints.

3.1.5.6 Requirements Definition

As illustrated in the previous section, there is a direct connection between LAI and systems engineering in the area of requirements. The requirements analysis and verification found in systems engineering are beneficial to the processes of LAI and value stream mapping. Early, clear definition of requirements is essential for any project, regardless of the management approaches being used. Requirements provide the goals that guide a project through the various stages of development [14].

3.1.5.7 Benchmarking

Found within LAI, Six Sigma and systems engineering, benchmarking is an essential tool for programs seeking to improve beyond current levels or seek to achieve "world-class" levels. The importance of benchmarking to Six Sigma has already been discussed, in the "tools and techniques" section of Six Sigma. Within LAI, benchmarking is an enabling practice in the Lean Enterprise Model [32]. The

International Council on Systems Engineering (INCOSE) has established a working group to identify examples of "world-class" and best practices, to aid future systems engineering efforts [30]. Without doubt, benchmarking is a universally encouraged practice and belongs in the tool-set to aid reusable launch vehicle development.

CHAPTER 4 APPLICATION

With a basic understanding of the tools and techniques employed by the Lean Aerospace Initiative, Six Sigma and systems engineering, as well as identification of those areas of overlap between the three quality initiatives, those tools can now be applied to the problem of reusable launch vehicle development. Because of a strong foundation in common sense and infusion within modern engineering teachings, many of the tools are already in place within the Air Force and NASA efforts. Beyond the initial implementation, additional incorporation of these tools appears to offer considerable benefit to the Air Force in their quest for a military spaceplane.

4.1 Modeling and Simulation

Recommended in the SE and LAI approaches, modeling and simulation (M&S) provide many benefits to the program team, especially in the early stages of development. Several examples exist of the use of M&S within the current RLV development efforts. One such example is the AFRL Human Effectiveness Group in Mesa Arizona that has developed simulators to test human in the loop operations for close proximity missions of the SMV. These simulations are useful in determining the level of autonomy required, the number of sensors needed to provide adequate situational awareness for operators and the level of skill and training those operators require to handle the SMV in orbit [58].

Often a modeling and simulation effort is performed in conjunction with other sets of analysis. This was the case with the military utility analysis (MUA) conducted by the Developmental Planning Directorate of the Space and Missile Systems Center (SMC/XR) and the Aerospace Corporation. Completed in 1999 for Air Force Space

Command (AFSPC), the MUA examines not only a modeling and simulation effort, but also a mission analysis, technical assessment and life cycle cost analysis [49].

The modeling and simulation portion, of the MUA, included campaign level modeling using the System Effectiveness Analysis Simulation (SEAS) and Thunder programs. The contribution of a fleet of SMVs operated to support of fictitious theater operations, set in 2015, was assessed. This analysis is useful in determining decision, deployment and operational timelines to effectively utilize SMVs. Additionally, this information can be used to help develop requirements for fleet size, turn around times and first stage responsiveness.

The human in the loop work performed by AFRL and the military utility analysis conducted by SMC/XR and the Aerospace Corporation are two examples of how modeling and simulation are currently being used in the development of reusable launch vehicles. Both examine different aspects of the SMV to advance the understanding of operational issues and requirements. The MUA highlights the fact that modeling and simulation are not performed in isolation, but rather are conducted as part of a larger analysis effort. As identified by the Lean Aerospace Initiative and systems engineering, modeling and simulation can offer considerable benefits to a program and, as illustrated in these two examples, is an integral part of the current reusable launch vehicle development effort.

4.1.1 *Issues in Application*

There are a few key points that must be remembered when using modeling and simulation in development efforts. First, the models and simulations used are only as good as the information provided. Great care must be taken to insure the accuracy of data, as it is currently known. Only with proper data input and skillful analysis will relevant, realistic and useful results emerge. Furthermore, the models and simulations represent only a basic understanding of reality. Many complex interactions cannot be captured to match real world circumstances. For this reason, the results of M&S must be understood in their context, with full knowledge of the assumptions and limitations imposed. While modeling and simulation can be very useful in validating system requirements and refining concepts of operations, they are merely an input into the decision making process and not a substitute for thoughtful, well informed decision making.

4.1.2 *Recommendations*

The current modeling and simulation analyses under the Air Force SOV and SMV development efforts are on the right track. Further M&S activity should continue in a similar manner. Future M&S activities should help further refine requirements and begin to provide further insight into all aspects of MSP operations. While a great deal of attention is paid to the capabilities and on-orbit operations of systems, the ground and support infrastructure is equally important. At least part of the future M&S efforts should concentrate on the supporting operations of the SOV and SMV systems. With continued modeling and simulation activity, the Air Force can continue to define the characteristics

and capabilities of the SOV and SMV systems, which will serve to gain increased support from top-level decision makers.

4.2 Baseline Current System

Found within elements of all three modern quality initiatives, examining a baseline system can be very beneficial in the development of subsequent programs. Within the LEM, the enabling practice of performing benchmarking acknowledges the presence of other systems and recommends learning from their experiences [32]. The benchmarking activities found within Six Sigma also serve to define a baseline level of performance [21]. In order to develop the requirements used within the systems engineering process a basic understanding of current capabilities is critical [30]. While the Air Force does not operate an existing military spaceplane, the Shuttle Transportation System (STS) operated by NASA is the first generation of reusable launch vehicles and offers a wealth of information for future development.

In 1997 the Space Propulsion Synergy Team (SPST) developed "A Guide for the Design of Highly Reusable Space Transportation" [51]. The SPST was comprised of professionals from NASA, industry and academia. The guide was developed to help designers and decision makers focus on key factors and relationships in order to produce more responsive, dependable and affordable systems. They developed sets of desirable design and program features from the existing shuttle system and team member experience. To rank each recommendation the team utilized the Quality Function Deployment (QFD) technique. Figure 4-1 identifies the top 20 recommended design features. The score along the horizontal axis represents each recommendation QFD score

and is used for ranking purposes only. The pluses and minuses (+, -) to the right of each recommendation indicate whether an increase or decrease in that factor is called for. A complete listing of all design and program features is located in Appendix D.

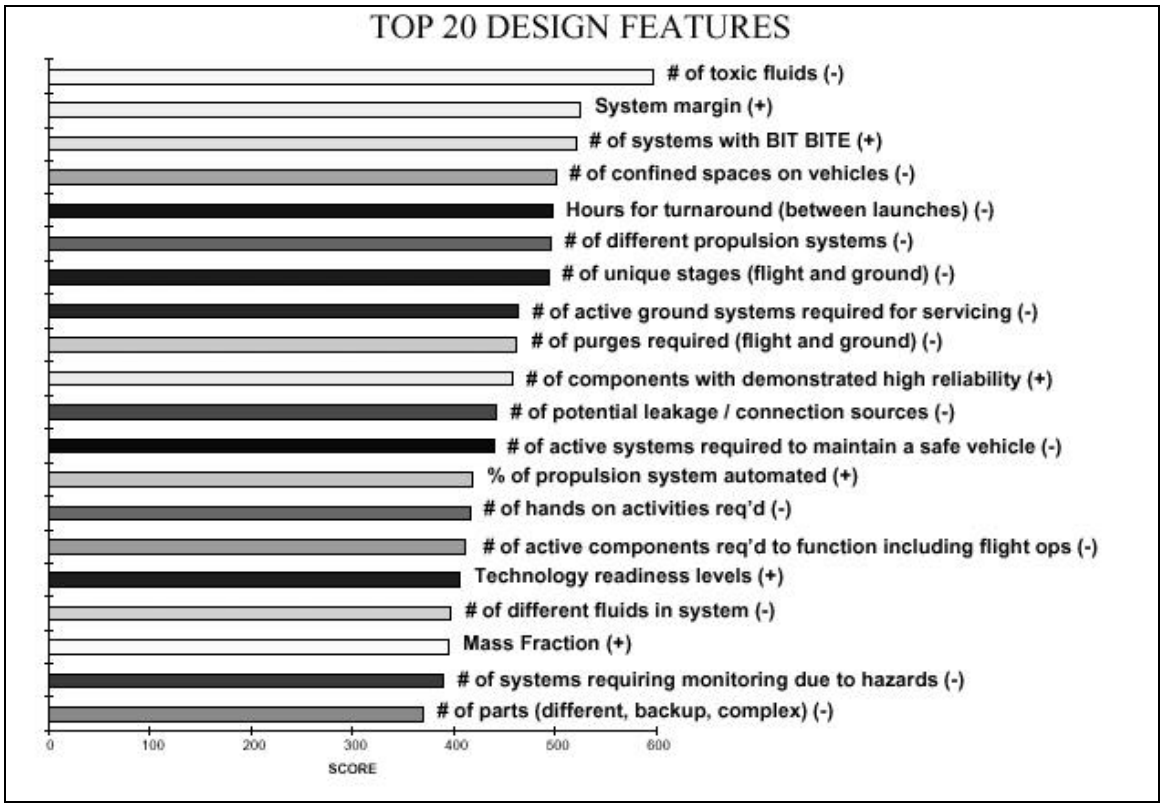


Figure 4-1 Top 20 Desired Design Features for Reusable Launch Vehicles [51]

Topping the list of desired design features is a reduction in the number of different toxic fluids used in both flight and ground operations. As a benchmark the shuttle utilizes ten different toxic fluids, from the hypergolic fuels used in the auxiliary power units (APU) to the waterproofing agents used for the tile thermal protection system (TPS). These toxic fluids are significant contributors to the number of keepout zones, which prevent the execution of other work and require costly infrastructure support. The guide offers several improvement techniques, from simply using different fuels, to the

use of batteries instead of fuels to provide power, improvements in thermal systems, and a switch to electronic actuators from the current hydraulic versions. The guide provides descriptions, shuttle benchmarks and recommendations for improvement for each of the 64 design features and 18 programmatic features [51].

A second example of Space Shuttle benchmarking is the work completed by Robert Johnson, Chief of Fluids, Mechanics and Structures branch at Kennedy Space Center (KSC) [26]. Utilized by the SOV technology office of AFRL, this work focuses on baselining the current operational architecture and making recommendations on how to reduce the time required preparing a space vehicle for its next launch. Many of the recommendations, such as reduction of toxic fluids and increases use of automated built-in-tests (BITs), are also included in "A Guide for the Design of Highly Reusable Space Transportation" [25]. The inclusion of manpower and time factors in this analysis makes it particularly useful when trying to reduce operational timelines to achieve the Air Force desire of airplane-like operation. Another example of recommendations is improvements in the design of line replaceable units (LRU). On the shuttle, some LRU replacements require the removal of LRUs in perfect working condition, which would not otherwise be touched. This removal causes each LRU to be re-tested and revalidated, drastically increasing the time required between launch. With a more accessible design, the LRUs could be replaced with minimal impact to other systems. The goal is to design LRUs "one deep," with no other system needing to be touched [26].

These two examples of shuttle baselining provide some insight to the benefits of such activity. With a thorough understanding of current capabilities and limitations, the

designers of future systems can avoid the mistakes made in the past and provide new levels of performance, reliability, time and cost savings.

4.2.1 *Issues in Application*

Benchmarking and baselining are sound and universally accepted practices to identify the best aspects of existing operations and to determine what areas of current systems require improvement. Care must be taken to understand what aspects of operation need to be overhauled to ensure improved performance. It is simply not enough to copy existing operations or pick-and-choose between a handful of operational practices. Each aspect of a benchmarked operation needs to work together to provide a coherent operational system.

4.2.2 *Recommendations*

The Space Shuttle has provided an excellent source for benchmarking. The meticulous inspection of every aspect of shuttle operations has provided a wealth of information for future MSP development. This type of analysis should continue, but may not fulfill all the needs of MSP development. As identified within Six Sigma, benchmarking of dissimilar systems and operations can also provide a great deal of knowledge [21]. Additional benchmarking activity should focus on systems that currently employ the fast paced, dynamic operations sought the SOV and SMV systems. As an example, since airplane-like operations are the goal of the Air Force MSP programs, flight-line operations would serve as a good benchmark. The incredibly fast operations of an automotive “pit” crew may also provide useful information in ground operations. While this may seem far-fetched, the importance of understanding that

potential improvements may come from a variety of sources, some unexpected, cannot be overstated.

4.3 Spiral Development/Incremental Improvements

As discussed earlier, all three quality initiatives suggest an incremental or spiral approach to system development. This recommendation is being implemented within the NASA efforts and translates to the Air Force development. With the Space Shuttle as a first generation RLV, NASA anticipates many generations of RLVs; each subsequent system improving performance and reliability over the last, as illustrated in Figures 4-2 and 4-3.

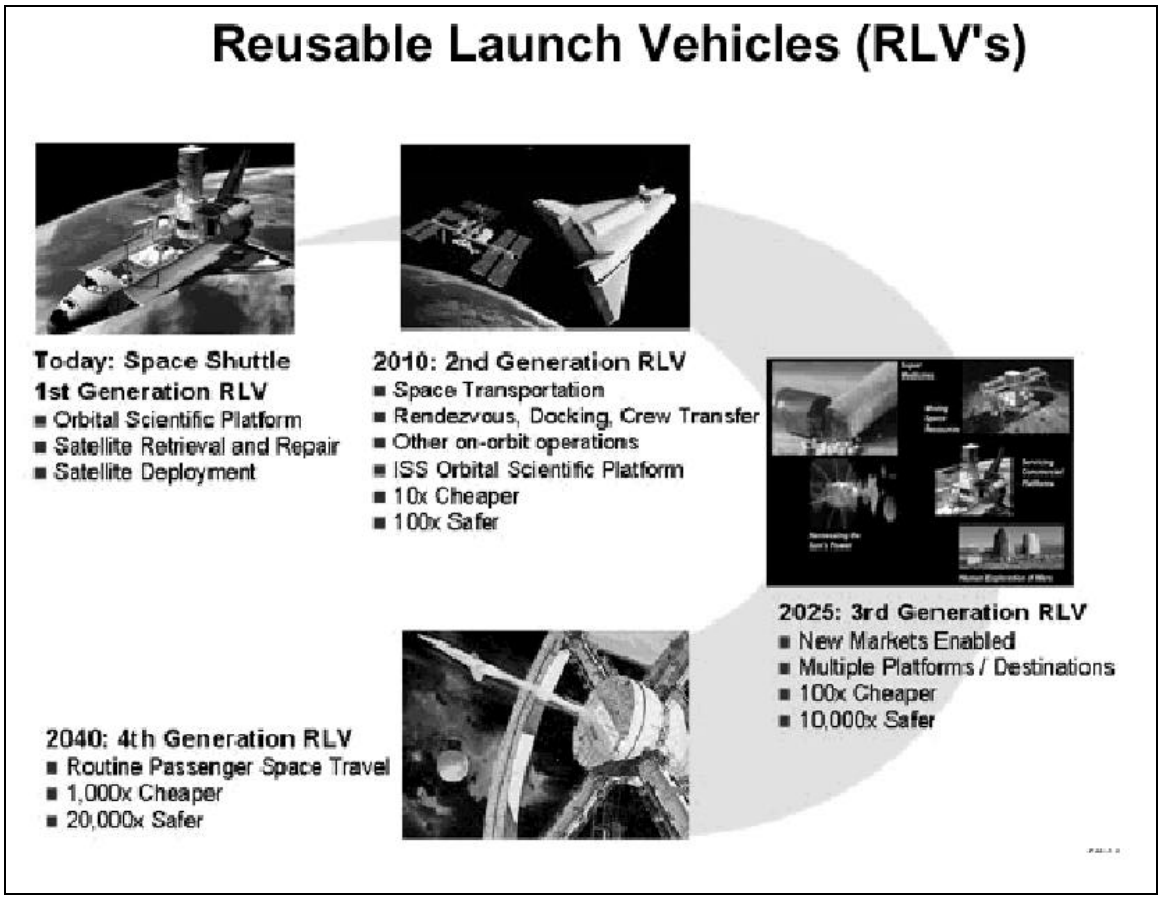
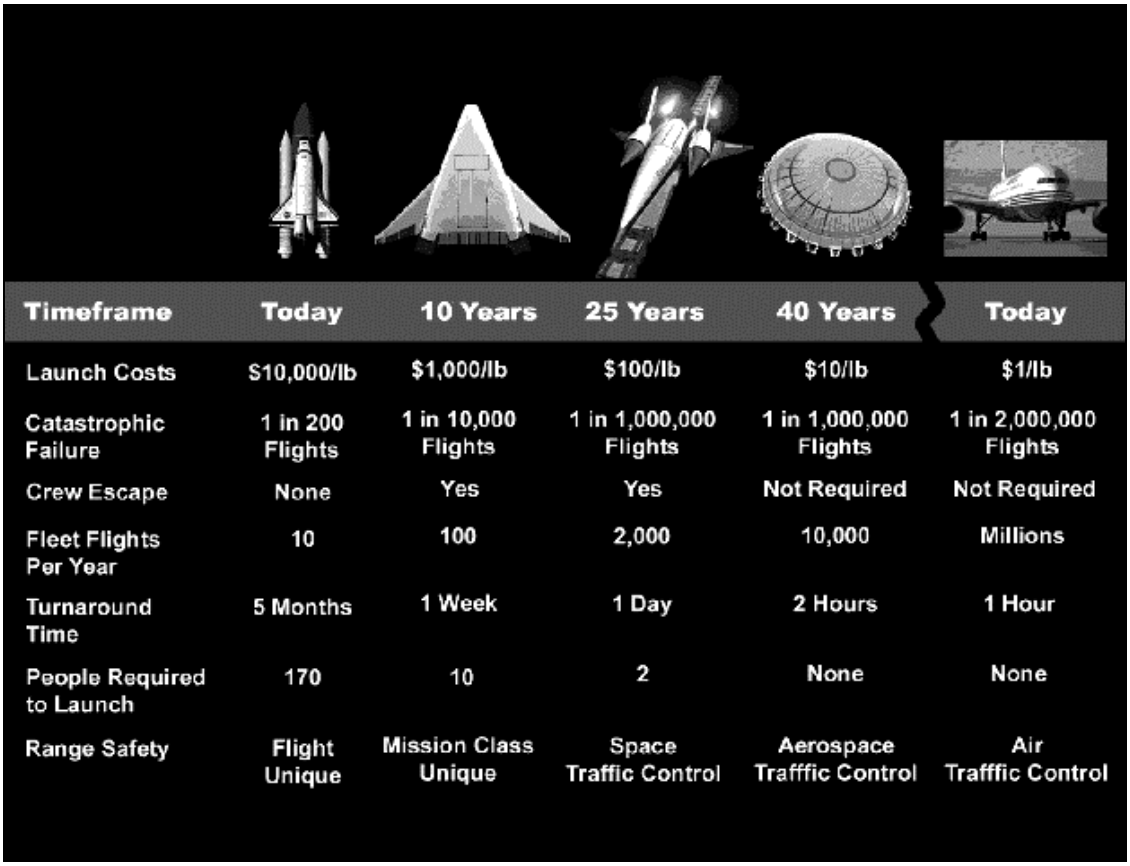


Figure 4-2 Planned Multigenerational RLV Development at NASA [29]

As NASA's Reusable Launch Vehicle web page explains:

> "The Space Shuttle is the ***first generation*** reusable launch system and represents only a part of what is possible in space. NASA's first goal is to develop the technology for a ***second generation*** RLV that is ten times less expensive and ten times more safe. NASA's investment in airframe and propulsion technologies and the demonstration of those technologies on the X-33, X-34 and X-37 experimental vehicles will accomplish this goal. A ***third generation*** RLV will enable new markets, provide a platform for new destinations and will be 100 times less expensive and 100 times safer. The plan for developing the new technologies needed to meet requirements for the third generation is called Spaceliner 100" [29].



Timeframe	Today	10 Years	25 Years	40 Years	Today
Launch Costs	$10,000/lb	$1,000/lb	$100/lb	$10/lb	$1/lb
Catastrophic Failure	1 in 200 Flights	1 in 10,000 Flights	1 in 1,000,000 Flights	1 in 1,000,000 Flights	1 in 2,000,000 Flights
Crew Escape	None	Yes	Yes	Not Required	Not Required
Fleet Flights Per Year	10	100	2,000	10,000	Millions
Turnaround Time	5 Months	1 Week	1 Day	2 Hours	1 Hour
People Required to Launch	170	10	2	None	None
Range Safety	Flight Unique	Mission Class Unique	Space Traffic Control	Aerospace Trafffic Control	Air Trafffic Control

Figure 4-3 RLV Generational Features [29]

The Second Generation Reusable Launch Vehicle Program, headquartered at Marshall Space Flight Center, is in the early phase of program development. Learning from problems experienced during the Space Shuttle development, NASA has increased

the preparation done prior to full-scale development. Extra work done early will demonstrate that the technology needed has matured to the required levels. With a "tech-freeze" scheduled for 2005, NASA hopes development will continue smoothly until initial operations begin, around 2012. The use of a "tech freeze" means technologies developed after 2005 will not be included in the initial production of the Second Generation Reusable Launch Vehicle. Upgrades to the current shuttle fleet will extend the life of the STS until the replacement vehicle is ready to begin operation [48].

The Air Force is looking to capitalize on NASAs efforts, by placing the capabilities of the Space Operations Vehicle between the second and third generation RLVs [17]. This will allow the Air Force to benefit from the technical advancements made for the second generation RLV while preserving some technological superiority over non-military systems. The SOV plans a "tech freeze" around 2010 with an initial operational capability in 2014 [16]. The incremental approach is not confined to complete systems, but is also present in the development activities used to mature the technologies necessary for those systems. By partnering with NASA on some of the various X-Vehicle programs, the Air Force is able to include its unique requirements in current technology programs with minimal financial expenditure [58].

The most ambitious of these technology demonstration programs is the X-33. Developed under a joint agreement between NASA and Lockheed Martin's Skunk Works, the X-33 will demonstrate the technology required for a future single-stage-to-orbit (SSTO) RLV [39]. The X-33 is planned to conduct 15 autonomous sub-orbital missions reaching speeds over 19,000 kilometers per hour in the coming years. Among the many technologies being demonstrated are composite fuel tanks, linear aerospike

engines, advanced thermal protection systems (TPS), and integrated Global Positioning System (GPS) guidance. The linear aerospike engine is not a new concept, but until recently has been too technically challenging to build and operate. The basic concept is to use the airflow surrounding the rocket's exhaust as the nozzle. This will allow the engine to be 75% smaller than standard engines, a necessary size and weight improvement required for SSTO. The wedge shaped, wingless design of the X-33 is an evolution from earlier lifting body experiments conducted between the Air Force and NASA [39].

A more modest demonstrator, the X-34 will advance flight and data testing as well as ground operations. The X-34 is an unpiloted, winged vehicle being developed by Orbital Sciences Corporation. The first of three planned vehicles is unpowered and serves as a structural test vehicle in drop tests from an L-1011. The following two vehicles will be powered sub-orbital flights reaching speeds of Mach 8 and altitudes of 80 kilometers. The program's objectives include demonstrating new lightweight composites, a new thermal protection system, new avionics, rapid turnaround/re-flight capability, inclement weather landings, and performance of the FASTRAC engine [40].

Unlike the X-33 and X-34, which are sub-orbital demonstrators, the X-37 will eventually conduct orbital tests [36]. The X-37 is being developed as a 50/50 cooperative agreement between NASA and Boeing with an additional $16 million being contributed by the Air Force. With a total program cost of $173 million, the Mach 25 vehicle will demonstrate 41 airframe, propulsion and operational technologies [8]. Similar to the X-34, the first tests will be unpowered drop tests from a B-52. These tests are planned to begin in 2001, with orbital powered tests in 2002 and 2003. The orbital versions will be

released from the Space Shuttle, remain in orbit for several days performing tests, reenter the atmosphere and land like an airplane [41]. The X-37 is a 120% scale derivative of the X-40A, also built by Boeing for the Air Force. The X-40A is a prototype design of the Space Maneuver Vehicle and does not utilize the advanced thermal protection materials, rocket engine and experiment bay found on the X-37. From the X-37 point of view, the X-40A testing is seen as a risk mitigation step [10]. The production of the X-37 is also an example of the combination of many sound techniques. As Dave Manly, Boeing Phantom Works X-37 program manager stated in a 1999 Space Daily report:

> "Through Phantom Works, we are able to apply best practices and approaches from across Boeing—in this case, rapid prototyping, lean manufacturing, avionics, and three-dimensional modeling and simulation – to help us improve the affordability, quality and performance of this product" [8].

Figure 4-4 illustrates the variety in design present among the X-33, X-34 and X-37 vehicles.

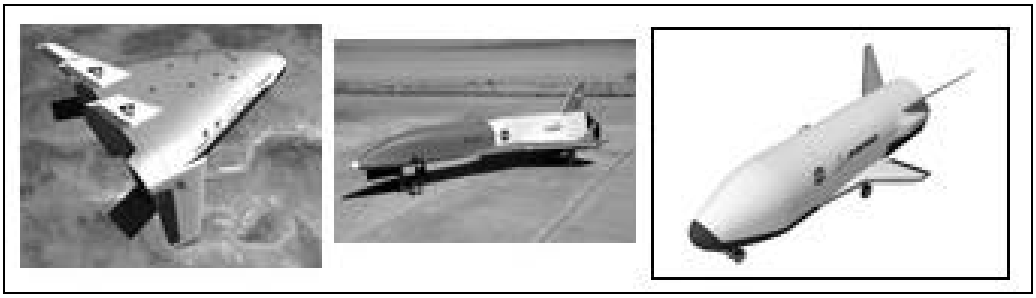


Figure 4-4 X-33, X-34 and X-37 [64]

NASA is also developing other X-vehicles that may serve to advance the development of reusable launch vehicles. The X-38 is a prototype for a crew return vehicle (CRV) designed to act as a lifeboat for crewmembers of the International Space Station [42]. The X-43 is a scramjet-powered aircraft developed to advance hypersonic

flight technologies [43]. Appendix B contains NASA factsheets on each of the X-vehicles discussed.

4.3.1 *Issues in Application*

Without question, the use of X-Vehicles and the plan for multiple generations of reusable launch vehicle systems are a superb use of spiral development/incremental improvements technique advocated by all three quality initiatives. Recent experience in the various X-Vehicle programs provides additional guidelines for the use of this technique. The technologies being demonstrated must be reasonably limited in scope. Of course, they must push the current boundaries of technology, but a single program should not attempt to push too many technologies at once. Both the X-34 and X-37 represent programs with a reasonable scope. Their efforts are on schedule and appear to demonstrate the intended level of technology development. This is not the case with the X-33. Nearly two years behind schedule; the X-33 is in danger of failing to perform a single test flight [37]. Many, including a former X-33 designer and a congressional staffer, are critical of the high-risk high-payoff strategy employed on the X-33. In a recent CNN news article, Dave Urie, a former designer on the X-33 program, stated "It was in my view a mistake to abandon well-known and well-tested technology." The article also quotes Tim Kyger, a former congressional staffer, as stating, "I think the X-33 will never fly, and I'm not alone in that opinion" [37]. Jerry Grey, editor-at-large of *Aerospace America*, had this to say about the X-33 setbacks:

> "What went wrong? The first, and by far the most important, flaw in the program was the original requirement that it provide SSTO capability. The key features in lowering costs of a space launch system—which was the program's main goal—are reusability and operational simplicity. Imposing the SSTO requirement exacerbated the technical risk. The budget was simply inadequate for the level of technology development needed" [19].

In order to achieve the necessary weight limits to achieve SSTO, the X-33 must utilize new oddly shaped composite fuel tanks and the un-flown linear aerospike engine. Both systems represent new technology developments, which have led to considerable cost and schedule overruns [37]. The technical challenges associated with SSTO are understood within the Air Force SOV effort. The technical readiness of a SSTO design is considered "on the ragged edge" by William Gillard, Program Manager of the Space Operations Vehicle Technology Office [16]. For this reason, the Air Force is favoring a two-stage-to-orbit (TSTO) design utilizing more mature technologies for its proposed SOV. All this is not to say that SSTO will never be realized. Rather, the current technology levels do not support such operations. But, with modest, steady technology programs, such a system may be realized in the third generation of reusable launch vehicles.

Another issue related to the multigenerational approach exists within the Air Force SMV development. As stated in the SMV CONOPS, the SMV will act to further clarify issues for future SOV development [5]. Inherent in this stepping stone role of the SMV lies a delicate balance. The SMV must, in and of itself, demonstrate sufficient military utility to justify procurement. However, it must also demonstrate a necessity for the space operations vehicle, or the much larger, more expensive SOV may never proceed beyond the planning stage. During the Space Maneuver Vehicle Military Utility Analysis conducted by SMC/XR and the Aerospace Corporation, first-stage

responsiveness was identified as a driving factor in the utility of a SMV [49]. With this fact established, MSP supporters may face a difficult challenge advocating SMV development without an SOV and potentially face further difficulty advocating for the SOV after the SMV is developed.

4.3.2 *Recommendations*

The use of X-vehicles as technology demonstrators and the multigenerational approach to RLV development are good examples of the application of spiral development/incremental improvements, and should continue at a modest pace. Overly ambitious projects like the X-33 will likely not yield the benefits of more manageable programs such as the X-34 and X-37. Once the technologies required for RLV development are demonstrated in the various X-vehicles, they must transition to operational systems. Plans need to be established to insure this transition of technology from test to operations is a smooth one. With a high degree of similarity between the X-37 and SMV, the transition for this system will likely occur with little incident. The transitions required for the SOV system will require greater attention, because of the complexity of the SOV system. Working closely with NASA on the second generation RLV can help alleviate this technology transition.

4.4 Integrated Product Teams

Strongly advocated within both LAI and SE, the use of integrated product teams (IPTs) has become essential in the development of complex modern systems. This practice is adopted by the Air Force. The MSP IPT is comprised of members throughout the Air Force. Included in this integrated team are representatives from AFRL, SMC,

and AFSPC. Together they serve the roles of MSP advocate, end user, developer and analysts [58]. With most of the technology development conducted within NASA, this team continues the long-standing and mutually beneficial tradition of the Air Force/NASA partnership. In fact the Air Force liaison to NASA on RLV issues, serves as the Deputy Program Manager for the X-37. These partnerships are an excellent step towards integrating the MSP effort within NASA and the Air Force, but researches of previous development efforts might suggest further action. As identified by Forsberg and Mooz, one of the reasons the Clementine and Mars Pathfinder projects were so successful was the use of co-located IPTs [14]. The current Air Force IPT is anything but co-located. With the SMV office in Albuquerque NM, the SOV office in Dayton OH, AFSPC in Colorado Springs CO, and SMC in Los Angeles CA, the IPT is spread throughout the CONUS. Spread out, they cannot take advantage of the rapid communication, shared knowledge and improved cooperation found with co-location.

4.4.1 *Issues in Application*

Conventional wisdom regarding integrated product teams, is that to maximize effectiveness they should be co-located [14]. The current location diversity of the MSP IPT seems to be a product of the organizational structure of the Air Force itself. With operational commands, such as AFSPC, providing concepts of operation, Material Command providing acquisitions, and AFRL supporting technology demonstration, physical separation in development of new programs is standard. This separation is compounded by the unique nature of the SOV system. Operating for part of its mission in the atmosphere, the SOV may require air-breathing propulsion. Development of air-

breathing systems is conducted at Wright-Patterson Air Force Base. Meanwhile, the SMV will operate almost exclusively in orbit, and therefore development efforts occur at Los Angeles Air Force Base and Kirtland Air Force Base. This would seem to be a major and unnecessary hurdle to impose on RLV development. However, because the current role of the RLV effort is advocating reusable launch vehicle development, this physical separation is actually advantageous. With small teams located throughout the Air Force, support can be won across a broad base of Air Force decision-makers. Once the go-ahead decision is made, however, development should continue from a single program office.

4.4.2 *Recommendation*

With the space procurement and operations separated into two major commands within the Air Force, the current MSP IPT structure is appropriate. Recent events suggest that the split nature of space development and operations may not be ideal and could undergo significant transformation. In the January 2001 "Report of the Commission to Assess United States National Security Space Management and Organization" it was recommended that the Space and Missile Systems Center be reassigned from Air Force Materiel Command to Air Force Space Command [45]. Such an action would "create a strong center of advocacy for space..." and would translate to improved support for space programs, including the SOV and SMV [45]. With a single command overseeing MSP development, the MSP IPT should have an easier task integrating their activities. While the Air Force may face reorganization in the future, it is doubtful such a merger would ever include NASA. The current relationship between NASA and the Air Force, in the

area of RLV development, has a strong background, built over many years, and should continue well into the future. The arrangement is mutually beneficial to both parties and offers the greatest promise for RLV development.

4.5 Value Stream

As identified by Weiss and Warmkessel, the definition of requirements, found within the system engineering process, can be very useful in the mapping of a products value stream [59]. While a complete value stream analysis of the SOV system, the SMV system or the current development efforts have not been accomplished, an attempt has been made at identifying the multiple facets involved in achieving SMV launch responsiveness. To achieve the level of responsiveness required to meet the Air Force objective of airplane-like operation requires a complex web of interactions to effectively work together. Within the SMV MUA, introduced in the modeling and simulation section of this chapter, the Aerospace team began to assess the interaction between areas falling within the five distinct areas of satellite control, payload & mission, SMV, launch system, and range support [49]. The interactions identified are represented in Figure 4-5. It demonstrates the complexity of the issue of responsiveness and highlights the wide range of factors that may be overlooked if only a cursory examination of the topic is conducted. Often times the performance of a weapon system is viewed as unique feature of the specific machine in question and not the network of supporting systems required ensuring weapon system effectiveness.

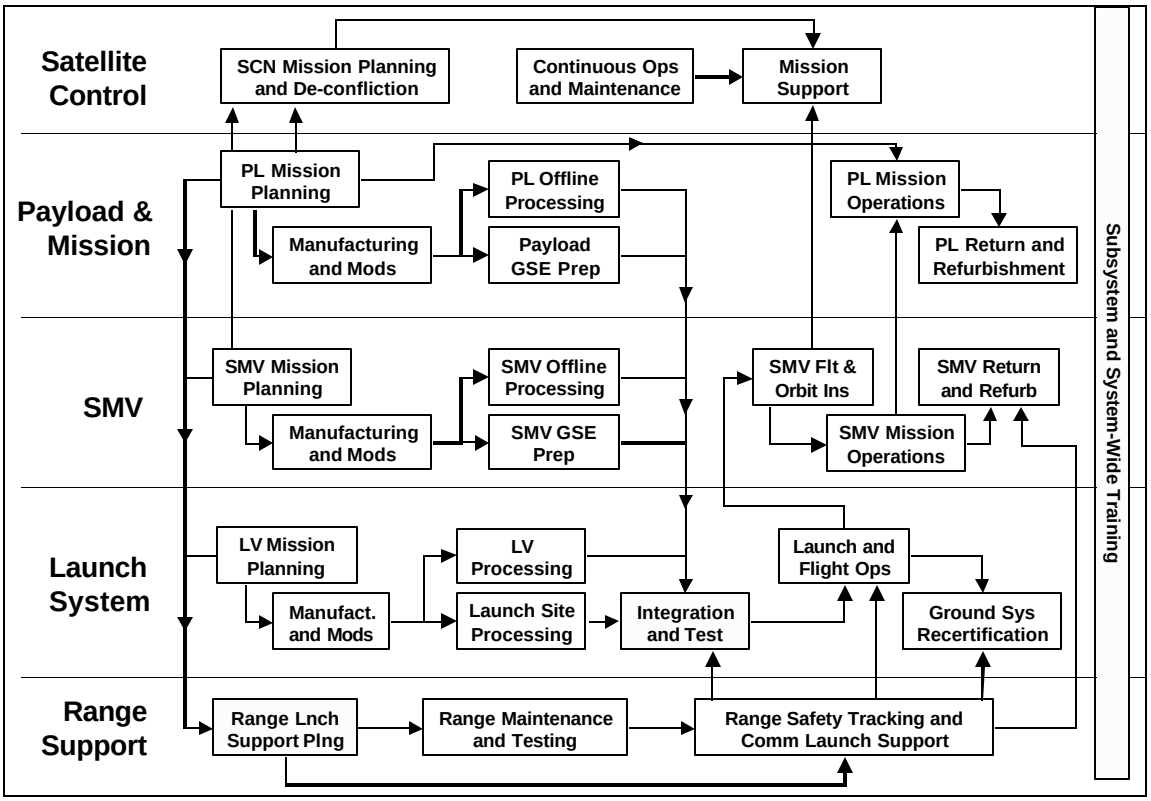


Figure 4-5 SMV Interactions to Achieve Responsiveness [49]

While this analysis of interactions is not value stream analysis, in the strictest sense, it does represent many of the attributes of a value stream. By identifying all of the pertinent contributions to launch responsiveness, areas not of benefit and areas where improvements are required can be identified.

4.5.1 *Issues in Application*

Perhaps the single biggest issue related to value stream mapping is completeness. Only by completely identifying all relevant contributions to the final product can value stream mapping be beneficial. Since a large component of value stream mapping is the interactions of each of the contributing steps, any oversight could render the analysis useless. Additionally, the non-contributing aspects must be identified for removal. If one

such activity goes unidentified, the waste it generates will continue and hamper overall system performance.

4.5.2 *Recommendations*

Value stream mapping offers two distinct opportunities of improving the development of RLVs within the Air Force. First, with responsiveness and turn around time being critical factors for military RLVs, by mapping the value stream of ground operations the Air Force can eliminate wasteful and time consuming practices. This will also serve to minimize the manpower required for ground operations and help to ensure an adequate level of skill for each required action. These savings will greatly contribute to the goal of achieving airplane-like operation. The second area of benefit is found within the development effort itself. The value stream for the entire development process can be mapped to identify what activities will best lead to an operational system. This mapping will also identify which activities are wasteful in the development process, a necessity given current manpower and financial shortages experienced throughout the Air Force.

4.6 Requirements Definition

A key element of systems engineering, the clear definition of requirements is critical to any development program. In the case of the MSP it is a critical yet missing component. While AFSPC has produced a concept of operations for both the SOV and SMV, from which AFRL based their technical and system requirement documents, definitive user requirements are still forthcoming [2][3][4][5]. One of the major activities for the AFRL team is to “coax requirements out of AFSPC” [57]. This is understandable

given the revolutionary nature of the SOV system. While work with the NASA efforts does help develop some requirements, distinct military requirements must come from within the Air Force [58].

4.6.1 *Issues in Application*

The lack of military RLV requirements is compounded by the potential versatility of the SOV and SMV systems. They can do too much for too many. As part of the SMV MUA, conducted by the Aerospace Corporation and SMC/XR, a thorough review of Air Force, DoD, and national literature identified potential missions for the SMV system. Also considering the technical limitations and possible payloads, the team identified over sixty potential missions. The complete list, contained in Appendix C, covers a diverse range of missions including monitoring drug trafficking, treaty verification, remote sensing, spacelift, and space information denial [49]. Seemingly, with each additional mission comes an additional customer. Potential national security users of the SOV system include Air Force Space Command, Air Combat Command, the National Reconnaissance Office, the Central MASINT Office, Drug Enforcement Agency, and the Departments of State and Energy. While it may seem with so many potential users that requirements would be easy to come by, the opposite is true. It may be that in a world where procurement dollars are scarce, each agency is reluctant to voice a need for a system external to their organization. Choosing instead to keep their needs and therefore financial backing close to home. Another possible reason for the lack of requirements being voiced is the novelty and unproven nature of the system. Each agency may be waiting to determine what capabilities the SOV system will actually possess, before

adding their unique demands. Whatever the reason, a lack of definitive requirements is present and must be overcome in order for the development to successfully continue.

4.6.2 *Recommendations*

Some form of union must be achieved among potential users in order to develop a single set of specific system requirements. Whether this union is accomplished by means of a MSP conference, attended by potential users, or through a series of user IPT meetings is not as important as the product of the union. Another hurdle in achieving a single requirements list exits in the compartmentalized classification systems used by the diverse array of potential users. Some form of mechanism needs to be established to handle this sensitive issue. Without a single requirements list, the potential military benefits of the SOV and SMV systems are diminished and the development costs increased.

4.7 Gain Top-Level Support

Finally, all three quality initiatives agree on the necessity for top level leadership support. Whether leadership serves as a change agent, as identified in Six Sigma, or facilitate the effective use of IPTs, leadership must completely support the activity for there to be any chance of programmatic success [30][44]. Within the Air Force, there appears to be this level of support for the SOV system. During a panel discussion at the AIAA Space 2000 Conference, both AFSPC Commander, General Eberhart, and AFMC Commander, General Lyles, voiced their support for RLV development within the Air Force [7]. General Eberhart stated that it is not a question of "if" RLVs will be developed within the Air Force, it is a question of "when." He continued by saying it

will be a technology driven path and that the Air Force should keep its eyes on the future and get there as quickly as it can. General Lyles, offered his strong support for the current Air Force and NASA partnership and suggested that RLVs will be essential in order to prosecute new missions in the future. While there is strong support within the leadership of the Air Force, this sentiment is not equally matched in the national leadership. Since all development activities within the military are dictated by the financial and political decisions made in Washington, this is where the leadership support must be secured. The current national policy, first stated in the National Space Transportation Policy of 1994 and echoed in the National Space Policy of 1996, limits the Air Force to the development of expendable launch vehicles (ELVs) and assigns RLV development to NASA [55][56]. The Air Force is only allowed the resources to maintain the most meager effort. The Air Force MSP program offices consist of two military and three full-time contractors for SMV and another three contractors for SOV, sustained by Congressional add-money each year [57][58].

4.7.1 *Issues in Application*

With the largest hurdle to MSP development found in current national policy, it is difficult to suggest recommendations without treading into charged, high-level political discussions. This area is as complex as the technical challenges involved in the engineering activities of RLV development. Political support can be a precarious thing, requiring constant attention and upkeep. With this said, a few areas for improvement may be cautiously broached.

4.7.2 *Recommendations*

First, the efforts to advocate a military spaceplane should continue and begin to expand beyond the confines of the Air Force. Support must be sought at the political level. Here a "champion," acting as a change agent, must be won to continue advocacy in the political environment. With growing support in both the military and political arenas, the prospects of obtaining an operational MSP are greatly increased. There is still the matter of national policy, limiting the Air Force to ELV development. Again the "Report of the Commission to Assess United States National Security Space Management and Organization" offers potential support in this area. Another of the unanimous recommendations of this report is establishing space as a national security priority. To that end, the commission recommended a re-examination of national space policy. This promising sentiment is strengthened by the fact that the chairman of the commission was the Honorable Donald H. Rumsfeld, the new Secretary of Defense [45]. While the actions of high-level political figures cannot be forecast from a single document, the overall political environment does appear to be ripe for garnering MSP support.

Table 4-1 summarizes the findings of this thesis. The first column lists the seven identified tools and techniques offering the most promise to RLV development. The second column recognizes the modern quality initiatives that utilize each of the techniques. The third column briefly states examples of current tool-set use within the RLV development efforts of NASA and the Air Force. Finally, the fourth column recaps the recommendations for future use within the Air Force RLV efforts.

Table 4-1 Application Summary

Tools and Techniques	Identifying Quality Approach	Current Examples	Recommendations
Modeling and Simulation	• Lean Aerospace Initiative • Systems Engineering	• Human-in-the-loop Simulation • Campaign Analysis during SMV/MUA	• Continue Modeling and Simulation Efforts • Develop ground operations simulation to aid in system design
Baselining/ Benchmarking	• Lean Aerospace Initiative • Six Sigma • Systems Engineering	• Guide for the Design of Highly Reusable Space Transportation • Shuttle Operations Benchmarking	• Continue to utilize shuttle as benchmark • Examine unrelated operations • Ensure integration of findings in design
Spiral Development/ Incremental Improvements	• Lean Aerospace Initiative • Six Sigma • Systems Engineering	• X-Vehicles • Multigenerational RLVs	• Continue with modest development efforts • Identify plans to transition technologies to operational systems
Integrated Product Teams	• Lean Aerospace Initiative • Systems Engineering	• MSP IPT (AFSPC, AFRL, SMC) • Air Force/NASA Relationship	• Organize developmental organizations within operational command • Continue Air Force/ NASA partnership
Requirements Definition	• Systems Engineering	• Concept of Operations • System Requirements Document • Technical Requirements Document	• Hold conference among potential users to obtain concensus on requirements • Implement mechanism to include diverse requirements
Value Stream	• Lean Aerospace Initiative	• SMV Responsiveness Interactions	• Map ground operations • Map SMV/SOV development efforts
Gain Top-Level Leadership Support	• Lean Aerospace Initiative • Six Sigma • Systems Engineering	• Strong Support from Air Force Leadership currently exists	• Update National Policy • Gain "Champion" within government • Continue MSP advocacy

CHAPTER 5 CONCLUSIONS

In the analysis of the Lean Aerospace Initiative, Six Sigma and systems engineering and in their application to the reusable launch vehicle efforts of the Air Force and NASA, several key points on the use of quality initiatives emerge. The first point addresses pros and cons of using a mix of approaches versus the adoption of a single initiative. The second two points relate to the use of tools and techniques to a particular program. The fourth area examines the selection of a quality approach to match the objectives of a specific program. Striking to the heart of modern quality initiatives, the final point addresses the relevance of codified approaches to quality improvement.

5.1 Overlap of Initiatives

The first point is that no one initiative monopolizes the quality world. That is, none of the three initiatives discussed completely encompassed the other two or completely filled all aspects of modern quality. While there is considerable overlap, each approach represents a unique method at resolving development issues, bringing innovative techniques to light. By examining which tools are best to use for a particular project, program management teams will likely employ a mix of techniques from each initiative and perhaps the tools of many other approaches. In selecting techniques in this manner, project teams will be well equipped to handle a variety of potential issues. This versatility does come with a cost. By not following the prescribed actions of one specific initiative, a development team may not be able to call upon the resources, experience and training of organizations such as the Lean Enterprise Initiative or the Six Sigma Academy. Additionally, the structure, provided by following a specific approach, might

facilitate greater and more rapid improvement. Many companies, including General Electric, Polaroid, Allied Signal, Dupont, etc., who have adopted Six Sigma and enjoyed dramatic improvements, serve to illustrate this point [21]. With this limitation noted, this thesis has shown that for development programs, such as RLV, an application of a variety of techniques from multiple sources is appropriate and, at least for the RLV effort, preferred.

5.2 Tailoring of Tools and Techniques

The second notable point is that the tools and techniques of any approach must be tailored to meet the unique needs of each program. The tools presented by the three programs are broadly introduced, to allow use by a wide range of potential programs. This means the same tool may manifest itself differently in different programs. To a private company seeking to increase profits, incremental/spiral development may mean a series of annual financial goals. But, to a development program such as RLV, incremental/spiral development means the use of multiple technology demonstration vehicles before achieving an operational system and then gradually improving the performance of that system with separate subsequent systems. By altering the sound, broad-based tools of the Lean Aerospace Initiative, Six Sigma and systems engineering, the reusable launch vehicle efforts of the Air Force and NASA, or any other development effort, can optimize application of the various techniques to match their unique circumstances.

5.3 Synergy of Tools and Techniques

The third key point is that while the tools and techniques were identified as stand-alone practices, they interact and support each other with impressive synergy. To illustrate this point, recall the role the requirement definition process played in the development of product value streams [59]. To extend this example, consider the use of IPTs suggested in Chapter 4 to help derive a single set of system requirements. Also recall the impact leadership support may play in the potential re-organization of SMC under AFSPC, which will simplify the work of the MSP IPT [45]. This clearly shows the linkage between the identified tools and reinforces the point that modern quality initiatives overlap one another.

5.4 Matching Initiatives to Programs

Despite the considerable overlap among initiatives, key differences in the nature of each approach suggest programs should tend to favor different initiatives at different times. For example, if an organization seeks to reduce waste in their processes, the adoption of the Lean Aerospace Initiatives would be best. An organization seeking to increase profits may choose, as so many others have, to implement Six Sigma. For technically complex programs involving the integration of multiple components, systems engineering is clearly the suited. Over the entire life-cycle, a single program may want to incorporate each initiative as the focus of a program shifts from developing a product, to refining a product and finally realizing a profit with that product. In selecting which initiative to use, a program must first understand their current position and define their immediate objectives.

5.5 Role of Quality Initiatives

Finally, evidence of the application of quality techniques without first hand knowledge of the source indicates several interesting points. Simultaneously, it illustrates both the tools' sound foundation in common sense and the infusion of quality initiatives into modern engineering education. It also speaks to the fact that even modern quality initiatives, seeking to highlight their individuality, rely on basic concepts, proven over many generations. Today, an engineer doesn't think twice about applying modeling and simulation or utilizing technology demonstration to reduce risk. Those tools and others like them just make sense and have been educated into the minds of developers. A codified quality approach is not required to identify the usefulness of a tool. And yet, a new quality approach seeking legitimacy cannot ignore proven techniques and will therefore incorporate their usage. The natural question then emerges, what role, if any, do modern quality initiatives serve? Modern quality initiatives advocate, re-educate and otherwise offer a supporting framework for the use of quality techniques. They can concisely present tools and thus save potential users time and effort that would otherwise be spent on research. The International Council on Systems Engineering is an excellent example an organization performing these roles and services to the general public [23]. While the step-by-step following of a single quality initiative's technique may not be required, the roles these organizations play and the support they can offer certainly justify their existence.

Selecting and wholeheartedly pursuing a single quality initiative may have more to do with setting a tone for and conveying a message to an organization than it does with the programmatic adoption of various tools and techniques. Management's acceptance of

a quality approach declares a deep commitment to a particular program and reinforces the importance of customer satisfaction and cost-savings to the project team. Further, it lays the foundation for how work will be conducted and establishes a standard for workers to follow. By stepping forward and accepting one quality initiative as an organization's plan for improvement, management sets a new tone for the program. In quality terms, the act of accepting a single initiative, whether it be the Lean Aerospace Initiative, Six Sigma, systems engineering or some other approach, serves as a significant event to shift the operational paradigm of the organization.

5.6 Areas For Further Research

This thesis has explored the use of modern quality teachings in the development of reusable launch vehicle systems within the Air Force. In doing so, a few areas have been identified as beyond the scope of this thesis. One such area is the commercial development activities occurring around the world. Since no one can be certain where the next breakthrough will occur, it is suggested that future research focus on the role quality initiatives play in commercial programs and what advancements commercial RLV development can bring to the Air Force and NASA efforts. Similarly, the specific activities underway within industry to support X-Vehicle development should also be explored. This would allow a deeper investigation into the technical areas of RLV development and potentially offer many new applications of quality initiatives.

5.7 Final Remarks

This thesis has identified many areas of overlap between the Lean Aerospace Initiative, Six Sigma and systems engineering. These overlaps were used to identify tools

and techniques of unquestionable merit. Furthermore, the application of these tools to the reusable launch vehicle efforts of the Air Force and NASA found a high level of existing incorporation. Benchmarking, modeling and simulation, spiral/incremental development, and integrated product teams are already well utilized within the current RLV programs; while gaining leadership support, value stream mapping, and requirements definitions have experienced limited implementation. The continued use of these seven techniques will serve to advance the current state of reusable launch vehicle development and may one day lead to the realization of the long standing goal of an operational military spaceplane.

The application of quality techniques to the RLV efforts of the Air Force and NASA has served as an example of the ways different approaches can be used to improve quality. The overlap among the three initiatives discussed was more extensive than originally anticipated. Despite this overlap in basic techniques, subtle differences and nuances in each initiative's application warrant distinction from one another. Anyone seeking to improve their product or process, whether businessman or engineer, would do well to examine multiple alternative approaches from a variety of fields, gleaming the best techniques from each, before determining a course of action.

Appendix A: Overarching and Enabling Practices of the Lean Enterprise Model [32]

Identify and Optimize Enterprise Flow
Establish models and/or simulations to permit understanding and evaluation of the flow process
Reduce the number of flow paths
Minimize inventory through all tiers of the value chain
Reduce setup times
Implement process owner inspection throughout the value chain
Strive for single piece flow
Minimize space utilized and distance traveled by personnel and material
Synchronize production and delivery throughout the value chain
Maintain equipment to minimize unplanned stoppages
Assure Seamless Information Flow
Make processes and flows visible to all stakeholders
Establish open and timely communications, among all stakeholders
Link databases for key functions throughout the value chain
Minimize documentation while ensuring necessary data traceability and availability
Optimize Capability and Utilization of People
Establish career and skill development programs for each employee
Ensure maintenance, certification and upgrading of critical skills
Analyze workforce capabilities and needs to provide for balance of breadth and depth of skills/knowledge
Broaden jobs to facilitate the development of a flexible workforce
Make Decisions at Lowest Possible Level
Establish multi-disciplinary teams organized around processes and products
Delegate or share responsibility for decisions throughout the value chain
Empower people to make decisions at the point of work
Minimize hand-offs and approvals within and between line and support activities
Provide environment and well-defined processes for expedited decision making
Implement Integrated Product and Process Development
Use systems engineering approach in product design and development processes
Establish clear sets of requirements and allocate these to affected elements of the product and processes
Definitize risk management
Incorporate design for manufacturing, test, maintenance and disposal in all engineering phases
Design in capability for potential growth & adaptability
Establish effective IPTs
Involve all stakeholders early in the requirements definition, design and development process
Use the “Software Factory” process
Implement design to cost processes
Maintain continuity of planning throughout the product development process

Develop Relationships Based on Mutual Trust and Commitment
Build stable and cooperative relationships internally and externally
Establish labor-management partnerships
Strive for continued employment or employability of the workforce
Provide for mutual sharing of benefits from implementation of lean practices
Establish common objectives among all stakeholders
Continuously Focus on the Customer
Provide for continuous information flow and feedback with stakeholders
Optimize the contract process to be flexible to learning and changing requirements
Create and maintain relationships with customers in requirements generation, product design, development and solution-based problem solving
Promote Lean Leadership at all Levels
Flow-down lean principles, practices and metrics to all organizational levels
Instill individual ownership throughout the workforce in all products and services that are provided
Assure consistency of enterprise strategy with lean principles and practices
Involve union leadership in promoting and implementing lean practices
Maintain Challenges of Existing Processes
Establish structured processes for generating, evaluating and implementing improvements at all levels
Fix problems systematically using data and root cause analysis
Utilize cost accounting/management systems to establish the discrete cost of individual parts and activities
Set jointly established targets for continuous improvement at all levels and in all phases of the product life cycle
Incentivize initiatives for beneficial, innovative practices
Nurture a Learning Environment
Capture, communicate and apply experience-generated learning
Perform benchmarking
Provide for interchange of knowledge from and within the supplier
Ensure Process Capability and Maturation
Define and control processes throughout the value chain
Establish cost beneficial variability reduction practices in all phases of product life cycle
Establish make/buy as a strategic decision
Maximize Stability in a Changing Environment
Level demand to enable continuous flow
Use multi-year contracting wherever possible
Minimize cycle-time to limit susceptibility to externally imposed changes
Structure programs to absorb changes with minimal impact
Establish incremental product performance objectives where possible
Program high risk developments off critical paths and/or provide alternatives

Appendix B: X-Vehicle Fact Sheets

NASA Facts

National Aeronautics and
Space Administration

Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523
Voice 661-258-3449
FAX 661-258-3566
pao@dfrc.nasa.gov

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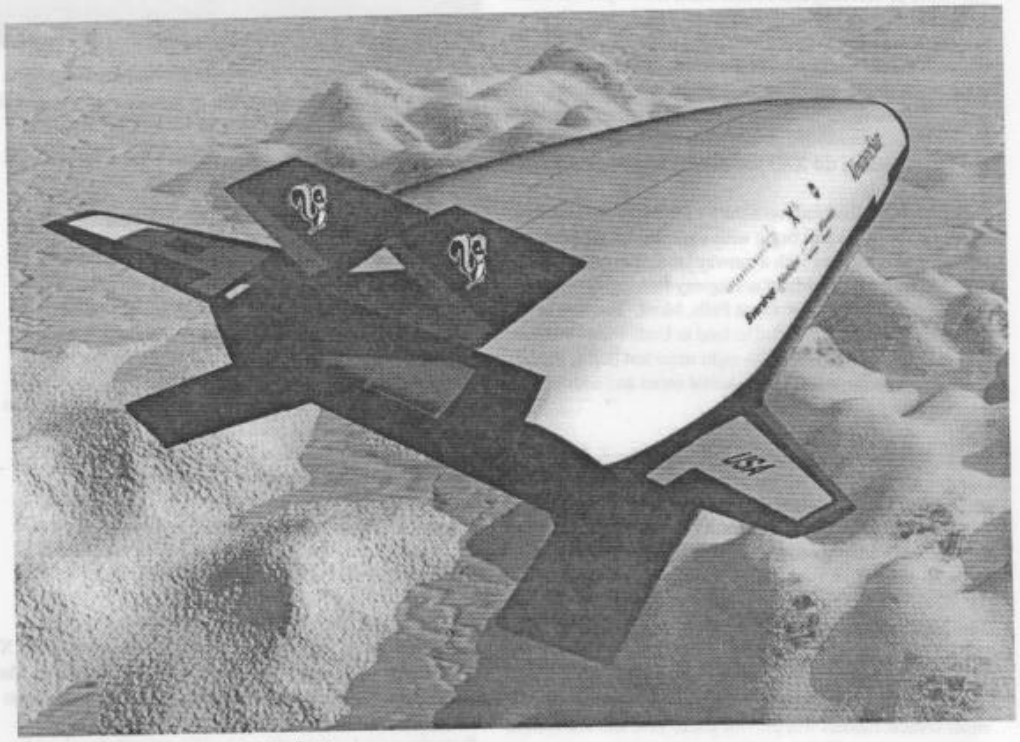
X-33 Advanced Technology Demonstrator



An artist's rendition of the X-33 in flight.

The X-33 is being developed under a joint agreement between NASA and Lockheed Martin's Skunk Works as a technology demonstrator of a future single-stage-to-orbit Reusable Launch Vehicle (RLV).

Two significant goals of NASA's Reusable Launch Vehicle development program are lowering the cost of putting a pound of payload into space from $10,000 to about $1,000, and dramatically increasing the reliability of space flight. By reducing the cost of placing payloads into low earth orbit, commercial RLVs would create new opportunities for space access and significantly improve U.S. economic competitiveness in the worldwide launch marketplace.

The first test flight of the X-33, designed to fly as high as 55 miles and reach speeds of 12,000 mph (Mach 15), is expected during the summer of 2000. A series of up to 15 test flights is planned, sending the X-33 to the edge of space, followed by its atmospheric reentry and aircraft-like landing. The test program, along with associated ground-based research and development work, is expected to provide Lockheed Martin the information and technology to proceed with development of a commercial RLV called VentureStar. When operational, VentureStar is expected to eventually replace the Space Shuttles as NASA's next-generation Space Transportation System. NASA would then be a customer, not the operator, of the commercial RLV.

The X-33, 63 feet long and 68 feet wide, is a 53 percent scaled prototype of the proposed VentureStar. The design of both vehicles is based on the wingless lifting body concept pioneered at the NASA Dryden Flight Research Center and tested in six unique aerodynamic configurations between 1966 and 1975. Data from the lifting body program contributed to the design and operational profile of the Space Shuttles, and is being used again in the X-33 and the proposed VentureStar.

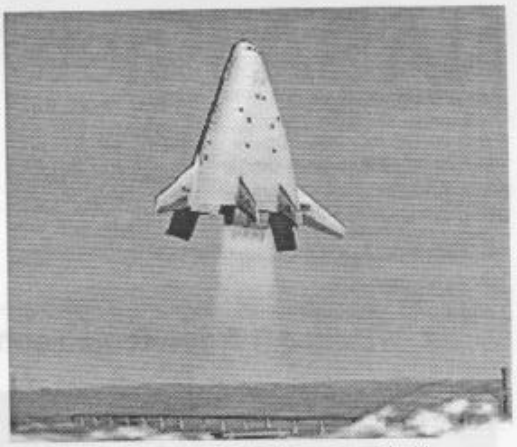
Each of the 15 suborbital missions for the uncrewed, autonomously flown X-33 will begin with a vertical launch from Edwards AFB and end with a runway landing at one of two sites, Michael Army Airfield at Dugway Proving Grounds, Utah, or Malmstrom AFB, Great Falls, Mont. The first five flights are currently scheduled to land in Utah, followed by two at Malmstrom AFB. Up to eight more test flights may be flown based on the results of the initial series and additional test objectives that must be met.

On the 950-mile flights to Malmstrom AFB, the X-33 will be airborne about 20 minutes, reach an altitude of about 55 miles, and achieve speeds of about 12,000 mph. The flights to Dugway, 450 miles from Edwards AFB, will take about 14 minutes, have a top speed of 8,300 mph and a peak altitude of about 30 miles.

The Vehicle

The wedge-shaped X-33 features an airframe built of titanium and composite materials. Small aft-mounted elevons and two small vertical rudders will provide pitch, yaw, and roll control in the atmosphere. Eight reaction control motors — gaseous jets — will be used for control at very high altitudes where the atmosphere is too thin for aerodynamic control surfaces.

Nestled tightly inside the rear half of the airframe are two liquid hydrogen tanks made of graphite epoxy. The forward half of the airframe is filled with an aluminum liquid oxygen tank. Together, they will fuel the two J-2S Linear Aerospike engines that will power the X-33 to speeds of Mach 15 (15 times the speed of sound) and altitudes of more than 260,000 feet during the test flights. Engine thrust at launch will be 410,000 lbs.



The X-33, with a mix of liquid hydrogen and liquid oxygen powering the vehicle's two linear aeropsike engines, lifts off from the launch facility at Edwards Air Force Base, Calif.

Linear aerospike engines were first developed more than 30 years ago, but were not considered mature enough for space flight until recent advances in materials and manufacturing. They use the same type of fuel as most standard rocket engines but do not have the familiar bell-shaped nozzle. The engines use the atmosphere as part of its nozzle. The airflow surrounding the rocket's exhaust plume keeps it contained so the engine is working at peak efficiency through its entire burn cycle, unlike traditional rocket engines which cannot compensate for variations in atmospheric pressure.

A linear aerospike engine is about 75 percent smaller than a standard rocket of comparable thrust, which translates to a lighter spacecraft and lower operating costs.

NASA Dryden contributed to the X-33/VentureStar design process by testing a one-tenth scale, half-span model of the X-33 at speeds of about 750 mph with an SR-71 Blackbird. The model, with a linear aerospike engine, was mounted on a test fixture attached to the upper fuselage of the SR-71. During flight the model validated Lockheed's computational predictive tools about the aerodynamic performance of the spacecraft design, and showed how the engine plume would interact with the aerodynamics of the vehicle. The engine was not hot fired during the flights, although gaseous helium and liquid nitrogen were cycled through the engine during the tests.

The X-33's exterior is covered with several types of Thermal Protection System (TPS) materials. These heat resistant

X-33 Advanced Technology Demonstrator simulation is flown by Steve Ishmael.

materials will shed searing temperatures generated by high speeds through the atmosphere much like the tiles used on the Space Shuttles. A carbon-carbon cap covers the nose and can withstand temperatures of 2,000 degrees (F). Metallic Inconel honeycomb tiles, used for temperatures between 1,300 to 2,000 degrees (F), cover the entire bottom of the vehicle plus leading edges of the rudders and wings, and the rear portions of the fuselage. Flexible Nomex insulation cover the upper surfaces of the vehicle where temperatures are not expected to exceed 900 degrees (F).

A Global Positioning System in the X-33 will be coupled to the vehicle's flight control and inertial navigation systems to keep the craft on a precise flight path from launch to landing. The vehicle will fly autonomously with each test flight individually programmed into the flight control and navigation systems. Test conductors at the X-33 Flight Operations Center at Edwards AFB will also have the ability to control the vehicle during flight.

Thousands of sensors on the vehicle will collect performance and status data throughout each flight. On-board data transmitters will send the information to the ground where test personnel at the X-33 Flight Operations Center and NASA and Air Force Mission Control Centers will monitor the status of all systems, the overall operation of the vehicle, and flight safety.

Gross vehicle weight at launch will be 273,000 lbs., with 210,000 lbs of that amount represented by the combined weight of the liquid oxygen and liquid hydrogen fuel.

Dryden's X-33 Connection

Contributions by the Dryden Flight Research Center to the government-industry team developing the X-33 program are significant and represent a span of more than three decades, beginning with design data collected by the Center's lifting body program that is easily recognized in the X-33's appearance.

Dryden's role in the X-33 program encompasses a wide variety of tasks and disciplines, including engineering support in aerodynamics, structural and thermal dynamics, flight controls and flight operations, flight test planning, range and tracking support, and providing ground support.

Along with the scaled model tests with the SR-71, other Dryden aircraft have played an important part in the X-33's development.

The durability of the TPS materials was demonstrated on a series of six F-15 flights at speeds above Mach 1. The materials, including the metallic tiles and sealing compound, were flown attached to the F-15s flight test fixture and subjected to high speeds and maneuvering dynamics. Similar tests on TPS materials used on Space Shuttles were flown at Dryden early in that development program.

Early in the X-33's final design stages, a scaled model of the vehicle was dropped from a large radio-controlled "mothership" to test and verify the glide characteristics of the spacecraft.

Telemetry and instrumentation components that will be used at the Dugway landing site were tested by a high-flying Dryden F-18 after they were set up in an operational configuration at Edwards.

One of NASA's ER-2 aircraft was used as a surrogate X-33 to completely check out and test the entire radar and telemetry range from Edwards to Dugway.

The Center will be the lead agency for range support during the test flights. Radar and telemetry tracking of the vehicle during flight will be carried out by Dryden's Western Aeronautical Test Range (WATR), supported by an Extended Test Range Alliance with the Air Force Flight Test Center, Edwards AFB, that includes the use of Air Force range, radar, and communications equipment. Range support will extend from Edwards all the way to Montana, including Utah, to furnish exact vehicle positioning at all times during flight through radar and telemetry. Telemetry received from the vehicle by range equipment will furnish a real-time performance picture to test personnel monitoring the vehicle in the X-33 Operations Control Center.

The Flush Air Data System (FADS) used on the X-33 was developed at Dryden. FADS, in flight, will generate data on air speed and vehicle attitude and feed this information

into the flight control computers to maintain the desired flight path. FADS uses tiny ports to collect the aerodynamic data instead of using conventional probes that extend into the air stream. Information generated by FADS is also monitored by test personnel on the ground as the flight progresses.

A flight simulator developed at Dryden was used to evaluate the flying qualities and performance characteristics of the X-33. The simulator, with a NASA pilot "flying" the vehicle through the planned autonomous mission profile, was used to evaluate the vehicle's flight characteristics in a variety of test scenarios.

Dryden's avionics laboratory personnel have been supporting development of the vehicle's flight control software and that support will continue when the vehicle arrives at the Edwards launch site for preflight systems integration tests.

Members of the X-33 test team at the Edwards launch site and the two landing sites are receiving logistics and technical support from Dryden as the facilities are being prepared for flight operations. Included in the support is integrating the use of the Dryden Mobile Operations Control Center as a backup launch and mission control facility.

The Flight Operations Center

The X-33 Flight Operations Center, which includes the Operational Control Center and launch and pre-flight facilities, is located in the Haystack Butte area of Edwards AFB. Construction of the facility was completed in March 1999.

The site, south of the Air Force Research Laboratory Propulsion Directorate (formerly Phillips Laboratories) and east of Rogers Dry Lake, is essentially a small-scale spaceport that will have the capabilities of servicing and launching the X-33 from the same site.

The $32 million Center is expected to have a crew of about 50 people during flight operations.

One of the goals of the X-33 program is to demonstrate that the spacecraft can be serviced and launched on another flight in a matter of days. During the flight test program servicing crews have the goals of two seven-day turnaround periods and one two-day turnaround period.

The Government-Industry X-33 Team

The NASA X-33 program is managed by the Marshall Space Flight Center, Huntsville, Ala. The budget for the program, through the year 1999, was $941 million.

Lockheed Martin Skunk Works heads the industry team. The Skunk Works, based in Palmdale, Calif., received the NASA contract to design and develop the vehicle on July 2, 1996.

Other major industry X-33 team members are: Allied Signal Defense and Space System, Teterboro, N.J., avionics for flight control and major subsystems; B.F. Goodrich Aerospace/Aerostructures, Chula Vista Calif., TPS; Boeing Rocketdyne Division, Canoga Park, Calif., linear aerospike engines; GenCorp Aerojet, Sacramento, Calif., reaction control systems; Michoud Space Systems (Lockheed Martin), New Orleans, La., liquid oxygen tank; Alliant Techsystems, Minneapolis, Minn., liquid hydrogen tanks; Sanders, So. Nashua, N.H., vehicle health monitoring system; and Sverdrop, Tullahoma, Tenn., general contractor for the X-33 Flight Operations Center.

NASA X-33 team members include, besides the Marshall and Dryden centers; Stennis Space Center, Miss., engine tests; Wallops Flight Facility, Va., launch site ground support and communications equipment; Ames Research Center, Mountain View, Calif., design and development support of TPS; Johnson Space Center, Houston, Tex., TPS testing; Kennedy Space Center, Fla., launch system expertise; Glenn Research Center, design and test support for engine health monitoring system; Langley Research Center, Va., wind tunnel tests and structural tests of critical airframe parts; Jet Propulsion Laboratory, Pasadena, Calif., small experiment that may be flown aboard the X-33.

The Air Force Flight Test Center, Edwards AFB., is providing support in flight planning, range control, vehicle instrumentation, and range safety responsibilities, while the Air Force Research Laboratory Propulsion Directorate is providing logistics support for the Flight Operations Center.

January 2000

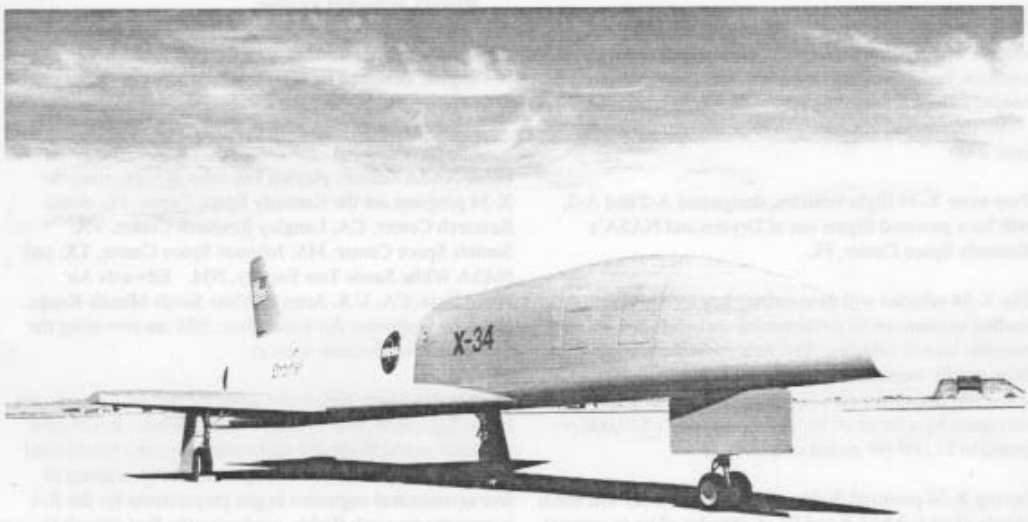
NASA Facts

National Aeronautics and
Space Administration

Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523
Voice 661-258-3449
FAX 661-258-3566
pao@dfrc.nasa.gov

FS-2000-01-060 DFRC

X-34 TECHNOLOGY TESTBED DEMONSTRATOR



PROJECT SUMMARY

NASA's Dryden Flight Research Center, Edwards, CA., the Agency's premier flight testing Center, is supporting a nationwide government-industry team in the X-34 Program —one of a number of flight demonstration efforts aimed at increasing safety and reliability while reducing the cost of getting into space.

The X-34 project is managed by NASA's Marshall Space Flight Center in Huntsville, AL, and led by prime contractor Orbital Sciences Corporation, Dulles, VA. Dryden's support of X-34 and its sister reusable launch vehicle programs—X-33 and X-37—involves flight and data testing as well as ground operations.

The unpiloted, winged X-34 vehicles are 58.3 feet long, have a 27.7-foot wingspan and stand 11.5 feet tall. It will be air-launched from Orbital's L-1011 airplane and will land autonomously on lakebeds or concrete runways using on-board computers.

The first of three X-34 vehicles, a structural test vehicle designated A-1, began captive-carry flights June 1999. These captive-carry flights check for potentially hazardous flight conditions due to the modifications made to the L-1011, which enable it to carry the X-34. When a commercial airplane like the L-1011 is altered, the Federal Aviation Administration (FAA) must certify that the changes have not adversely affected the plane's safe operation.

Dryden technicians are assisting in upgrading the A-1 vehicle with structural modifications and integrating avionics, hydraulics, landing gear, and other hardware needed to turn it into a flight vehicle – now known as A-1A — for unpowered glide tests in New Mexico during the year 2000.

Two more X-34 flight vehicles, designated A-2 and A-3, will have powered flights out of Dryden and NASA's Kennedy Space Center, FL.

The X-34 vehicles will demonstrate key technologies leading to commercial development and operation of reusable launch vehicles. This new technology could dramatically increase safety and reliability in accessing space and reduce the cost of putting a pound of payload into space by a factor of 10, i.e., from today's $10,000 per pound to $1,000 per pound or less.

During X-34 powered flights, the suborbital craft will reach speeds of up to Mach 8 and fly at altitudes of up to approximately 50 miles. Among the program objectives:

- serve as a testbed for new technologies requiring a high-speed, high-altitude flight environment,
- demonstrate performance of new, lightweight composite materials,
- demonstrate new (re-entry) thermal protection systems,
- demonstrate new, low-cost avionics systems,
- demonstrate rapid turnaround/re-flight capability with minimum personnel and equipment,
- demonstrate subsonic flight and landing capabilities through inclement weather,
- demonstrate performance of the new FASTRAC engine, designed by Marshall Space Flight Center engineers to be simpler, cheaper, and needing less maintenance than current engines.

Other NASA Centers playing key roles in supporting the X-34 program are the Kennedy Space Center, FL; Ames Research Center, CA; Langley Research Center, VA; Stennis Space Center, MS; Johnson Space Center, TX; and NASA White Sands Test Facility, NM. Edwards Air Force Base, CA; U.S. Army's White Sands Missile Range, NM; and Holloman Air Force Base, NM are providing the Department of Defense support.

The Dryden Flight Research Center located on Edwards Air Force Base, Edwards, CA, is NASA's premier installation for aeronautical flight and suborbital research. Established at this Mojave Desert site in September 1946, a group of five aeronautical engineers began preparations for the X-1 supersonic research flights, producing the first aircraft to fly faster than the speed of sound.

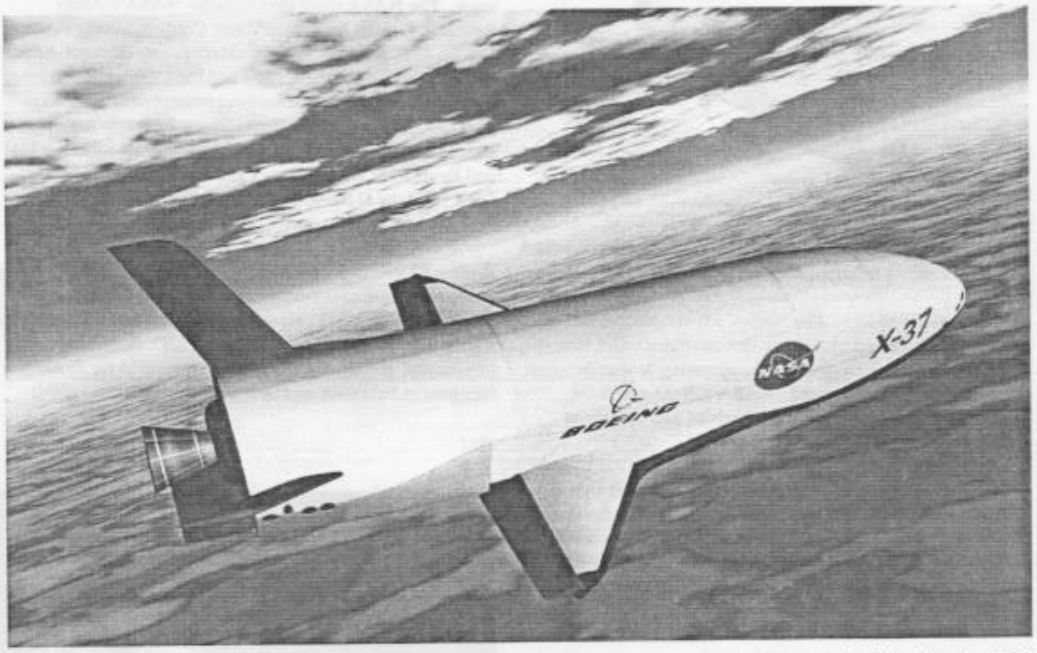
NASA Facts

National Aeronautics and
Space Administration

Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523
Voice 661-258-3449
FAX 661-258-3566
pao@dfrc.nasa.gov

FS-2000-05-070-DFRC

X-37
Advanced Technology Demonstrator



NASA Dryden Flight Research Center is participating in a NASA/Boeing cooperative agreement to build and fly the X-37 Advanced Technology Demonstrator. NASA and The Boeing Company entered into the $173 million cooperative agreement in July 1999 to develop the new experimental space plane. The U.S. Air Force is committing $16 million to demonstrate technologies needed to improve future military spacecraft. NASA selected Boeing Phantom Works, Advanced Space and Communications, of Seal Beach, Calif., in December 1998 for negotiations leading to the cooperative agreement.

The overall objective of the X-37 program is to meet NASA's requirement for the Future X Pathfinder Program through a high-value, flight-focused program capable of raising the readiness level across a broad range of Earth-to-orbit, on-orbit flight and ground system technologies required to dramatically lower the cost of space transportation. As part of NASA's Access to Space pillar, the specific goal of the X-37 and NASA's other reusable technology demonstrators is to reduce the

cost of getting into space from $10,000 to $1,000 per pound while increasing reliability.

The uncrewed X-37 will be NASA's first "Access To Space" reusable launch vehicle demonstrator to fly in both orbital and reentry environments, operating at speeds up to 25 times the speed of sound. NASA's X-33 and X-34 technology demonstrators are suborbital and operate at lower speeds.

The X-37 will demonstrate technologies aimed at significantly reducing the cost of space flight. These technologies include avionics and flight control software improvements, ground and flight operations, structures and mechanical systems, propulsion, and thermal protection system technologies.

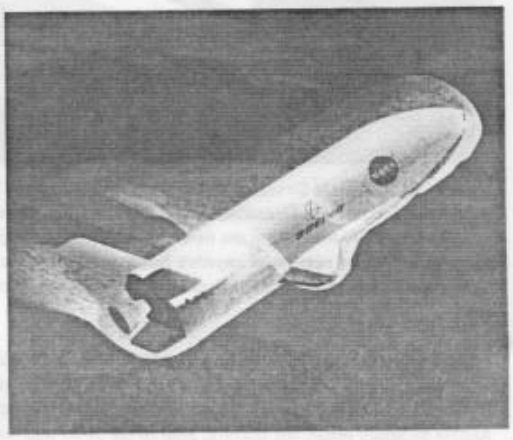
Current plans call for the X-37 to be flown captive-carry on Dryden's B-52 carrier aircraft, then dropped from the B-52 for approach and landing tests later. Following successful atmospheric flight tests, the X-37 will be ferried into orbit aboard a space shuttle for orbital and atmospheric reentry test flights. The first unpowered flight test of the X-37 from Dryden's B-52 is planned for fall 2001.

Two orbital tests are planned for 2002 and 2003. After the X-37 is deployed, it will remain in orbit up to 21 days, performing a variety of experiments before reentering the atmosphere and landing. Various locations are being studied as landing sites.

The X-37 measures 27.5 feet long with a wingspan of about 15 feet. It has an experiment bay 7 feet long and 4 feet in diameter. Its shape is a 20-percent larger derivative of the X-40A, an unpowered Air Force vehicle also designed and built by Boeing, which was released from a helicopter and glide-tested in 1998. The X-40A, which lacks the X-37's advanced thermal protection materials, rocket engine, experiment bay and other spacecraft systems, will be drop tested from a helicopter to reduce risk prior to expanded testing with the X-37.

The government-industry team will share the cost of the program roughly 50-50. In addition to Dryden, NASA's Marshall Space Flight Center leads the X-37 government team. The NASA team also includes NASA's Ames Research Center, Mountain View, Calif.; Kennedy Space Center, Fla.; Johnson Space Center, Texas; Goddard Space Flight Center, Greenbelt, Md.; and the Langley Research Center, Hampton, Va. Other government participants are the U.S. Air Force Flight Test Center, Edwards Air Force Base, Calif.; the Air Force Space and Missile Systems Test and Evaluation Directorate, Vandenberg Air Force Base, Calif.; and the U.S. Army Aviation Technical Test Center, Fort Rucker, Ala.

Boeing Phantom Works of Seal Beach leads the X-37 industry team. Other Boeing facilities participating in the program are located in Huntington Beach, Calif.; Palmdale, Calif.; Seattle, Wash.; and St. Louis, MO. Assembly, integration, checkout and tests are planned at the Boeing facilities in Palmdale and Seal Beach in 2000 and 2001.



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National Aeronautics and
Space Administration

Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523
AC 805-258-3449
FAX 805-258-3566
pao@dfrc.nasa.gov

FS-1998-03-038-DFRC

X-38

Back to the Future For a Spacecraft Design

Engineers at NASA's Dryden Flight Research Center, Edwards, Calif., and the Johnson Space Center, (JSC) Houston, Texas, are flight-testing the X-38, a prototype spacecraft that could become the first new human spacecraft built in the past two decades that travels to and from orbit. The vehicle is being developed at a fraction of the cost of past human space vehicles. The goal is to take advantage of available equipment, and already developed technology for as much as 80 percent of the spacecraft's design.

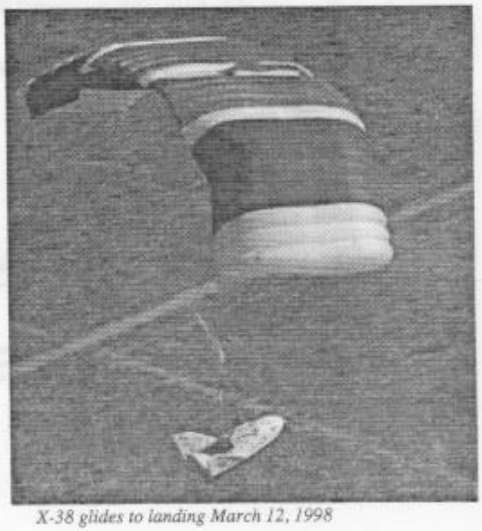
Using available technology and off-the-shelf equipment significantly reduces cost. The original estimates to build a capsule-type crew return vehicle (CRV) were more than $2 billion in total development cost.

According to NASA project officials, the X-38 concept and four operational vehicles will be built for approximately one quarter of the original $2 billion cost.

Current Status

Atmospheric drop tests of the X-38 at the Dryden Flight Research Center are underway and will continue for the next two years. Three test vehicles will be used. The drop tests will eventually increase in altitude to 50,000 feet and will include longer flight times for the test craft before its parafoil is deployed.

B-52 and X-38 in flight



X-38 glides to landing March 12, 1998

Full-scale, unpiloted "captive carry" flight tests began at Dryden in July 1997 in which the vehicle remained attached to the NASA B-52 aircraft. Unpiloted free-flight drop tests from the B-52 began in March 1998. In 2000, an unpiloted space test vehicle is planned to be deployed from a Space Shuttle and descend to a landing on earth. The X-38 crew return vehicle is targeted to begin operations aboard the International Space Station (ISS) in 2003.

Project Goals

The immediate goal of the innovative X-38 project, is to develop the technology for a prototype emergency CRV, or lifeboat, for the ISS. The project also intends to at develop a crew return vehicle design that could be modified for other uses, such as a possible joint U.S. and international human spacecraft that could be launched on the French Ariane 5 booster.

In the early years of the International Space Station, a Russian Soyuz spacecraft will be attached to the station as a CRV. But, as the size of the crew aboard the station increases, a return vehicle that can accommodate up to six passengers will be needed. The X-38 design uses a lifting body concept originally developed by the Air Force's X-24A project in the mid-1970's. After the deorbit engine module is jettisoned, the X-38 would glide from orbit unpowered like the Space Shuttle and then use a steerable, parafoil parachute, a technology recently developed by the Army, for its final descent to landing. Its landing gear would consist of skids rather than wheels.

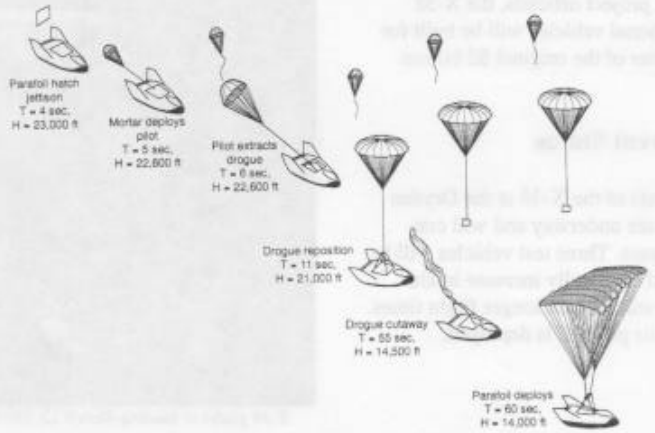
Technology

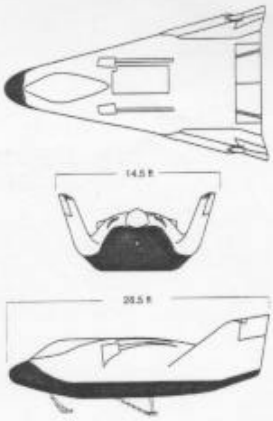
Off-the-shelf technology doesn't mean it is old technology. Many of the technologies being used in the X-38 have never before been applied to a human spacecraft.

The X-38 flight computer is commercial equipment that is currently used in aircraft, and the flight software operating system is a commercial system already in use in many aerospace applications. The video equipment on the atmospheric test vehicles is existing equipment, some of which has already flown on the Space Shuttle for other NASA experiments. The electromechanical actuators that are used on the X-38 come from a previous joint NASA, Air Force, and Navy research and development project.

An existing special coating developed by NASA will be used on the X-38 thermal tiles to make them more durable than the tiles used on the Space Shuttle. The X-38's primary navigational equipment, the Inertial Navigation System/Global Positioning System, is a unit already in use on Navy fighters.

X-38 First Flight Profile





Three view of X-38

Future Plans

Although the design could one day be modified for other uses such as a crew transport vehicle, the X-38 would strictly be used as a CRV in its current design. It is baselined with only enough life support supplies to last about nine hours flying free of the space station in orbit. The spacecraft's landing will be totally automated, although the crew will be able to switch to backup systems, control the orientation in orbit, pick a deorbit site, and steer the parafoil, if necessary. The X-38 CRV has a nitrogen gas-fueled attitude control system and uses a bank of batteries for power. The spacecraft will be 28.5 feet long, 14.5 feet wide, and weigh about 16,000 pounds.

An, in-house development study of the X-38 concept began at JSC in early 1995. In the summer of 1995, early flight tests were conducted of the parafoil concept by dropping platforms with a parafoil from an aircraft at the Army's Yuma Proving Ground, Yuma, Arizona. In early 1996 a contract was awarded to Scaled Composites, Inc., of Mojave, Calif. to build three full-scale atmospheric test airframes. The first vehicle airframe was delivered to JSC in September 1996, where it was outfitted with avionics, computer systems, and other hardware in preparation for the flight tests at Dryden. A second vehicle was delivered to JSC in December 1996.

Team Approach

About 100 people are currently working on the project at Johnson, Dryden, and the Langley Research Center in Hampton, Va. This is the first time a prototype vehicle has been built-up in-house at JSC, rather than by a contractor; an approach that has many advantages. By building up the vehicles in-house, engineers have a better understanding of the problems contractors experience when they build vehicles for NASA. JSC's X-38 team will have a detailed set of requirements for the contractor to use to construct the CRVs for the ISS. This type of hands-on work was done by the National Advisory Committee on Aeronautics (NACA), NASA's predecessor, before the space age began.

Dryden conducted model flights in 1995. The 1/6 scale-model of the CRV spacecraft using a parafoil parachute system was flown 13 times. The results showed that the vehicle had good flight control characteristics and also demonstrated good slideout characteristics

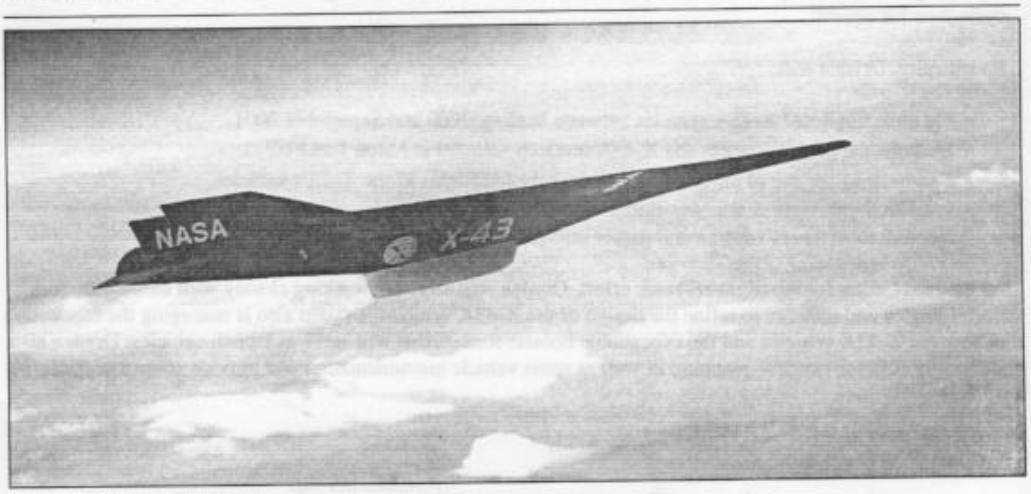
X-38 team members at work

March 1998

National Aeronautics and
Space Administration

Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523
AC 805-258-3449
FAX 805-258-3566
pao@dfrc.nasa.gov

FS-1998-03-040 DFRC



Artist conception of X-43A

Dryden and the Hyper-X Program

Project Background

An experimental hypersonic flight-research program, called Hyper-X, will be among the most significant projects underway at the NASA Dryden Flight Research Center, Edwards, Calif., during the next few years.

The multi-year NASA/industry Hyper-X program seeks to demonstrate airframe-integrated, "air-breathing" engine technologies that promise to increase payload capacity for future vehicles, including hypersonic aircraft (faster than Mach 5) and reusable space launchers.

Conventional rocket engines are powered by mixing fuel with oxygen, both of which are traditionally carried onboard the aircraft. The Hyper-X vehicles, designated X-43A, will carry only their fuel — hydrogen — while the oxygen needed to burn the fuel wil come from the atmosphere. By eliminating the need to carry oxygen aboard the aircraft, future hypersonic vehicles will have room to carry more payload. Another unique aspect of the X-43A vehicle is that the body of the aircraft itself forms critical elements of the engine, with the forebody acting as the intake for the airflow and the aft section serving as the nozzle. These technologies will be put to the test during a rigorous flight-research program at NASA Dryden.

NASA Dryden's Role

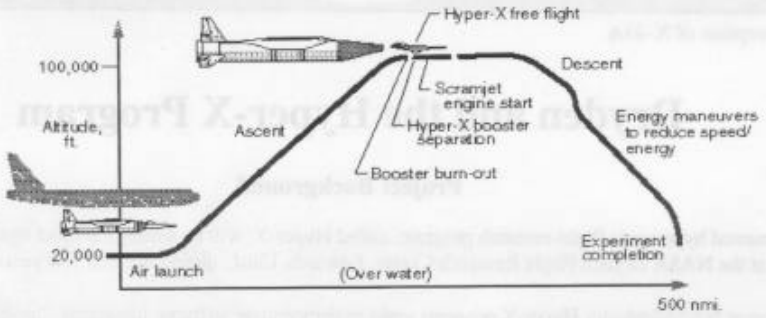
NASA Dryden has several major roles in Phase I of the Hyper-X program, which is a joint Dryden/NASA Langley Research Center program being conducted under NASA's Aeronautics and Space Transportation Technology Enterprise. Dryden's primary responsibility is to fly three unpiloted X-43A research vehicles to help prove both the engine technologies, the hypersonic design tools and the hypersonic test facilities developed at Langley. NASA Langley, Hampton, Va., has overall management of the Hyper-X program and leads the technology development effort.

Through this Langley/Dryden/industry partnership, the Hyper-X program fulfills a key Agency goal of providing next-generation design tools and experimental aircraft to increase design confidence and cut the design cycle time for aircraft.

Specifically, Dryden will:

- Fly three unpiloted X-43A vehicles between January 2000 and September 2001.
- Evaluate the performance of the X-43A research vehicles at Mach 7 and 10.
- Demonstrate the use of air-breathing engines during flights of the X-43A vehicles.
- Provide flight research data to validate results of wind tunnel tests, analysis and other aeronautical research tools used to design and gather information about the vehicles.

As the lead Center for the flight-research effort, Dryden engineers are working closely with their colleagues from Langley and industry to refine the design of the X-43A vehicles. Dryden also is managing the fabrication of both the X-43A vehicles and the expendable booster rockets that will serve as launch vehicles. Dryden also will perform flight-research planning as well as some vehicle instrumentation and provide control of the tests.



Unlike conventional aircraft, the X-43A vehicles will not take off under their own power and climb to test altitude. Instead, NASA Dryden's B-52 aircraft will climb to about 20,000 feet for the first flight and release the launch vehicle. For each flight the booster will accelerate the X-43A research vehicle to the test conditions (Mach 7 or 10) at approximately 100,000 feet, where it will separate from the booster and fly under its own power and preprogrammed control. Flights of the X-43A will originate from the Dryden/Edwards Air Force Base area, and the missions will occur within the Western Sea Range off the coast of California. The current flight profile calls for launching the X-43A vehicles heading west. The flight path for the vehicles varies in length and is completely over water.

The B-52 Dryden will use to carry the X-43A and launch vehicle to test altitude is the oldest B-52 on flying status. The aircraft, on loan from the U.S. Air Force, has been used on some of the most important projects in aerospace history. It is one of two B-52s used to air launch the three X-15 hypersonic aircraft for research flights. It also has been used to drop test the various wingless lifting bodies, which contributed to the development of the Space Shuttle. In addition, the B-52 was part of the original flight tests of the Pegasus booster. Modified Pegasus® boosters will serve as the launch vehicles.

Current Status

On Aug. 11, 1998, the first piece of hardware was delivered to NASA — a scramjet engine that will be used for a series of ground tests in NASA Langley's 8 Foot High Temperature Tunnel. This engine could later be used for flight if necessary.

Orbital Sciences Corp., Dulles, Va., is designing and building three Pegasus-derivative launch vehicles for the series of X-43A vehicles, a process that Dryden will oversee. A successful critical design review for the launch vehicle was held at Orbital's Chandler, Ariz., facility in December 1997.

NASA selected MicroCraft Inc., Tullahoma, Tenn., in March 1997 to fabricate the unpiloted research aircraft for the flight research missions, two flights at Mach 7 and one at Mach 10 beginning in 2000. Micro-Craft is aided by Boeing, which is responsible for designing the research vehicle, developing flight control laws and providing the thermal protection system; GASL Inc., which is building the scramjet engines and their fuel systems and providing instrumentation for the vehicles; and Accurate Automation, Chatanooga, Tenn.

Air-Breathing Scramjet Engine Technologies

This challenging ground and flight-research program will expand significantly the boundaries of air-breathing flight by being the first to fly a "scramjet" powered aircraft at hypersonic speeds. Demonstrating the airframe-integrated ramjet/scramjet engine tops the list of program technology goals, followed by development of hypersonic aerodynamics and validation of design tools and test facilities for air-breathing hypersonic vehicles. The scramjet engine is the key enabling technology for this program. Without it, sustained hypersonic flight could prove impossible.

Ramjets operate by subsonic combustion of fuel in a stream of air compressed by the forward speed of the aircraft itself, as opposed to a normal jet engine, in which the compressor section (the compressor blades) compresses the air. Unlike jet engines, ramjets have no rotating parts. Ramjets operate from about Mach 2 to Mach 5.

Scramjets (supersonic-combustion ramjets) are ramjet engines in which the airflow through the whole engine remains supersonic. Scramjet technology is challenging because only limited testing can be performed in ground facilities. Long duration, full-scale testing requires flight research. Hyper-X will help build knowledge, confidence and a technology bridge to very high Mach number flight.

Currently, the world's fastest air-breathing aircraft, the SR-71, cruises slightly faster than Mach 3. The highest speed attained by NASA's rocket-powered X-15 was Mach 6.7. The X-43A aircraft is designed to fly faster than any previous air-breathing aircraft.

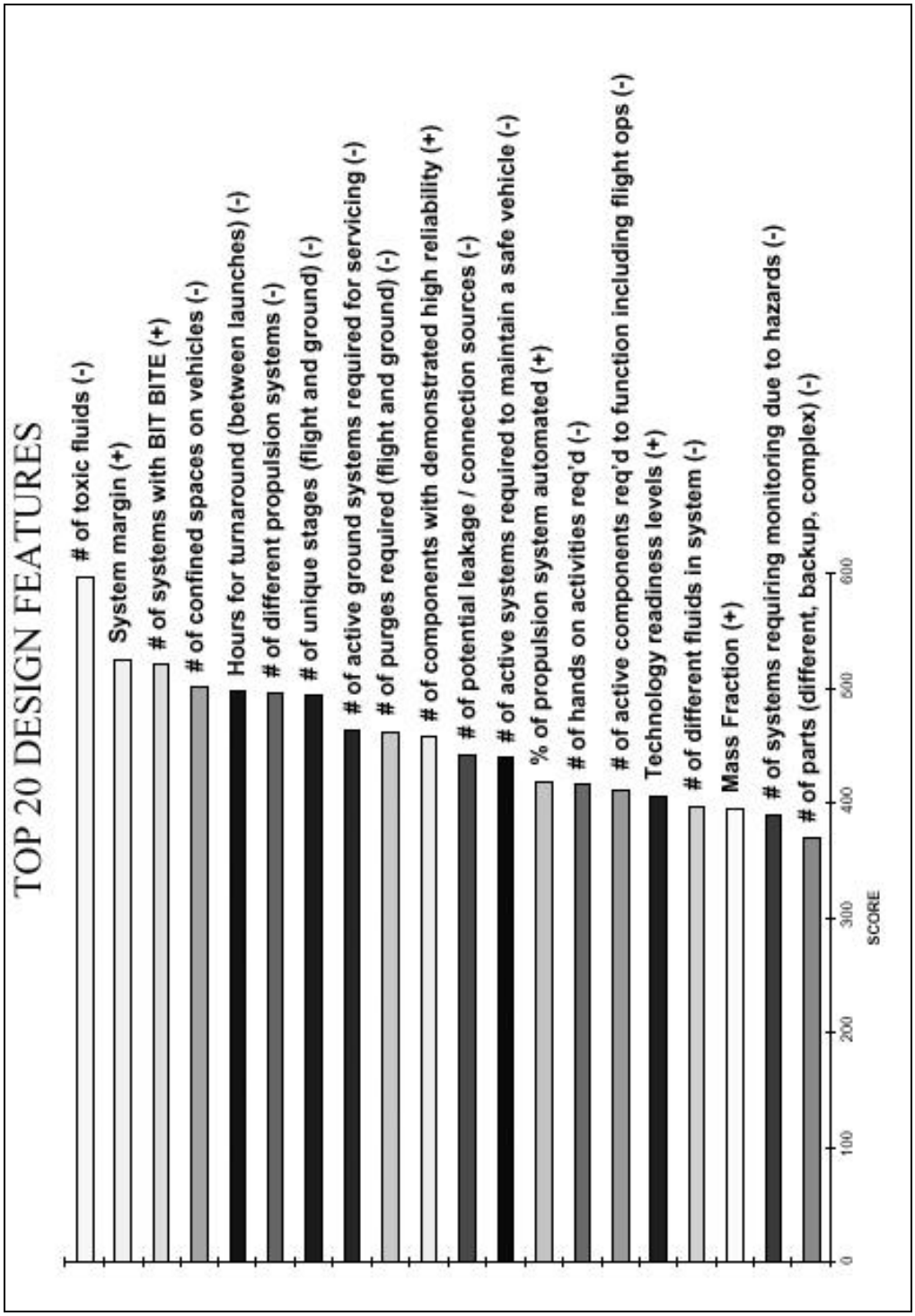
Appendix C: SMV Missions Identified by Aerospace Corporation & SMC/XR [49]

Mission	Area
Anti-Satellite	SC
Battle Management/C2 Augmentation	FE
Border Monitoring	Gov
Communications (Augmentation)	FE
Counterair	FA
Counter-Weapons of Mass Destruction	FA
D4EN Airborne Targets	FA
D4EN Terr. Targets w/Non-Nuclear	FA
D4EN Terrestrial Trgts w/Nuclear	FA
Defensive Counterspace	SC
Disaster Area Surveillance	Gov
Disaster Relief Support	Gov
Drug Enforcement Support	Gov
Drug Traffic Monitoring	Gov
Defensive Satellite Operations	SC
Electronic Warfare	SC
Exercise Support	SS
Global Agriculture Monitoring	Gov
Global Mobility	SS
Hard/Deeply Buried Target Detection	FE
Intelligence Preparation of Battlefield	Int
Intelligence Collection	Int
Launch Denial	FA
Mapping	FE
Mobile (Air) Target S&TW	FE
Mobile (Ground) Target S&TW	FE
Mobile (Sea) Target S&TW	FE
Navigation Augmentation	FE
Navigation Warfare	SC
Nuclear, Biological, Chemical Detection	FE
National Missile Defense Engagement	SC
National Missile Defense Warning	SC
Offensive Counterspace	SC
Operations Training Support	SS
Reconnaissance	Int

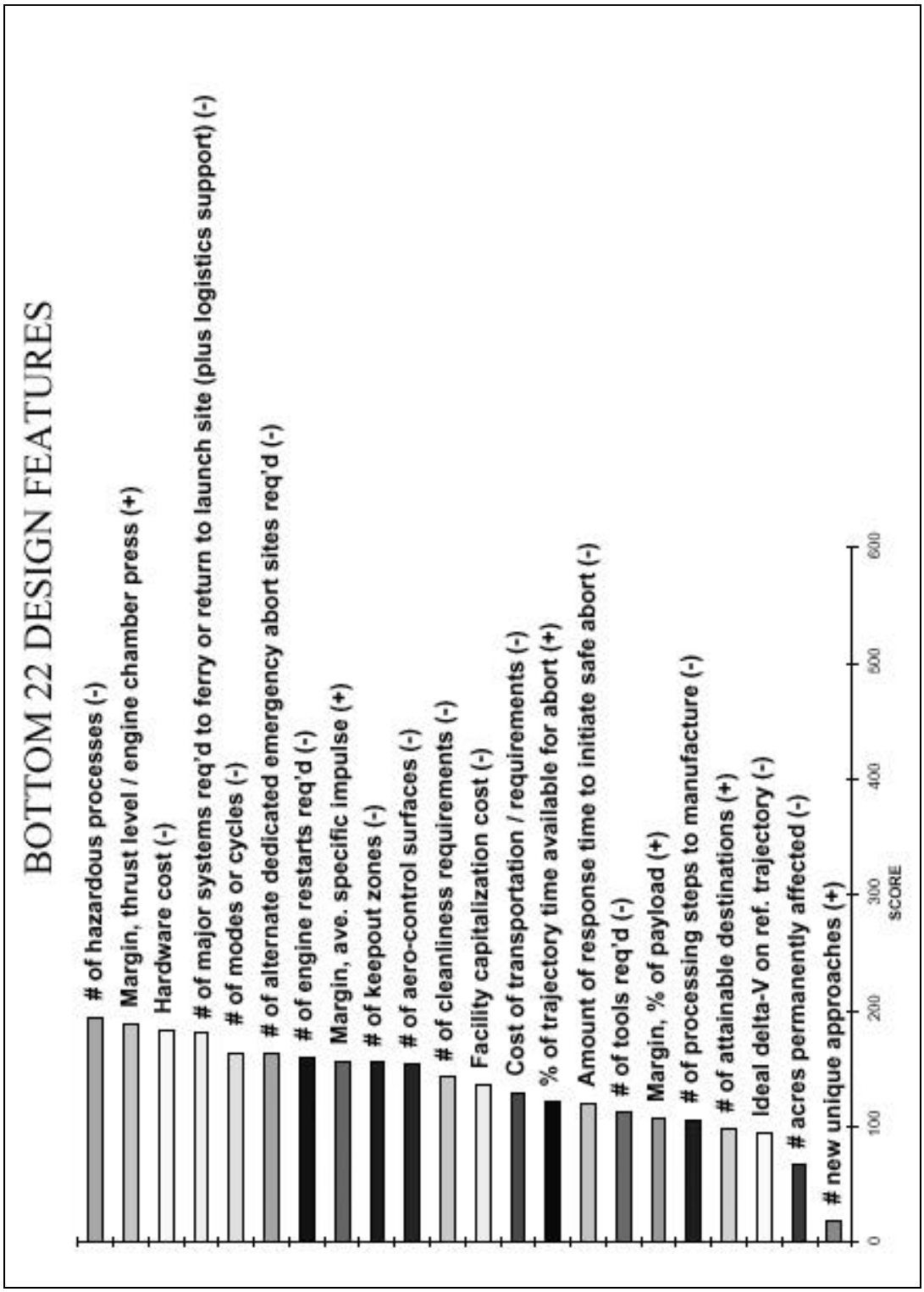
Mission	Area
Remote Sensing	Gov
Satellite Inspection	Int/SC
Satellite Maintenance	SS
Satellite Recovery	SS
Satellite Refueling	SS
Satellite Replenishment	SS
Satellite Repositioning	SS
Space Order of Battle Updating	SS
Space Assets Deployment	FE
Space Attack Warning	SC
Space Environment Forecasting	FE
Space Information Denial	SC
Space Nuclear Detection	FE
Space Object Cataloging	SC
Space Object Identification	SC
Space Surveillance	SC
Space Target BDA/Status	FE/SC
Space Test Support	SS
Spacelift	Int/FE
Strat. Relocatable Target Detection	FE
Target Designation	FE
Terrestrial Environment Measurement	FE
Terrestrial Nuclear Detection	FE
Terrestrial Target BDA/Status	Int/FE
Theater Intelligence Collection	Int/FE
Theater Targeting	Int
Theater Missile Defense Engagement	SC
Theater Missile Defense Tracking	SC
Treaty Verification Support	Gov
Unattended Ground Sensor Query	FE

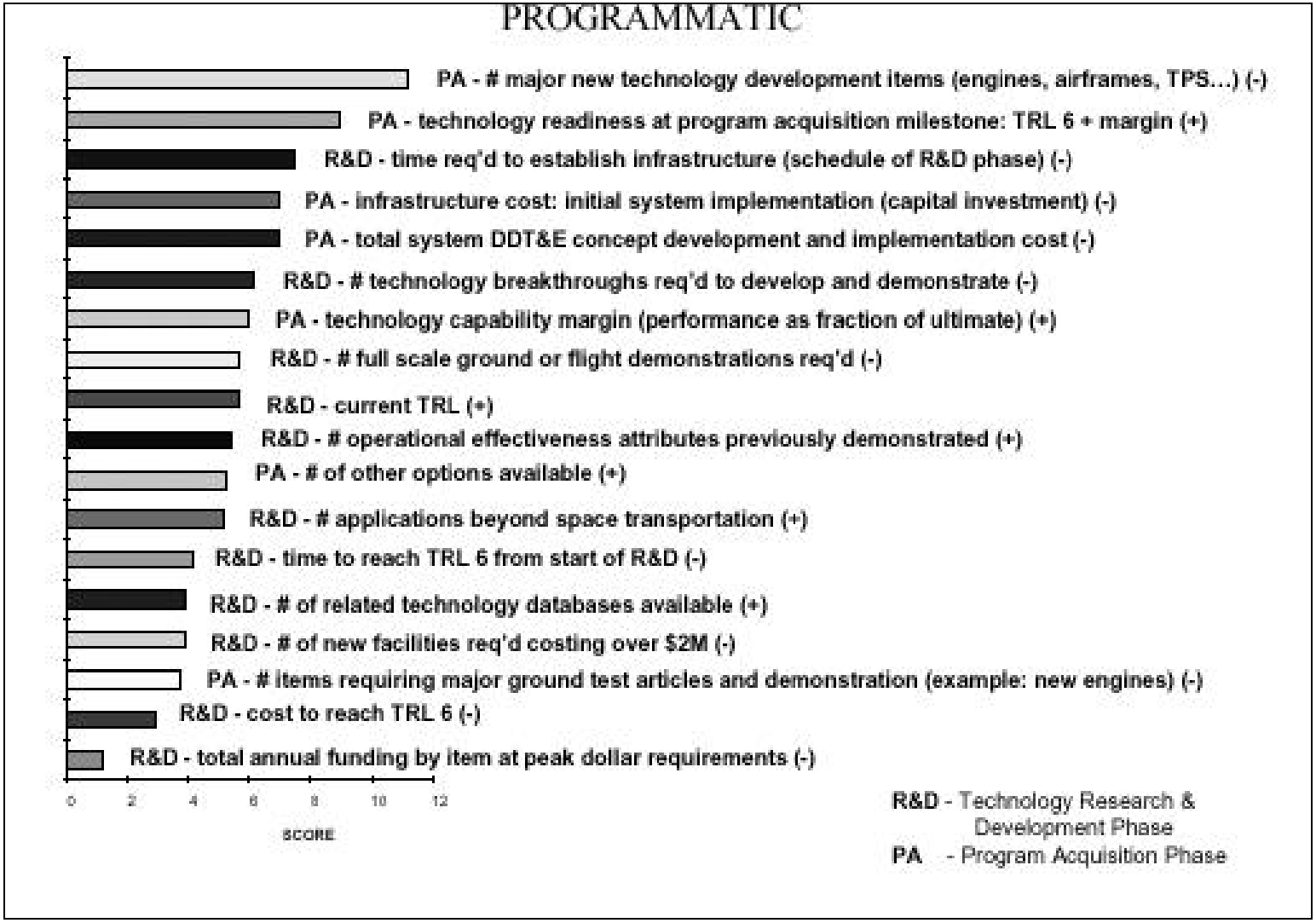
Int=Intelligence, FA=Force Application, FE=Force Enhancement, SC=Space Control, SS=Space Support, Gov=Government
BDA = Battle Damage Assessment
S&TW = Surveillance and Threat Warning

Appendix D: RLV Desirable Features [51]



MIDDLE 22 DESIGN FEATURES
# of expendables (fluid, parts, software) (-)
# of checkouts req'd (-)
pollutive or toxic materials (-)
of inspection points (-)
# of propulsion sub-systems with fault tolerance (+)
# of engines (-)
Ave. Isp on refer. trajectory (+)
# of manhours on sys between on/off cycles (LCF) or use (HCF) (-)
# of criticality 1 failure modes (-)
# of element to element interfaces requiring engineering control (-)
Hours to refurbish propulsion system (-)
# of physically difficult to access areas (-)
% of propulsion subsystems monitored to change from hazard to safe (+)
# of hours to refurbish launch site between each launch (-)
Mean time between major overhaul (-)
Amount of energy release from unplanned reaction of propellant (-)
# of manufacturing, test and operations facilites (recurring) (-)
# of ground power systems (-)
# of active engine systems req'd to function (-)
Margin, mass fraction (+)
Mean time between overhaul as % of $ cost of system (+)
Amount of real time inspection or repair (-)
0
100
200
300
400
500
600
SCORE


BOTTOM 22 DESIGN FEATURES
# of hazardous processes (-)
Margin, thrust level / engine chamber press (+)
Hardware cost (-)
# of major systems req'd to ferry or return to launch site (plus logistics support) (-)
# of modes or cycles (-)
# of alternate dedicated emergency abort sites req'd (-)
# of engine restarts req'd (-)
Margin, ave. specific impulse (+)
# of keepout zones (-)
# of aero-control surfaces (-)
# of cleanliness requirements (-)
Facility capitalization cost (-)
Cost of transportation / requirements (-)
% of trajectory time available for abort (+)
Amount of response time to initiate safe abort (-)
# of tools req'd (-)
Margin, % of payload (+)
# of processing steps to manufacture (-)
# of attainable destinations (+)
Ideal delta-V on ref. trajectory (-)
acres permanently affected (-)
new unique approaches (+)
0
100
200
300
400
500
600
SCORE


PROGRAMMATIC
PA - # major new technology development items (engines, airframes, TPS...) (-)
PA - technology readiness at program acquisition milestone: TRL 6 + margin (+)
R&D - time req'd to establish infrastructure (schedule of R&D phase) (-)
PA - infrastructure cost: initial system implementation (capital investment) (-)
PA - total system DDT&E concept development and implementation cost (-)
R&D - # technology breakthroughs req'd to develop and demonstrate (-)
PA - technology capability margin (performance as fraction of ultimate) (+)
R&D - # full scale ground or flight demonstrations req'd (-)
R&D - current TRL (+)
R&D - # operational effectiveness attributes previously demonstrated (+)
PA - # of other options available (+)
R&D - # applications beyond space transportation (+)
R&D - time to reach TRL 6 from start of R&D (-)
R&D - # of related technology databases available (+)
R&D - # of new facilities req'd costing over $2M (-)
PA - # items requiring major ground test articles and demonstration (example: new engines) (-)
R&D - cost to reach TRL 6 (-)
R&D - total annual funding by item at peak dollar requirements (-)
0
2
4
6
8
10
12
SCORE
R&D - Technology Research & Development Phase
PA - Program Acquisition Phase

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Vita

Captain Charles S. Galbreath graduated from Verdugo Hills High School in Tujunga, California in 1988. He entered undergraduate studies at Northrop University in El Segundo, California where he graduated with a Bachelor of Science degree in Aerospace Engineering in 1991. He was commissioned through Officer Training School in 1993. His first assignment was at Malmstrom AFB as a Minuteman Missile Combat Crewmember from 1993 to 1997. During this time he earned a Master of Administrative Science degree from the University of Montana. In September of 1997, he was assigned to the Developmental Planning Directorate of the Space and Missile Systems Center, Los Angeles AFB, California. Here he conducted analysis for such studies as the Launch on Demand Impact Study and the Space Maneuver Vehicle Military Utility Analysis. In August 1999, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to the 17th Test Squadron, Schriever AFB, Colorado.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
08-03-2001	Thesis	Mar 2000 - Mar 2001

4. TITLE AND SUBTITLE
QUALITY INITIATIVES IN THE AIR FORCE DEVELOPMENT OF REUSABLE LAUNCH VEHICLES

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Capt Charles S. Galbreath

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 P Street, Building 640
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/GSO/ENY/01M-03

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFRL/MLM
attn: Mr. Alan Taylor
2310 8th Street, Room 103
WPAFB OH 45433-7801 DSN: 785-3920

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This thesis identifies useful tools and techniques available to aid the Air Force development of a reusable launch vehicle (RLV). These tools are identified by comparing traits found within the Lean Aerospace Initiative, Six Sigma and systems engineering. While identified specifically for the RLV effort, these tools and techniques will be of use to many development programs. Historical perspectives of both RLV development efforts within the Air Force and origins of modern quality teachings are provided, to establish a common foundation of knowledge, upon which, further analysis can be conducted. This thesis, also, summarizes the current RLV effort within the Air Force and NASA. With the tool-set identified and the RLV effort enumerated, the tool-set and RLV effort are matched to determine the current level of integration. More importantly, the tools-set serves as the basis to form specific recommendations to aid the Air Force RLV effort.

15. SUBJECT TERMS
Quality, Systems Engineering, Lean Aerospace Initiative, Six Sigma, Reusable Launch Vehicle, Space Operations Vehicle, Space Maneuver Vehicle

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Milton E. Franke, ENY
U	U	U	UU	111	19b. TELEPHONE NUMBER *(Include area code)* (937) 255-6565 x4720