



NAVAL POSTGRADUATE SCHOOL

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THESIS

**QUALITY INITIATIVES IN THE COMMERCIAL
DEVELOPMENT OF REUSABLE LAUNCH VEHICLES**

by

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March 2015

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REUSABLE LAUNCH VEHICLES**

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ABSTRACT

This thesis examines positive tools and techniques accessible and helpful to improving quality of the Reusable Launch Vehicle (RLV). Over the last three decades, NASA has directly been involved in developing modern and technologically improved RLVs. The technologies were projected to facilitate cheaper access to orbital space, as evidenced by its past X-programs and space launch initiatives.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AST	Associate Administrator for Commercial Space Transportation
CGWIC	China Great Wall Industry Corporation
COMSTAC	Commercial Space Transportation Advisory Committee
CSL	Commercial Space Launch
DC-X	Delta Clipper Experimental
DC-XA	Delta Clipper Experimental Advanced
DOD	Department of Defense
DOT	U.S. Department of Transportation
EELV	Evolved Expendable Launch Vehicle
ELV	Expendable Launch Vehicle
FAA	Federal Aviation Administration
HLV	Hybrid Launch Vehicles
ICBM	Intercontinental Ballistic Missile
ISS	International Space Station
LAI	Lean Aerospace Initiative (Lean Advancement Initiative)
LEO	Low Earth Orbit
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NRO	National Reconnaissance Office
OTV	Orbital Test Vehicle
RLV	Reusable Launch Vehicles
SpaceX	Space Exploration Technology
SRB	Solid Rocket Booster
SS2	SpaceShipTwo
SSME	Space Shuttle's Main Engine
SSTO	Single-Stage-to-Orbit technology
STS	Space Transportation System
TAV	Trans-Atmospheric Vehicle
TSTO	Two-Stage-to-Orbit

ULA	United Launch Alliance
VSE	Vision for Space Exploration
X-20	Dyna-Soar
X-30	National Aerospace Plane
X-33	Venture Star
X-34	Advanced Technology Demonstrator

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I. INTRODUCTION

A. BACKGROUND

“No longer is space just a destination to reach; it is a place where we must be able to work in ways that are responsible, sustainable, and safe. And it is central to our security and the security of our allies, as space-based technology allows us to communicate more effectively, to operate with greater precision and clarity, and to better protect our men and women in uniform.”

“But, above all, this policy is about the boundless possibilities of the future... we seek to spur a burgeoning commercial space industry, to rapidly increase our capabilities in space while bolstering America’s competitive edge in the global economy... We do not fear the future; we embrace the future. Even in times of trial, we do not turn inward; we harness the ingenuity and talents of our people, we set bold goals for our nation, and we lead the world toward new frontiers.”

—President Barack Obama
on the New National Space Policy, 28 June 2010 [1]

The United States has traditionally been the leader in space exploration, but the times have changed. Access to space has become a formidable challenge for the United States in an era of very expensive systems and a federal budget under severe pressure. President Obama has challenged Space authorities to create more robust and efficient solutions for the country’s space system issues [1]. The president calls for more reliable, sustainable and secure solutions to open the doors to newfound frontiers in space technology in the new millennia and beyond. He suggests an increasing role by the commercial space sector [1].

The survival and progress of the U.S. partly depends on its ability to take advantage of its space-based assets in order to provide support to its national and homeland security objectives. Space forces have played a key role in the creation of strategic military and economic advantages [1]. Motivations for this new direction by the government emphasizing the commercial sector are brought on by the need to maintain telecommunication, reconnaissance and surveillance, and navigation satellites. Each of

these systems has a finite lifetime and requires periodic replacement. Doing this efficiently is imperative.

Launch vehicles are a critical component in achieving access to space. While government and commercial space activity continue to develop and enable new uses of space for the good of mankind, the accessibility to space is jeopardized by the high cost of launch vehicles. The high cost of today's space launch vehicles can be attributed to the technical challenges of space flight, low launch frequency, and the demand for increasingly greater vehicle reliability. Therefore, the goal—to bring space launch cost down from several hundred million dollars to single-digit millions—still remains today [2].

There is a demand to decrease the cost of space missions. This demand applies to all missions, whether scientific, commercial or military, and covers all facets of space missions (i.e., nonrecurring development costs, manufacturing, launch and operations). A large part of the problem is caused by the steep cost of access to space. Even when the launch cost may not be the most expensive facet of a given program, it effectively thwarts efforts to reduce the cost of other program elements. It is unfortunate to note, however, that launch costs have remained basically unchanged and considerably high in the last three decades.

Launch vehicles are at the core of space exploration and progress; as Hempstead and Worthington said, “it is the active element of a space transportation system, in the same way that an aircraft is to an airline” [3, p. 744]. There are two types of launch vehicles: reusable launch vehicles (RLVs), which are capable of returning from space, and can be refueled and later sent on another mission; and expendable launch vehicles (ELVs), which are deployed and then discarded after one use. For this thesis discussion will focus, primarily, on RLVs and how quality initiatives such as Lean Aerospace Initiative can lead to improved RLV quality and lower costs [4].

Technically speaking, there are no manned RLVs today; the closest to its definition of being reusable and manned was the space shuttle. But there is the X-37B Orbital Test Vehicle (OTV), which is an unmanned RLV, it is one-fourth the size of the

space shuttle [5]. The Air Force claims that the X-37's contributions to space exploration will result in making space access more routine, affordable, and responsive. Development of true RLV systems will bring a beneficial transformation to space operations by making it possible for the Air Force to shift from a launch on-schedule toward a launch on-demand approach, improving the Air Force's capability to provide space support in any theater of operation and assure access to space [6, p. 1]. In addition, the ability to provide maintenance and recovery of on-orbit assets will allow satellites to be designed with less expense and more capabilities. However, while it remains evident that RLVs potentially offer desired benefits, there exist complex technical problems and programmatic challenges that impede development of RLV systems.

1. Expendable Launch Vehicles

While President Obama emphasized commercial sector involvement in achieving space access, part of the problem in commercializing spacelift transportation is the high cost that comes with ELVs. The U.S. Air Force supported the Evolved Expendable Launch Vehicle (EELV) program that began in fiscal year 1995 and centered on cost-reduction of space transportation by developing standard boosters. The goal of this program was a 25 percent reduction in the cost of space launch and the hope that a 50 percent reduction in costs could be achieved. Although, in order to achieve this goal and fully exploit space—"continue to design, build, operate, sustain, and protect space-based assets"—cost reductions on the order of 10–100 times current cost were needed [7].

Despite its intentions this program is now faced with significant challenges. The expendable nature of EELVs cause significant inconvenience to the customer who has to pay the cost to build an entirely new vehicle since a new vehicle is needed for each launch. Furthermore, recently the EELV program has been under intense scrutiny from Congress because of the rising costs, shown in Table 1, mainly due to the escalating price of engines used on both the Atlas V and the Delta IV launch vehicles.

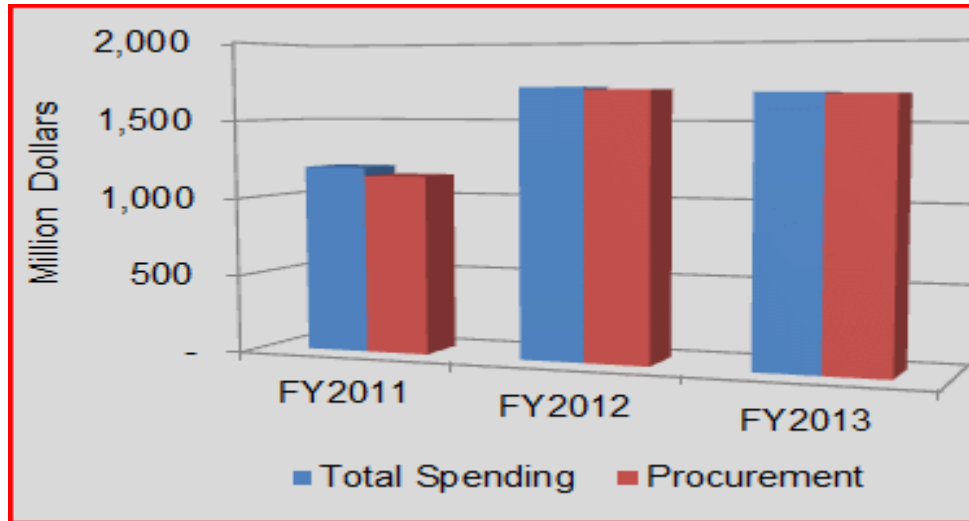


Table 1. EELV U.S. Defense Budget Charts (from [8])

From fiscal year (FY) 2011 to 2012 the Air Force's EELV budget request increased by more than 30 percent to \$1.72 billion, during a time when many program budgets were being cut. Shown in Table 2, for FY13, the EELV program is the space program that receives the most funding with expected direct total spending of \$1.69 billion, which is 100 percent procurement with no additional funds for research development, test and evaluation (RDT&E). In FY13, the U.S. Air Force purchased four launch vehicles (four and three procured in FY11 and FY12, respectively). According to the prime engines' supplier, Pratt & Whitney, the continued cost increases to the USAF resulted from the cancellation of several programs by the National Aeronautics and Space Administration (NASA). It is projected that if the cost-escalation proceeds at the same trends, the budget allotted for the EELV program will consume most of the \$7.06 billion (which has been reduced to \$5.39 billion in FY2013 budget) U.S. Department of Defense (DOD) space budget by the end of this decade [9]. Other top programs in the space budget include the Advanced EHF satellite system, the Mobile User Objective System (MUOS), the Defense Meteorological Satellite Program (DMSP), and the Wideband Global SATCOM (WGS) system.

Total Spending Procurement RDT&E # of Systems Bought				FY 2013 FY 2012 FY 2011				
<i>Note: Click on a program to view full profile</i>				Total Spending			PROC*	RDT&E*
Rank	System/Program Name	Type	User(s)	In Million U.S Dollars			In % of FY13 Total	
1	Evolved Expendable Launch Veh. (EELV)	System	USAF	1,687.8	1,716.2	1,198.3	100%	0%
2	Global Positioning System (GPS)	System	USAF	1,382.4	1,589.2	1,037.2	40%	60%
3	SBIRS - Space Based Infrared System	System	USAF	950.0	996.1	1,487.4	53%	47%
4	Advanced EHF	System	USAF	786.4	948.9	641.9	71%	29%
5	MILSATCOM System	System	USAF	275.5	374.4	644.8	17%	83%
6	MUOS - Mobile User Objective System	System	NAVY	167.4	482.1	894.5	13%	87%
7	Defense Meteorological Sat. (DMSP)	System	USAF	89.0	100.0	86.4	100%	0%
8	Wideband Global SATCOM (WGS)	System	USAF	48.9	805.5	634.2	75%	25%
9	DWSS National Polar-Orbiting (NPOESS)	System	USAF	-	43.0	173.0	0%	0%

PROC* = Procurement in % of total FY2013 DoD spending on the program
RDT&E* = Research Expenditures in % of total FY2013 DoD spending on the program

Table 2. DOD Space Programs and Expenses (from [10])

2. United Launch Alliance

Another important drawback to the EELV program is the lack of competition. In 2006, Lockheed and Boeing launch services merged to form the United Launch Alliance (ULA), which virtually monopolized the USAF launch market without additional incentives for cost-reduction, innovations or any provision to increase the quality of its services. The DOD currently depends exclusively on ULA.

ULA was created in order to streamline the U.S.'s access to space, in the hopes of reducing costs while at the same time encouraging innovations by combining the talent of the individuals behind Boeing with its Atlas Rockets and Lockheed with its Delta Rockets. By charter, ULA is a launch service company, which provides equal access to space among all its users. The rockets used by ULA include Delta II, Delta IV and Atlas V launch vehicles that span the spectrum of lift requirements, from medium lift to heavy lift. Both the Atlas V and the Delta IV were developed in coordination with the DOD with a budget of \$500 million. Boeing and Lockheed Martin funded the rest of the development process and sought to service national security requirements and the future commercial communication customer industry.

Since the government is ULA's only customer, DOD along with the National Reconnaissance Office (NRO) are obligated to pay more than a million dollars each year

to ULA just to maintain the EELV's capacity. Additionally, the costs of ULA are quite steep and it seems only the U.S. government can afford them. This is frustrating considering its early intentions of guaranteeing cheaper access to space and developing the commercial launch market.

B. POSSIBLE SOLUTION WITH RLV SYSTEMS AND QUALITY INITIATIVES

The key to a low-cost access to space is building a fully reusable launch vehicle. However, it has been decades since the first reusable launch vehicle, the space shuttle, was created and no real progress has been made since then. In the 1990s, several startup companies sprouted, lured by the promise of a profitable business in Low Earth Orbit (LEO) telecommunications spacecraft. Unfortunately, the failure of Globalstar, Iridium, and other commercial satellite companies caused much trouble for the space transport companies. Many commercially operating companies have disappeared due to lack of support and financial difficulties.

The ongoing commercial operations of various RLV companies versus the technological advances made by the government in exploring its options with RLVs, needs to be explored. Hence, this paper is dedicated to the investigation of the Lean Aerospace Initiative (LAI) quality initiative—which includes some Six Sigma and Systems Engineering (SE) concepts—instituted by commercial firms to propel advances in the current technologies in RLVs. Lean optimizes a process, eliminates waste, and strives for perfect quality. This quality initiative attempts to highlight design features that will allow current RLV technology to grow economically and be able to reliably accommodate a broader market sphere. Previously conducted market surveys suggest that the commercial space industry is competitive and bound to dictate flight rates that are half the current spacelift costs [11].

The LAI quality initiative was selected for a variety of reasons; it is a unique approach to the ultimate goal—customer satisfaction. The LAI was selected because its Lean concepts, principles, and practices can be applied to an industry with significantly different products and customers. LAI is a joint effort between industry, the

Massachusetts Institute of Technology (MIT) and the U.S. Air Force. Through its Lean impact, LAI has demonstrated major schedule savings; for example, the Atlas launch vehicle program reduced lead-time from 48.5 to 18 months [12]. Furthermore, it has been very instrumental in improving spacecraft testing and integration.

A graphical analysis of the final integration and testing of 224 spacecraft revealing sources of discrepancies is shown in Figure 1. MIT, using LAI, documented these results to characterize the distribution and costs of spacecraft discrepancies found during Integration and Test. As shown, 36 percent of the discrepancies found during Integration and Test are written against subsystems and 35 percent of the discrepancies were against the system level; with respect to levels of integration, both levels are considered to be costly to fix. So, it can be argued that solving system and subsystem problems would be the most cost effective way to reduce spacecraft discrepancies. Therefore, applying the principles of LAI can potentially improve cost savings and increase product quality and reliability [13]. LAI will be further explained in Chapter IV.

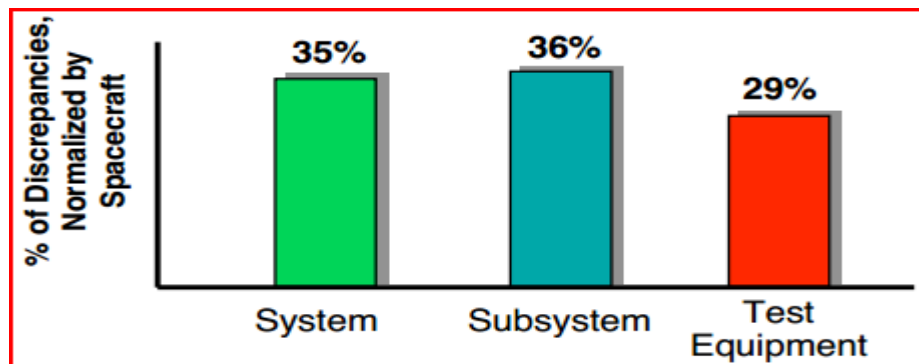


Figure 1. Distribution of discrepancies on an average spacecraft at the system level of integration, by area the discrepancy was written against (from [13])

Also, through the years LAI has evolved to transform enterprises on the elements Lean and the Six Sigma approach for its great reputation, wide propagated use, and many success stories from big companies like General Electric, Sony, AlliedSignal, and Motorola. The Six Sigma strategy involves the use of statistical tools within a structured methodology for gaining the knowledge needed to create products and services better,

faster, and less expensively than the competition; this initiative has typically produced an average cost savings of six figures per project [13]. In other words, Six Sigma stresses quality through the elimination of variation in all enterprise processes. A unified framework called Lean Six Sigma is emerging; enterprises usually adopt their own name, for example: [14]

- Rockwell Collins - *Lean Electronics*
- Raytheon - R6s
- USAF – *AF Smart Ops 21 (AFSO21)*
- NAVAIR – *AIRSpeed*
- Textron - *Textron Six Sigma*
- Boeing - *Lean+*
- United Technology - *ACE*
- Lockheed Martin - *LM21*

In addition, LAI, specifically the Lean Systems Engineering Working Group (LSE WG) of the International Council on Systems Engineering (INCOSE), have determined ways to synergize the area of Lean and SE; both have some similarities and differences, but share a common goal of delivering the best product or system life cycle value to the customer with minimum resources [15]. SE grew out of the space industry to help deliver flawless complex systems is focused on technical performance and risk management [15]. LSE is the application of six Lean principles (five classical ones plus “respect the people in your program” principle) and Six Sigma principles to SE in order to enhance the delivery of value to the customer. LSE developed a major product called Lean Enablers for SE (LEfSE); a comprehensive checklist of 194 enablers formulated as practices and recommendations of SE, and containing tacit knowledge on how to prepare for, plan, execute, and practice SE and relevant aspects of enterprise management using Lean thinking [16]. Each enabler enhances a program’s value and reduces some waste.

Released in June 2012, “The Guide to Lean Enablers for Managing Engineering Programs,” is the result of a one-year collaborative project between LAI, the Project Management Institute (PMI), and INCOSE. Compared to the Lean Enablers for SE (LEfSE) product, mentioned above, this guide contains 10 themes of major engineering program management challenges and 43 Lean Enablers (with 286 sub enablers) to overcome these challenges, and better integrate program management and SE. The findings show that programs using the Lean Enablers have significantly stronger performance across multiple dimensions that include cost, schedule, quality, and stakeholder satisfaction [17].

RLVs have been considered as lucrative alternatives for space access for a number of reasons. Although about \$1 billion of the DOD budget has been saved due to the retirement of the Space Shuttle [18], space access is made possible exclusively only by ELVs. Because RLVs offer the ability to return to Earth and be employed again, the price tag on the structure of an RLV might be amortized over multiple rollouts, potentially reducing the price of entry to space for state and commercial users. A rocket that might be used several or a number of times would enhance the economics of spaceflight by reducing the associated fee for each launch and increasing the U.S. Air Force's spacelift and NASA's expeditions by changing the usual launching agenda toward on-demand operations. The goal to launch frequently and inexpensively can still be achieved through continuous successful partnerships and cooperation between the Air Force, NASA and private industry; which will provide safe, reliable, affordable and responsive launch systems and technologies necessary to assure and sustain future efficient access to space.

C. GOVERNMENT RLV INTRODUCTION

The Space Transportation System (STS), which is the space shuttle, was first flown in 1981 and was retired June 2011. It was the primary means of launching American and some international people into orbit. It was comprised of an orbiter, which looked much like a regular aircraft. On both sides the rocket had two Solid Rocket Boosters (SRBs). It had a massive cylindrical external tank, which held the fuel for the orbiter's engines. The rocket's external tank was the sole section of the craft that could not be reused. Technically, the space shuttle was partly successful as it was a reusable launch vehicle, however economically, experts say, it failed miserably. It would be hard to disagree.

Despite being reusable, the shuttle required as long as two months to be rebuilt for the next launch, and needed several thousand personnel and support systems. The agency projected that it would fly up to 50 missions each year at an operating cost of about \$10.5 million for each flight. In reality, the five space shuttles: Atlantis, Challenger, Columbia, Discovery and Endeavour were launched on a total of 135 missions; less than five times

each year. Furthermore, the cost for a shuttle launch amounted to roughly \$20,000 per kg—far more expensive than many expendable launchers [19]. It failed to accomplish the guaranteed cost savings.

Over the years, the government has had several launch vehicle programs that have been plagued with numerous issues. NASA has had the responsibility for upgrading the Space Shuttle and for technology development of new RLVs. For over thirty years the U.S. administration, the U.S. commercial launch industry and NASA have been on the hunt for strategies that would substantially cut the price tag on launching satellites into space through various investigations and improvement programs.

NASA embarked on an ambitious series of experimental vehicle, or X-vehicle, programs. In addition to the Shuttle, there have been numerous attempts to develop a new RLV but all failed or were prematurely cancelled. Furthermore, all shared a common issue: lack of technology maturity of fundamental components to meet the needs of RLV safety, reliability, affordability and responsiveness. For example, in the 1990s, NASA attempted two rocket-powered RLV technology experiments, the X-33 and X-34. These were joint venture programs established between NASA and industry. The government has not been successful in its efforts, and with the United States moving to emphasize the commercial space sector; efforts are shifting toward development of commercial RLVs.

D. PURPOSE

The main purpose of this thesis is to investigate the role LAI quality initiatives play in commercial programs and advancements commercial RLV development can bring to the Air Force and NASA efforts at developing launch vehicles.

E. RESEARCH QUESTIONS

This research addresses the commercial development of RLVs. The subsequent chapters address the following questions:

1. What is a reusable launch vehicle (RLV)?
2. What is the current demand for RLVs and what advancements commercial RLV development can bring to the government?

3. What is Lean and what role LAI quality initiatives play in commercial programs?

F. BENEFITS OF STUDY

This thesis identifies techniques within Lean Aerospace Initiative (LAI) that are employed by market players today and also best suited for the RLV effort. Additionally, this thesis provides a historical perspective of both RLV development efforts within the government and industry, also origins of modern quality teachings to establish a universally accepted foundation of knowledge, upon which further examination can be based upon.

G. SCOPE AND METHODOLOGY

As has been observed in the last years, the most notable growth in the RLV industry, whether for government or commercial use, has been in the design of suborbital RLVs tailored specifically to serve the burgeoning personal spaceflight market. In July 2008, Scaled Composites and Virgin Galactic released the first White Knight Two aircraft, which will serve as the air launch platform for the Space Ship Two suborbital vehicle under development. Specific activities within industry and private development efforts such as SpaceX, Blue Origin, and Scaled Composites and their partnership with Virgin Galactic will be addressed in Chapter II.

Furthermore, provided 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. The research of this thesis continues the efforts of previous thesis work by Endicott [20], Matuzsak [21] and Galbreath [6]. Endicott's research considered Lean practices in space launch operations with emphasis on systems that are developed, processed, and launched through the most reliable, responsive, and cost effective means. Matuzsak examined how Lean principles associated with elimination of wasteful practices can be applied toward improving scheduling activities at the U.S. space launch ranges at Cape Canaveral and Vandenberg Air Force Base (AFB). Galbreath's study concerned the use and application of Lean

practices, Six Sigma, and system engineering for the development of RLVs. In addition, MIT did extensive research on commercial RLV systems development utilizing LAI [6].

The first step is to conduct a literature review of both quality and RLV topics to determine what quality initiatives were lacking in government RLV efforts. Step two, analyzes LAI quality approaches and identifies its useful techniques and practices. This will provide the necessary background information required to conduct subsequent analysis and make recommendations for improvement. The useful techniques and practices are then applied to the current RLV efforts to determine how LAI quality initiatives are already being used and how they can further benefit government RLV development.

H. DOCUMENT ORGANIZATION

Chapter I—Introduction contains an overview and rationale for research into LAI and RLV efforts.

Chapter II—RLV Development contains two subsections of background information to help the reader to understand both historical attempts and current efforts in RLV development within the government and industry. The first section contains early testing of reusable launch technology by NASA and the Air Force. The second section addresses specific activities within industry and private development efforts such as SpaceX, Blue Origin, and Scaled Composites and their partnership with Virgin Galactic.

Chapter III—Demand for RLVs contains three subsections. The first subsection provides an estimate of manned space flight costs; including the Mercury, Gemini, Apollo, Skylab, and Space Shuttle programs. In the second subsection, the commercialization of space is discussed. In the third subsection, quality is defined and introduced to the reader for better understanding.

Chapter IV—Analysis of LAI has two subsections. The first subsection provides the origins of the principles of Lean and LAI. In the second subsection, necessary background information on various LAI tools and techniques are provided to conduct subsequent analysis and make recommendations for RLV effort improvement.

Chapter V—Application discusses the useful tools and techniques examined to determine applicability of research and conclusions.

Chapter VI—Conclusions and recommendations concludes with a summary of findings and provides recommendations for further areas of study.

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II. REUSABLE LAUNCH VEHICLE DEVELOPMENT

The history of RLV development, insight into current thinking and a basic understanding of the prevailing RLV effort provide the framework from which analysis may be thoughtfully undertaken. Similarly, an appreciation for the current commercial RLVs will prove beneficial. 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 history of RLVs and their current programs.

A. RLV BACKGROUND

The concept of Reusable Launch Vehicles (RLVs) is an old idea. The idea of the RLV can be traced back to 1928, and since that time a great many proposals have been made. The classic book, *The Frontiers of Space* (1969), vividly illustrates a number of RLV concepts, all of which were technically feasible at that time. During the last few decades the idea of sending payloads into space using RLVs has gained momentum. The U.S. government has invested in RLVs for many years and continues to do so. In the 1960s, during the Apollo missions, it was observed that certain economies could be achieved by developing reusable space vehicles; it appeared to make sound economic sense to reuse a launch vehicle that cost as much as a small airliner, rather than throw the launch vehicle away after using it only once (like ELVs).

RLVs can be classified into two main types defined according to the mode of takeoff and landing. They can be horizontal or vertical takeoff vehicles with either horizontal or vertical landing capabilities. An RLV may be categorized further as being single-stage-to-orbit (SSTO) or two-stage-to-orbit (TSTO). In the future, state of the art RLVs will incorporate advanced control systems that will make them much safer and more reliable than expendable launch vehicles. This will permit launches from inland sites because there will be no requirement for used rockets to splash down in the ocean. They may well herald an era when launches can take place from mainstream city airports, where the prevailing weather conditions are usually more predictable and benign than at coastal launch sites.

1. Government RLV Development: Early Testing of Reusable Launch Technology

In October 1957, the USAF briefly considered developing a small reusable reconnaissance space plane that would have been launched into orbit on the back of a Titan II missile—the X-20 Dyna-Soar [22]; see Figure 2. However, the X-20 program was canceled in 1963, about three years before the first scheduled flight, on the grounds of poorly thought out military objectives, lack of quality initiatives, and the DOD’s desire to design a very different type of space vehicle. Nevertheless, the research was not entirely wasted as it led to the development of the Space Shuttle’s delta wings [23].



Figure 2. Dyna-Soar (X-20) (from [22])

After the X-20 project was shelved, the Air Force conducted the Trans-atmospheric Vehicle (TAV) studies, a military space vehicle with horizontal takeoff and landing features (like an airplane) throughout the late 1980s and 1990s. The program investigated rocket and air-breathing Single-Stage-To-Orbit (SSTO) and TSTO vehicles [24]. The key idea of the TAV, also known as the “Black Horse” [26] shown in Figure 3, was to place a handful of well-trained individuals at the site of an uprising or terrorist incident anywhere on Earth within an hour of launch [25].



Figure 3. Trans-Atmospheric Vehicle (Black Horse) (from [26])

Unfortunately, two of the three TAV SSTO test vehicles constructed were unsuccessful in the course of testing because of their excessive weight characteristics; the third vehicle was launched but it was not a great success [27]. Subsequently, this vehicle also failed during testing as a result of a manufacturing defect; although the defect could have been quite easily remedied (possibly through the application of quality initiatives like LAI)—the TAV program was terminated in 1988 [28].

After the failure of the TAV program, NASA and the USAF conducted joint research on RLV technology in the form of the new National Aerospace Plane (X-30) [29], shown in Figure 4. Further political interference and additional military requirements specified that the X-30 be made capable of transporting people but this was too much of a challenge for the existing design. Despite these requirements, the X-30 program ran from 1986 to 1994 but it did not produce a flight-worthy spacecraft capable of carrying people. The program was eventually terminated because of severe budget reductions implemented during the post-cold war era.

Despite the vehicle's failure, data from the program were put to good use in succeeding research and development work. The program's other notable accomplishments included the following: the design and ground testing of mixed cycle engine elements; the design and sub-scale testing of the linear rocket; development of extreme temperature components; and the manufacture of slush hydrogen [28].

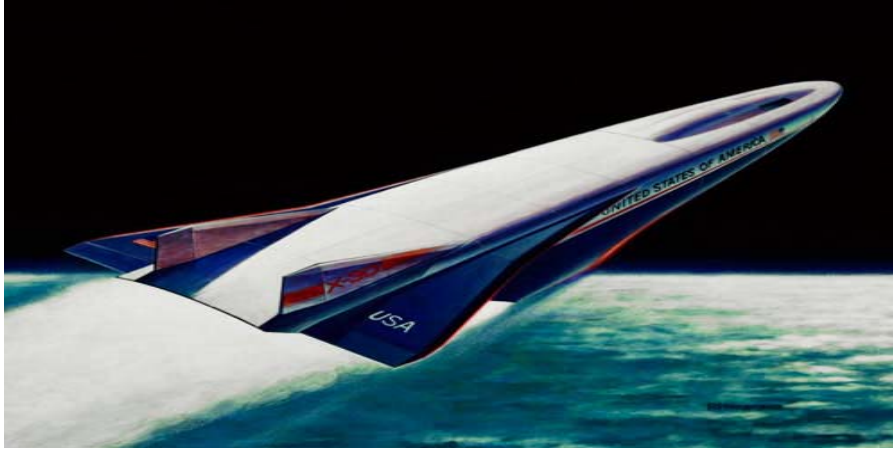


Figure 4. National Aerospace Plane (X-30) (from [29])

Between 1992 and 1997, the USAF invested roughly \$115 million on scientific studies for RLVs. NASA invested an additional \$1 billion, not including the funds necessary for the development of the Space Shuttle [30]. Most of these funds were allocated to programs and ideas that started out in the Delta Clipper Experimental (DC-X) program. These programs and principles included the construction of the X-33 and X-34 for NASA.

The DC-X [31], shown in Figure 5, started as a privately owned venture, financed through the Strategic Defense Initiative Organization, and maintained by the USAF Phillips Laboratory located at Kirtland Air Force Base in Albuquerque, New Mexico. McDonnell Douglas constructed the DC-X during the early 1990s to provide a one-third-scale model for the conceptual SSTO vehicle. The results of the eight DC-X test flights proved its capability to combine vital subsystems necessary for the upcoming RLVs, with features for sub-orbital and orbital expeditions. The DC-X was a key component in proving that it was possible to create space vehicles whose operational costs were fairly low [32].



Figure 5. Delta Clipper Experimental (DC-X) (from [31])

In 1996, NASA and the DOD within the RLV Program improved the DC-X technology, leading to the creation of the Delta Clipper Experimental Advanced (DC-XA) space vehicle. The principal objectives of the program were to test improved reaction control systems, advanced composite cryogenic tanks, as well as other improvements to enhance its operability. Later in 1996, the DC-XA successfully completed three test flights, where it further demonstrated rapid turnaround with a small labor force. Events were proceeding well but disastrously, on the fourth test flight, serious damage occurred to DC-XA when a loose fitting in a helium pressurization line caused one of the legs to fail to deploy on landing; it has not flown since July 1996 [33]. This is yet another quality problem that could have been mitigated if quality initiatives like LAI were applied.

From 1995 to 2001, NASA worked with industry to create two RLV models, the X-33 “Venture Star” and the X-34 “Advanced Technology Demonstrator,” shown in Figures 6 and 7, respectively, with the intention that private industry would take over its development, operation and financing. The X-33 was a NASA-Lockheed Martin joint program whose brief was to design and build a sub-scale prototype of a large RLV based on SSTD technology, with vertical takeoff and airplane-landing capabilities.



Figure 6. Venture Star (X-33) (from [34])

The ultimate goals were for the Venture Star to reduce launch costs from approximately \$10,000 to \$1,000 per pound of payload to LEO to reduce business and technical risks, and thereby produce a cost-effective SSTD rocket system capable of replacing the Space Shuttle [36, p. 17].

The X-34, shown in Figure 7, was a joint endeavor with NASA and Orbital Sciences Corporation that sought to develop, test and demonstrate RLVs with TSTD technologies. The technical objectives included 25 test flights per year, subsonic and hypersonic flight (Mach 8 at 250,000 feet), autonomous flight operations, the use of composites (in structures, tanks, lines, and ducts), and low cost avionics [35]. Unfortunately, a joint NASA/Orbital Sciences Corporation review of the project in 2000 identified risks of inadequate system testing, single-string avionics, and the lack of auto-land validation. To ensure safety and mission success of the X-34 would have required increased government technical insight, hardware testing and integrated systems assessments [35].



Figure 7. Advanced Technology Demonstrator (X-34) (from [37])

NASA ended the X-33 and X-34 program in March 2001, publicly stating that the expense to accomplish them was excessive compared to the expected advantages gained but that was not the whole truth. The actual reasons for the cancellation can really be attributed to a chain reaction of bad key decisions about construction and not applying proper LAI approaches to the X-33. First, the linear aerospike engine was too technically challenging to build and operate. The basic concept was to use the airflow surrounding the rocket's exhaust as the nozzle. This would have allowed the engine to be 75 percent smaller than standard engines, a necessary size and weight improvement required for SSTO [36, p. 20]. Rocketdyne decided that the main engine ramps should use a heavy copper alloy, which caused major changes to the flight control surfaces because the center of gravity of the RLV was shifted towards the rear of the craft. Furthermore, the weight of the liquid hydrogen fuel tank (LH2)—a large multi-lobed structure—had to be lowered. The decision was made to build one out of composite materials, but this proved to be a great challenge, as the workforce had very little experience in building large-scale composite structures. The LH2 composite tank failed on multiple occasions during extensive testing as forewarned by the engineers [36].

At the outset, the engineers and designers had protested when they were informed of a management decision to build a composite LH2 tank. Faced with a project failure, Lockheed Martin and X-33 NASA managers gave the green light to proceed with the fabrication of the new tank made from alloys (subsequently used in the Space Shuttle). However, it was too late for the project. In 2001, due to the lack of a solution for the LH2 tank failures the program was officially canceled after five years of development [36].

NASA spent about \$1.2 billion on the X-33 alone, and not one flight vehicle was ever tested. Lockheed Martin spent approximately \$356 million. NASA invested \$205 million on the X-34 [38]. The disappointments of the X-33 and X-34 programs, and of the X-30 program before them, made some observers cynical about NASA's capacity to create a second-generation RLV—the Space Shuttle was the first generation RLV.

a. *First Generation RLV*

To date, the Space Shuttle has been the only successful partial RLV. Unfortunately, the lower costs that were considered to be associated with reusable launch systems were not realized during the Shuttle mission era [39]. William Harwood, CBS News space consultant, has covered America's space program full time for more than 25 years, focusing on Space Shuttle operations, planetary exploration and astronomy. Harwood has asserted that mainly cost, safety and reliability issues had a negative influence on the Space Shuttle program. Ultimately these were the three principal factors that triggered the demise of the Space Shuttle program [40].

The order to cancel the Space Shuttle Program was made by the Bush Administration and it left the United States, pioneers in this field, dependent on the Russians as a means to continue manned space exploration. Some of the principal reasons why the Shuttle Program was canceled are considered below by examining the pros and cons of Space Shuttle operations.

b. *Space Shuttle Design Considerations and Operations*

It was originally conceived as a spacecraft that could be launched into space on the back of a rocket and return to Earth by landing glider like on a runway. The method envisaged was that of a reusable spacecraft that could be easily repaired between missions at relatively low cost. Furthermore, each Space Shuttle was designed to carry out several missions each year.

c. *Space Shuttle Operations in Reality*

While it was developed within the original development cost and time estimates given to President Richard M. Nixon in 1971, the operational costs, flight rate, payload

capacity, and reliability were worse than anticipated [41]. The main reasons that led to the demise of the Space Shuttle program were the unacceptable costs of materials and labor needed to repair each shuttle and replace damaged components after each mission. The real costs were more than twice those estimated at the outset. Furthermore, the turnover rate for getting each Space Shuttle launch ready after a previous mission was much longer than anticipated. The Shuttle never achieved the high launch frequency needed to realize cost savings.

When these facts are considered together, and bearing in mind that the Space Shuttle was aging technology, it is not surprising that the program was canceled. A new launch vehicle is needed. The Obama administration wants the new spacecraft to be developed and paid for by the private sector and not out of public funding. In “A Critical Parameter Optimization of Launch Vehicle Costs,” a thesis by Todd Herrmann, it is stated that the ability to achieve the lower production costs of an RLV is due to the fact that the costs can be amortized over the duration of the system because of multiple flights achieved per vehicle [42]. To attain an increased frequency of flights, a variety of technology and market strategies will be necessary. The participation of the commercial space industry and open markets will enable safer, dependable, inexpensive and reactive modern technologies that will be required for the quick turnaround times required, and must do so in order to increase demand [39].

d. Space Shuttle’s Successor

In 2006, the U.S. Air Force Rapid Capabilities Office, with cooperation from NASA and Boeing, launched a program on a newly conceptualized test vehicle called the X-37B Orbital Test Vehicle (OTV) [44], shown in Figure 8. The X-37B OTV program was developed to test technologies that could be utilized in a dependable, reusable spacecraft that would be used by the Air Force. The X-37B, designed to launch on an Atlas V expendable launch system to conduct orbital operations for durations of up to nine months, is capable of landing like a jet airplane [43]. The technologies it tested includes: propulsion, navigation and control, sophisticated guidance, thermal defense systems, avionics, structures and seals designed for extreme temperatures, and reusable

insulation systems. The principal objectives behind the design of this new craft were twofold: to maximize reusability of spacecraft technologies for future space ventures of the U.S., and to launch scientific experiments that could be conducted in space, recovered and evaluated on Earth [43].



Figure 8. X-37B Orbital Test Vehicle (OTV) (from [44])

Currently, there are two X-37Bs that have flown a total of three missions: OTV-1, OTV-2 and OTV-3, respectively. OTV-1 (first X-37B) was launched in April 2010 and landed at Vandenberg on December 3, 2010 after 225 days in orbit—well below the 270-day orbital design limit for the vehicle [45]. In March 2011, OTV-2 (second X-37B) was test launched from Florida’s Cape Canaveral Air Force Station. The OTV-2 came back to Earth on June 16, 2012, after having spent nearly 15 months in orbit on a classified mission, making a successful landing at California’s Vandenberg Air Force Base [46]. The following year, the OTV-3 (first X-37B’s second mission) launch was delayed due to an upper-stage engine failure that occurred on an earlier Delta IV launch—ULA supplies both Delta IV and Atlas V launch systems; so they wanted to investigate and analyze the anomaly data enough to ensure a thorough crossover assessment for the OTV launch to be completed [47]. Final results revealed that the anomaly had no impact on the Atlas V engine and the OTV-3 was successfully launched December 11, 2012 and landed in October 2014 [48].

2. Commercial RLV Developments

The United States' commercial satellite market has an enviable reputation in commercial space operations, dating back to the 1960s. Since that time, commercial space ventures have soared and profited to a remarkable degree [49]. Today, there are a number of companies pursuing RLVs commercially; namely Armadillo Aerospace, Blue Origin, Masten Space Systems, UP Aerospace, Virgin Galactic, and XCOR Aerospace are all actively developing such RLVs. Space Exploration Technologies Corporation (SpaceX), meanwhile, is testing technologies for a reusable version of its Falcon 9 rocket with its Grasshopper demonstrator [50]. Virgin Galactic and Blue Origin will only be discussed in this section.

a. Virgin Galactic

Virgin Galactic, established by Sir Richard Branson, has achieved an important milestone in commercial RLV development by creating the first commercial spacecraft. As of 2008, the company has been conducting test flights for the next generation of private spacecraft. These developments boast more robust standards in the field of spacecraft technology in order to achieve new levels of safety, flexibility, frequency and cost effectiveness in transporting passengers into sub-orbit [52].

Virgin Galactic's sub-orbital spaceflight system (it will not achieve full orbit) is composed of two vehicles, the Spaceship Two (SS2) and WhiteKnight 2 (WK2), as shown in Figure 9 [51]. The reusable jet aircraft has four engines capable of high altitude and heavy lift missions, which include (but are not limited to), serving as a launch platform for the air-launched, reusable space plane, SS2. The SS2 uses a reusable hybrid rocket engine that contains none of the toxins found in solid rocket engines; the fuel is in solid form (rubber compound) and the oxidizer (Nitrous Oxide) is a liquid, both benign and stable, which enables the pilots to shut down the SS2 rocket engine at any time during its operation and glide safely back to the runway [52]. The SS2 and WK2, working together, permit versatile space access to various regions of the atmosphere, ranging from as low as the troposphere to as high as the thermosphere. They also provide

an extended duration of microgravity prior to re-entry into the Earth's atmosphere and the subsequent glide to a regular runway landing [53].



Figure 9. Spaceship Two (SS2) and WhiteKnight 2 (WK2) Design (from [51])

As of January 2014, SS2 has conducted: 31 successful test flights, with one other flight in June 2011 being canceled after the spacecraft failed to separate from its WK2, three rocket-powered test flights, in addition to 27 unpowered gliding flights [53]. The third rocket-powered test occurred on 10 January 2014, where the SS2 successfully launched to a planned altitude of 71,000 ft.—SS2's highest altitude to date—and at a maximum speed of Mach 1.4 [53].

b. Blue Origin

Blue Origin, established by Jeff Bezos, the founder of Amazon.com is another company attempting to develop a RLV. By dramatically lowering the cost of space flight, it is the intention of the company to permit as many people as possible to experience a space flight [54]. This vision will be achieved by the development of novel RLVs that will use reusable rocket-powered vertical take-off and vertical landing (VTVL) systems. The New Shepherd (suborbital) vehicle consists of two reusable modules, one for the crew and one for the propulsion systems [55]. The concept is that at peak altitude, the propulsion module shuts off its rocket engines, separates from the Crew Capsule, and the

Propulsion Module performs a powered landing while the crew capsule will eventually land under parachutes; see Figure 10 [56].

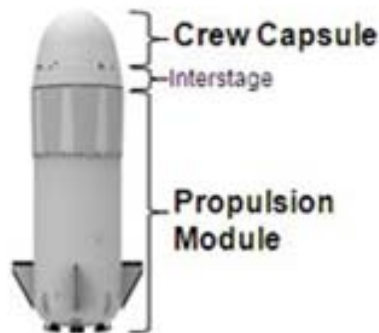


Figure 10. Early Prototype New Shepard Vehicle (from [56])

On November 13, 2006, the company launched and safely landed *Goddard*, the first development vehicle in the New Shepard program, designed to take a small number of astronauts into sub-orbital space [57]. In June 2011, Blue Origin successfully flew their second test vehicle on a short hop mission. Unfortunately, the test vehicle was lost in August 2011 during a developmental test at Mach 1.2 at an altitude of 45,000 feet. The reason for catastrophic crash was that flight instability produced an inappropriate angle of attack that triggered the range safety system to terminate thrust on the vehicle [58]. Despite this setback, with the lessons-learned, work continued on the development of the next vehicle.

In April 2012, Blue Origin successfully tested the design of its next-generation space vehicle, completing a series of wind tunnel tests to refine the aerodynamic characteristics of the spacecraft's unique biconic shape. Blue Origin successfully completed a System Requirements Review (SRR) of its orbital space vehicle on May 15–16, 2012. This SE process was used to assess the space vehicle's ability to meet safety and mission requirements, and evaluate the technical readiness of the design, the concept of operations, the feasibility of project development plans, and planned verification activities [59].

In addition, Blue Origin is incrementally developing the BE-3, a reusable first-stage booster for its future orbital program; see Figure 11 [60]. The objective is that it will utilize the same VTVL system technology as the New Shepard Propulsion Module and after landing the orbital booster can be refueled and launched again, allowing improved reliability and lowering the cost of human access to space [61]. On November 20, 2013, the BE-3 rocket engine was successfully tested at Blue Origin's facility in Van Horn, Texas, namely thrust at 110,000 pounds for 145 seconds to boost the ship, shut down for 4.5 minutes to allow the vehicle to coast beyond the atmosphere, restart and throttle down to 25,000 pounds of thrust to make a controlled, vertical landing, simulating a mission on the company's suborbital New Shepard vehicle [62].



Figure 11. Orbital Reusable Booster System (RBS) (from [60])

In summary, there are many ongoing and considerable technological and programmatic challenges on the part of both governments and private enterprises in the development of low-priced and feasible RLVs. The critical next move is the integration and further development of current technologies into a practical launch vehicle.

III. DEMAND FOR REUSABLE LAUNCH VEHICLES

By any fiscal measurement, space is big business. It is perhaps worth reflecting on the total sums (and projected sums) spent by the United States on piloted spaceflight initiatives from 1959 to 2015 (see Figure 12). This will facilitate understanding of the rationale behind the drive to decrease the costs of humans accessing space and why RLV and associated technologies will be so important. This information was compiled by Claude Lafleur, who is also the author and editor of the “The Spacecraft Encyclopedia,” which presents exhaustive data about every spacecraft ever launched [63].

A. ESTIMATES OF MANNED SPACE FLIGHT COSTS

As shown in Figure 12, the main focus on manned space flight has been placed on the Apollo program (~\$100 billion spent over ten years), Space Shuttle (~\$200 billion over 41 years), Space Station program (~\$70 billion over 30 years) and the Exploration program (~\$50 billion in 12 years); in all, the U.S. spent on space exploration \$486 billion over 57 years, an average of \$8.3 billion a year [63]. (All costs in 2010 dollars)

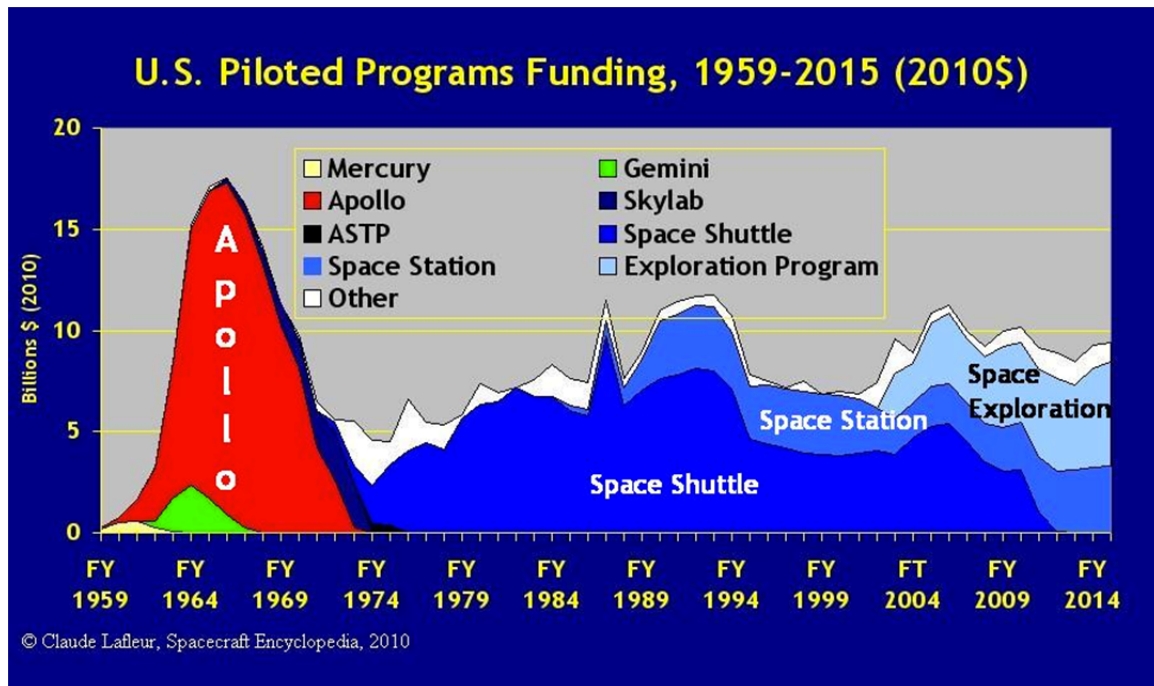


Figure 12. U.S. Piloted Programs Funding, 1959–2015 (2010\$) (from [64])

1. Mercury and Gemini Programs

Before the famous Apollo missions there were the (much less ambitious) Mercury and Gemini programs—the first tentative steps into space by the Americans [63]. Project Mercury (1959–1963) cost \$277 million in 1965 dollars, which translates into \$1.6 billion in 2010 dollars. Since six Mercury piloted missions were flown, each flight cost \$265 million in today's money.

The six-year Gemini program (1962–1967) cost \$1.3 billion in 1967 dollars. In today's money, that costs equate to some \$723 million for each of its ten piloted missions.

2. Apollo and Skylab Program

It is commonly reported in the media that the Apollo space program cost \$20 billion. However, that figure is quoted in the 1970s dollar value, which is the equivalent to more than \$100 billion today. Since eleven Apollo piloted missions were flown, the cost per flight was a staggering \$9.9 billion, perhaps the costs reflecting the complexity of the objective of landing a man on the Moon and returning him safely. The \$109 billion spent resulted in six lunar landings, which means that each lunar landing mission cost \$18 billion. Finally, the first era of the U.S. piloted program ended in 1975 with the Apollo-Soyuz Test Project [63]. The American portion of this U.S.-Soviet mission costs \$245 million at the time or \$1 billion at today's prices.

The Skylab space station program (1966–1974) was the next major initiative in space by America, and cost \$2.2 billion at the time (\$10 billion in 2010 dollars) [63]. Considering that three, three man astronaut teams spent a total of 510 days onboard Skylab, this means that each day spent by a single astronaut onboard cost \$5.5 million.

3. The Space Shuttle and Space Station Era

The Space Shuttle program lasted for 41 years and was perhaps the most complex and ambitious piloted space program to date [63]. Operations began in 1972 and ended in 2011 after cancellation of the program. Using the same math as above, the true cost of the

Space Shuttle program was \$198.6 billion in 2010 dollars; 134 Space Shuttle missions were scheduled, which means that each one cost approximately \$1.4 billion.

The International Space Station program began in 1985 and will last at least until 2024. For this 30-year-plus duration, some \$58.7 billion has been budgeted by NASA, equivalent to \$72.4 billion today. Each day spent onboard by an ISS crewmember costs about \$7.5 million (compared to \$5.5 million for Skylab per day) [63].

The International Space Station has been crewed since November 2000 by two to six astronauts at a time. From 2000 until 2015, the Space Station has 20,000 scheduled person occupation days [63]. To summarize, all the funds allocated to NASA for piloted space programs from 1959 to 2015 sums up to \$486 billion in 2010 dollars, a truly incredible sum.

To bring the costs up to date, NASA has been awarded \$17.7 billion in fiscal years 2013 and 2014 budgets by the U.S. government. Compared to the past this is a 0.3 percent decrease, or \$59 million, below the 2012 enacted level [65]. In the context of this thesis of particular interest is that funding has been provided *“to develop a Commercial Crew capability, with the intent of supporting a new industry that regains the capability to send American astronauts into space, from U.S. soil and ends the need to pay foreign providers to transport American astronauts to the International Space Station”* [66].

The clearly stated aim is to collaborate with commercial partners, to continue the development of RLVs that will provide cost effective access to space. In the context of previous manned space flight costs, it is obvious that the new era of manned space flight during the next decade or so must cost considerably less for commercialization of space to be successful with private funding. Therefore, to reduce costs, novel technologies and RLVs will have to play a key role.

B. COMMERCIALIZATION OF SPACE

In the case of the United States, the level of investment in space access has been continuously growing. In the U.S. alone, some 500 companies are directly engaged in space activity. As long ago as fiscal year 2000, the estimated revenue was \$122 billion

with as many as 27 U.S. states indicating that they wished to expand their space activity. This early expansion was made possible, among other factors, by the issuing of licenses for commercial spaceports. More than a decade later, the future remains bright with regard to the expansion of government, as well as commercial space activity. The only caveat to the business is the high cost of transporting into orbit. As demonstrated, the cost of manned space flight over the years has remained the most crucial threat to the exploitation of space, and it determines whether a company can realize fully the potential offered by space.

In general, launch vehicle demand (i.e., the forecast number of launches each year, for a particular period), is used as an independent variable to launch vehicle cost [67]. These numbers are useful in developing vital launch vehicle cost models. The general assumption is with respect to adequately proven demand. This has a direct influence on the cost per launch for a single RLV and becomes less compared to the ELV. The lower cost per launch promised by RLVs creates a demand in its own right, hence, increasing the demand for even more launches; a positive feedback loop. However, this is normally a rare occurrence; starting off, the new vehicle has to be created at a very low cost, and it must be shown to build a reliability history (ideally 100 percent reliable). Tables 3 and 4 convey previous launch reliability statistics on a vehicle or country-by-country basis. Ultimately, it is difficult to predict the change in demand for launches that will occur in future years. Consequently, the basis of all launch vehicle economic models is the current projected number of forecast launches.

On average, for the past several years, there have been 21 commercial launches per year and current projection shows 130 launches from 2013 to 2022; which is comparable to 2012's launch projection of 128 launches from 2012 to 2021 [68]. However, these numbers do not represent the addressable market for any given new launch vehicle. The initial launches to orbit are currently available in seven countries. These include the United States, Russia, France, Japan, China, India and Israel. Iran could be added as an eighth country but political considerations preclude its involvement with other countries at present. It is worth noting that additionally, the United States and Russia have multiple launch vehicles as well as multiple vehicle suppliers.

One important factor is the reliability of launches; the reliability statistics of recently retired space launch vehicles (failures include incorrect orbits) are shown in Table 3.

Vehicle	Successes/Tries		Actual Rate	Pred Rate*	Consc. Succes	Last Fail	Dates
Atlas 2/2AS	63	63	1.00	.98	63	None	1991-2004
Tsyklon 2	104	105	.99	.98	92	4/25/73	1967-2006
Delta 2	149	151	.99	.98	96	1/17/97	1989-2011
STS	132	135	.98	.97	22(A)	2/1/03	1981-2011
Ariane 4	113	116	.97	.97	74	12/11/94	1988-2003
Titan 2	17	17#	1.00	.95	17	None	1964-2003
Molniya M	277	296	.94	.93	4	6/21/05	1963-2010
Proton-K/DM-2M	40	42	.95	.93	7	11/25/02	1994-2006
Tsyklon 3	114	122	.93	.93	1	12/24/04	1977-2009
Proton-K/DM-2	101	109	.93	.92	15	10/27/99	1982-2012
Atlas 3(A/B)	6	6	1.00	.88	6	None	2000-2005
Soyuz-U/Ikar	6	6	1.00	.88	6	None	1999-1999
Proton-M/DM-2	6	6	1.00	.88	6	None	2007-2010
Proton-K/17S40	6	6	1.00	.88	6	None	1997-2002
Proton-K	26	29+	.90	.87	9	11/29/86	1968-2000
Ariane 5G(+,S)	22	25	.88	.85	15	7/12/01	1996-2009
Titan 4B	15	17	.88	.84	12	4/30/99	1997-2005
Titan 2(Star)	6	7%	.86	.78	6	10/5/93	1964-2003
M-5	6	7	.86	.78	4	2/10/00	1997-2006
SjTART(-1)	6	7	.86	.78	5	3/28/95	1993-2006
Proton-K/Briz-M	3	4	.75	.67	3	7/5/99	1999-2003
Falcon 1	2	5	.40	.43	2	8/3/08	2006-2009

Includes 11 orbital Gemini Titan 2 and 6 Titan 23G missions.

% Seven Titan 23G flights that flew suborbital profiles with Star 37 solid rocket motors providing the final orbital velocity increment. The single failure listed here involved the Star 37 stage.

+ Does not include one successful suborbital Proton-K test flight performed in 1970.

Table 3. December 2012 Retired Launch Vehicle Reliability Statistics
(from [69])

It is also useful to break down the launch vehicle reliability statistics according to the country of launch. This data will be important for commercial users of rockets when they come to select a launch site for their payload, demanding maximum reliability. Table 4 shows the 2012 launch total by country of first or core stage manufacture.

Country	Overall Launches (Failures)	By Orbit Type:		
		Earth-Orbit		Earth-Escape
		LEO	>LEO	Deep Space
Russia	26(2)	13(0)	13(2)	-
China	19(0)	10(0)	9(0)	-
United States	13(1)	6(1)	7(0)	-
Europe	8(0)	2(0)	6(0)	-
Ukraine	3(0)	-	3(0)	-
Japan	2(0)	2(0)	-	-
India	2(0)	2(0)	-	-
North Korea	2(1)	2(1)	-	-
Iran	3(2)[a]	3(2)	-	-

Table 4. 2012 Launch Total by Country of First or Core Stage Manufacture (from [69])

NASA and the DOD are pioneers in the space industry and its exploitation for commercial gain. Both organizations have a long and distinguished history that can be looked at as either successful or unsuccessful in terms of launch vehicle programs. Over the years, there has been a succession of failed or cancelled programs that have cost the U.S. government upwards of \$10 billion [36]. These huge costs were incurred contrary to NASA's clear policy objectives of lowering the costs associated with accessing space. The lowering of costs still remains as one of the primary goals focused on maintaining an economically viable space industry. R&D expenditures for new RLV technologies will be cheaper when combined with partnerships between private firms; government can easily adopt ways that reduce their direct outlay over an extended period of time [70]. The best way to achieve this goal is by the development of new commercialized RLV technologies. RLV research and deployment promises potentially to make the access of space less expensive and will utilize novel SSTD vehicles and indeed completely new launch methods, thus substantially decreasing the production and operating costs of current launch vehicles [36].

C. INTRODUCTION TO QUALITY

Quality is defined as “*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*” [71]. Today’s quality concepts stem from the Industrial Revolution that resulted in the development of mass manufacturing. During the early years of manufacturing, quality inspection was used to decide whether a worker’s job or a product met the requirements of the company. This simple pre-quality control system worked well when the volume of production was low; however, as organizations became larger, the need for a more effective systematic approach became necessary. Furthermore, with the emergence of the industrial society came freedom of choice for the consumer. Manufacturers now had to compete for business, and thus had to improve the quality of products and sell them at lower costs [71].

In 1911, Frederick W. Taylor helped to satisfy the need to improve quality and lower costs in the United States. He published “The Principles of Scientific Management,” which was the framework for improving worker performance by applying engineering principles and scientific methods. Taylor’s scientific management concept stated four rules:

1. Apply work methods based on scientific study of the tasks
2. Scientifically select, train, and develop each employee
3. Develop a healthy cooperation with workers
4. Equally divide work between management and workers. [72]

While manual labor quality began to improve as a result of Taylor’s efforts, other facets of quality continued to emerge. Walter Shewhart was the inventor of the control chart, and mentor of Dr. W. Edward Deming; he was known as the “father of statistical quality control” for developing the Shewhart Cycle Learning and Improvement Cycle that combined creative management [72]. Application of Shewhart’s statistical quality control came later as a result of World War production methods, and was advanced by Deming’s Plan-Do-Check-Act cycle, statistical analysis, Pareto analysis, and the works

of Juran, Crosby and Ishikawa [72]. So, in essence, quality development evolved from simple control, to engineering, to systems engineering from the 1940s to the 1970s.

However, until the 1980s, the United States had ignored quality techniques but Japan's high quality competition forced greater U.S. emphasis on statistical approaches that embraced the entire organization; a process that became known as total quality management (TQM). Today, the quality movement has matured and continues to spread throughout the United States, moving beyond manufacturing into service, healthcare, education and government sectors. Furthermore, new quality systems and approaches have evolved, for example ISO 9000 standards, Systems Engineering (SE), Lean Aerospace Initiatives (LAI), and Six Sigma are a few among many others; for the purpose of this thesis, LAI will only be discussed in further detail in the next chapter.

IV. ANALYSIS OF LEAN AEROSPACE INITIATIVE

There are many techniques found within the Lean Aerospace Initiative, which offer promise to the NASA and Air Force RLV 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 is conducted. Once identified, these tools are tailored for suggested use by the NASA and Air Force RLV effort.

A. LEAN AEROSPACE INITIATIVE

This background section summarizes the origins of Lean and the Lean Aerospace Initiative. It then discusses the Lean Enterprise Model (LEM) and other tools and techniques developed by LAI.

1. Origins of Lean

The Lean concept began as a manufacturing process known as the Toyota Production System (TPS) developed by the Toyota Motor Company, where the goal of the system was to increase production efficiency by reducing waste. TPS became an innovative automotive production and management system—further described in a book called *The Machine That Changed the World* by James P. Womack [73]. This book documented a comparative study of the Japanese, American, and European automotive industry conducted through the MIT's International Motor Vehicle Program (IMVP). The application of the word “Lean Manufacturing” was used by IMVP to describe a revolutionary manufacturing approach versus the conventional mass production approach [13, p. 15]; introducing Lean production and removal of wasteful practices as a new industrial paradigm in the U.S.

Later, in the early 1990s, “Lean Manufacturing” evolved into simply “Lean,” including the entire product development process, concepts of Total Quality Management, Continuous Improvement, Integrated Product Development, and Just-In-

Time inventory control [74]—explained in a book called “Lean Thinking” by James P. Womack and Daniel T. Jones. This book identifies five basic Lean principles to Lean thinking [75] that all vector towards optimizing value for the customer:

1. **Value:** Define what is of value to the customer and providing the right thing to the right place at the right time
2. **Value Stream:** Plan the value-adding stream of work activities from raw materials until the finished product is delivered to user while eliminating waste
3. **Flow:** After waste removal, organize the value stream to be a constant flow of work that is quick and seamless as possible, without any rework or backflow
4. **Pull:** Organize the supply chain based upon customer demand
5. **Pursuit of Perfection:** Continuous process improvement, product improvement, time saving and cost reduction activities

In essence, Lean was a way to specify value in a process or product as seen by the end user, identify and convert waste into value, and perform tasks more and more effectively [36, p. 16]. In other words, Lean is getting the right things to the right place at the right time, while minimizing waste. As a result, the use of Lean principles has been found to be very beneficial throughout almost the entire industrial enterprise as captured from the many case studies depicted in the book. Meanwhile, the Lean paradigm continued to develop and expand into the aerospace community and converged to form the Lean Aerospace Initiative (LAI), a collaborative research consortium formed among the Air Force, the aerospace defense industry and MIT.

2. The Lean Aerospace Initiative

LAI was formed in 1993 to identify and implement Lean principles and practices in Air Force acquisitions [76][77][78]. The initial research focused on several initiatives for the automobile and aircraft industries to put Lean philosophies into practice. Following very positive results in the automobile and aircraft sectors, LAI created the Test and Space Operations Group in 1998 to expand its research focus to explore the application of Lean to the space sector.

Mentioned in Chapter I, Annalisa Weigel’s work on Spacecraft System-Level Integration and Test Discrepancies, found that about a third of the discrepancies in

satellite testing were attributable to problems with the test equipment [36, p. 16]. There have also been other LAI research studies on the sources of delays and anomalies in the operation of satellites. David Steare's work on Space Launch Operations and Capacity Modeling found that the majority of launch delays were due to range crew rest requirements, a factor outside of the control of the launch customer [79]. Another LAI research study, David Ferris's work on Characterization of Operator-Reported Discrepancies in Unmanned On-Orbit Space Systems, discovered that the majority of on-orbit anomalies were unrelated to the spacecraft, but were instead due to the operational infrastructure on the ground [80].

LAI conducted research, and developed and deployed tools to support implementation of Lean principles in a series of six phases that outline a Lean process starting with the shop floor and ending with the entire networked enterprises; see Figure 13 [81]. Shown in Figure 13, LAI has evolved from a focus on Lean processes and tools to Enterprise Transformation and Enterprise Architecting Action Leadership. The holistic framework is utilized in enterprise transformation to capture the current state, envision the future state, and determine actions needed for transformation; while enterprise architecting enables greater system integration efficiency and effectiveness in achieving the desired future state. A Lean Enterprise is "an integrated entity that effectively and efficiently creates value for its multiple stakeholders by employing Lean enterprise principles and practices" [82].

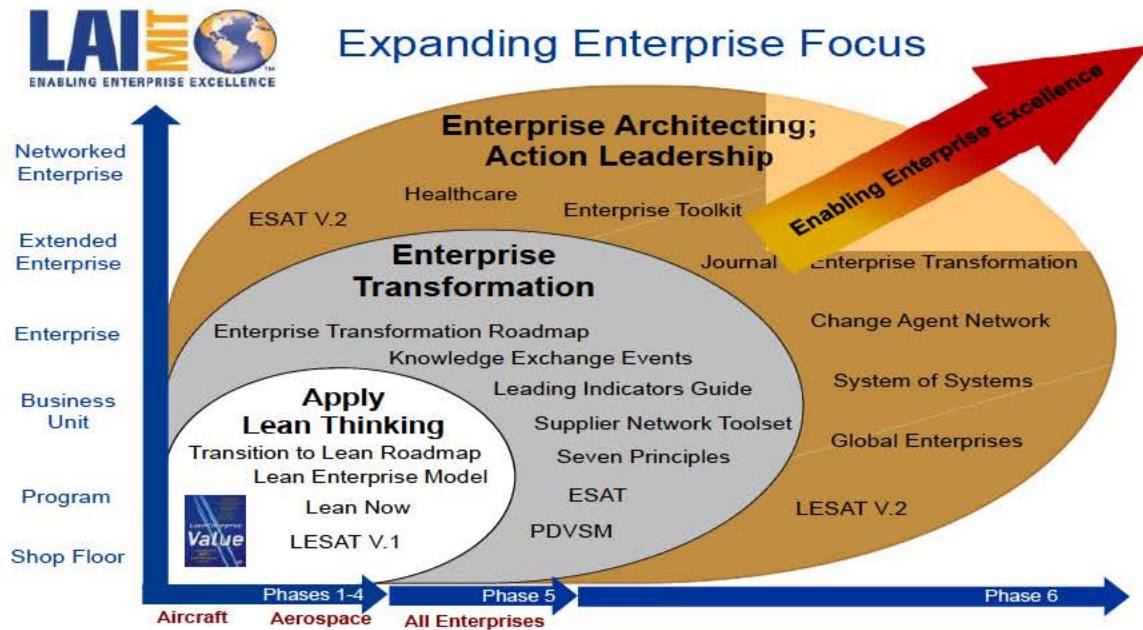


Figure 13. LAI's Expanding Enterprise (from [81])

The general principles underlying Lean Thinking as expressed by Womack and Jones can be elevated to reflect total enterprise interests and expanded to include all stakeholders. The following Lean Enterprise general principles are analogous to the five basic principles presented by Womack and Jones [82]:

- Identify stakeholders and specify value
- Identify the enterprise value stream and the enterprise level processes
- Make value flow continuously across all enterprise processes
- Let stakeholders pull value and engage in value exchange
- Pursue perfection across the enterprise

These principles are further described and summarized below in comparison with the original Lean Thinking principles in Table 5.

Lean Thinking Principles	Lean Enterprise Principles
Specify Value Customer defines value in terms of specific products/services having specific capabilities for a defined price.	Identify Stakeholders and Specify Value for Each Define value for each stakeholder in the enterprise. Strive for a win-win outcome, in which value creation and delivery is increased for all stakeholders.
Identify the Value Stream A value stream is the set of all end-to-end and linked actions required to transform raw materials into a finished product delivered to the customer. Waste in the value stream is eliminated to the maximum extent possible.	Identify Enterprise Value Stream and Enterprise Level Processes The enterprise value stream is the set of all end-to-end processes required to transform resources and materials into value delivered to enterprise customers and other stakeholders. Mapping the processes and showing their interactions makes sources of enterprise-level waste visible for elimination. It also identifies opportunities for value creation.
Make Value Flow Discard large-lot production; strive for “one-piece flow.” Modify traditional functional organization; create and empower integrated product teams along the value stream.	Make Value Flow Continuously Across All Enterprise Processes Identify and eliminate all impediments to smooth flow of executive/administrative actions, resource and material transactions and decisions, especially at process and organizational interfaces.
Let Customers Pull The customer pulls products from the enterprise rather than the enterprise pushing products onto customers. This pulling action cascades backward through the value stream, stage by stage, all the way to the supply chain, thus creating a “just-in-time” production system.	Let Stakeholders Pull Value and Engage in Value Exchange Each stakeholder pulls value from the enterprise value stream. Each stakeholder is engaged in an on-going value exchange with the enterprise. The enterprise strives to maintain a balance among the value expectations of its several stakeholders.
Pursue Perfection A process is implemented to assure on-going reduction in cycle times, production times, errors/defects, costs and all other resource inputs.	Pursue Perfection Across the Enterprise An on-going process is required to continuously search for opportunities to achieve ever-greater enterprise performance in value delivery to all stakeholders.

Table 5. Lean Thinking Principles and Lean Enterprise Principles (from [85])

In 2007, LAI’s board approved a name change to Lean Advancement Initiative (LAI) to reflect growing interest from other industries. As of January 1, 2013, LAI at MIT no longer has a consortium structure or Executive Board but continues to serve as a unique source for innovative ideas, research, collaborative transformation projects, and thought leadership; that enables enterprises to effectively, efficiently, and reliably create value in complex and rapidly changing environments [84].

With the basic Lean principles, LAI has sought to improve not only Air Force acquisitions but also the entire industrial enterprise and has created many tools to help realize this goal—described in the next section.

B. TOOLS

For the purposes of this thesis, “tools” are models, frameworks, approaches, analytical methods, and techniques that support the inferential extraction of information and its conversion to knowledge. The tools utilized for this thesis include the Lean Enterprise Model (LEM), incremental improvements, modeling and simulation, Integrated Product Teams (IPTs), and benchmarking current systems.

1. Lean Enterprise Model

The first model developed by LAI was the LEM, a model containing several tools and techniques designed to assess the Leanness of an organization or process [83]. The principles and practices mentioned above, along with research-based benchmarking data, encompass LEM and define what a Lean Enterprise should look like. The LEM consists of six guiding Principles, four enterprise level metrics, and LEM’s core twelve Overarching Practices (OAPs) with over sixty identified enabling practices contained within it. A tutorial on the breakdown of the LEM structure and the twelve OAPs, with a brief description, can be found at the Defense Acquisition University website: http://www.dau.mil/homepage%20documents/01_advanced_Production.pdf. The OAPs remain best practices; some reinforce focus on the customer, some are relationship difficulties based on mutual trust, some are of relevance to production development processes, and others are just good decision making techniques.

For this thesis, LAI was selected for its current role within the Air Force. LAI represents the Air Force’s plans to improve quality through collaboration between industry and the Massachusetts Institute of Technology (MIT) [86]. Jacques Gansler, past 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” [87]. 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. It is also important to remember that the size of each initiative's domain and overlap among initiatives will vary from program to program.

(1) Incremental Improvements

Incremental or spiral development is an enabling practice for LEM [83]. 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 [88]. Under the OAP 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. Concisely, to effect dramatic change within an organization takes time and would be too much to attempt all at once.

(2) Modeling and Simulation

Modeling and simulation (M&S) is another enabling practice within LEM; it plays an important role in LAI. M&S is used to permit understanding and evaluation of the flow process [83]. This provides many benefits to the program team including: insight to the value stream, identifying critical linkages and areas of potential waste, especially in the early stages of development. While M&S 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.

(3) Integrated Product Teams

Integrated Product Teams (IPTs) are utilized by LAI and provide the project manager with a balanced solution. The use of integrated teams is critical when developing a complex system that cuts across many disciplines. 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 [89]. An overarching practice within the LEM, Implement Integrated Product and Process Development, calls for the use of people

knowledgeable on all areas of the product's life cycle [83]. 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 [83]. Here, LAI is stating the use of basic SE principles, such as requirements 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.

(4) Benchmarking

Within LAI, benchmarking is an enabling practice in the LEM [83]. Benchmarking is an essential tool for programs seeking to improve beyond current levels or to achieve worldwide industry bests or best practices by competing with other industries around the world. 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. Without doubt, benchmarking is a universally encouraged practice and belongs in the tool-set to aid RLV development.

2. Leadership and Enterprise Strategic Analysis

Enterprise Strategic Analysis and Transformation (ESAT) is a method that serves as an integrated, analytical framework for diagnosing and improving overall enterprise performance; designed to optimize the enterprise value stream as a critical element in formulating a strategic business plan and transforming to a Lean Enterprise [90]. Basically, this method uses various tools to understand how products and services flow in an enterprise and where waste hinders those flows. ESAT provides a means for the senior leadership team to understand their enterprise, create an actionable vision for the future, plan the transformation and govern the execution.

3. Lean Roadmaps

LAI also developed the Transition-To-Lean (TTL) roadmap and associated three volumes about Lean that detail activities for implementation and expands upon the issues, tensions and barriers that are likely to be confronted at each task stage. The roadmap

further describes the enablers, tools, related references and case studies that can be accessed to promote successful completion of each task [91]. One tool for example, the LAI Enterprise Self-Assessment Tool (LESAT) 2.0, is used for self-assessing the current state of an enterprise and its readiness to change. The tool is organized into three assessment sections [92]:

- I. **Lean transformation/leadership:** Lean practices pertinent to the Lean transformation process with an emphasis on enterprise leadership and change management.
- II. **Life cycle processes:** Lean practices related to the “life cycle processes of an enterprise, i.e., those processes involved in product realization.
- III. **Enabling infrastructure:** Lean practices applicable to infrastructure support units.

Section I contains those Lean practices important to the Lean transformation process, with emphasis on enterprise leadership and change management. Additionally, LAI states the importance of senior management leading the way in “Transitioning to a Lean Enterprise: A Guide for Leaders,” because empowerment can only come from executive management. In order for the transition to be successful top management, who must buy-in and fully commit to the ideas of Lean, must lead it and be open minded to new concepts that may seem counter-intuitive [76][77][78]. Section II contains Lean practices pertinent to the life cycle processes of an enterprise—processes involved in product realization. Section III contains Lean practices pertinent to the infrastructure support units. Each section contains diagnostic questions, Lean practices, five capability levels, and Lean indicators. Each of these practices is focused at the enterprise assessment level, and the tool is supported by a Facilitator’s Guide as well as a LESAT calculator [92].

Later, LAI created the Lean Enterprise Transformation Enterprise Roadmap to replace the TTL roadmap. It provides a sequenced and detailed Lean-organizing framework for enterprise-wide transformation. A summary of all LAI’s co-evolving research, products, techniques and tools from 1994 to 2012 are illustrated in Figure 14.

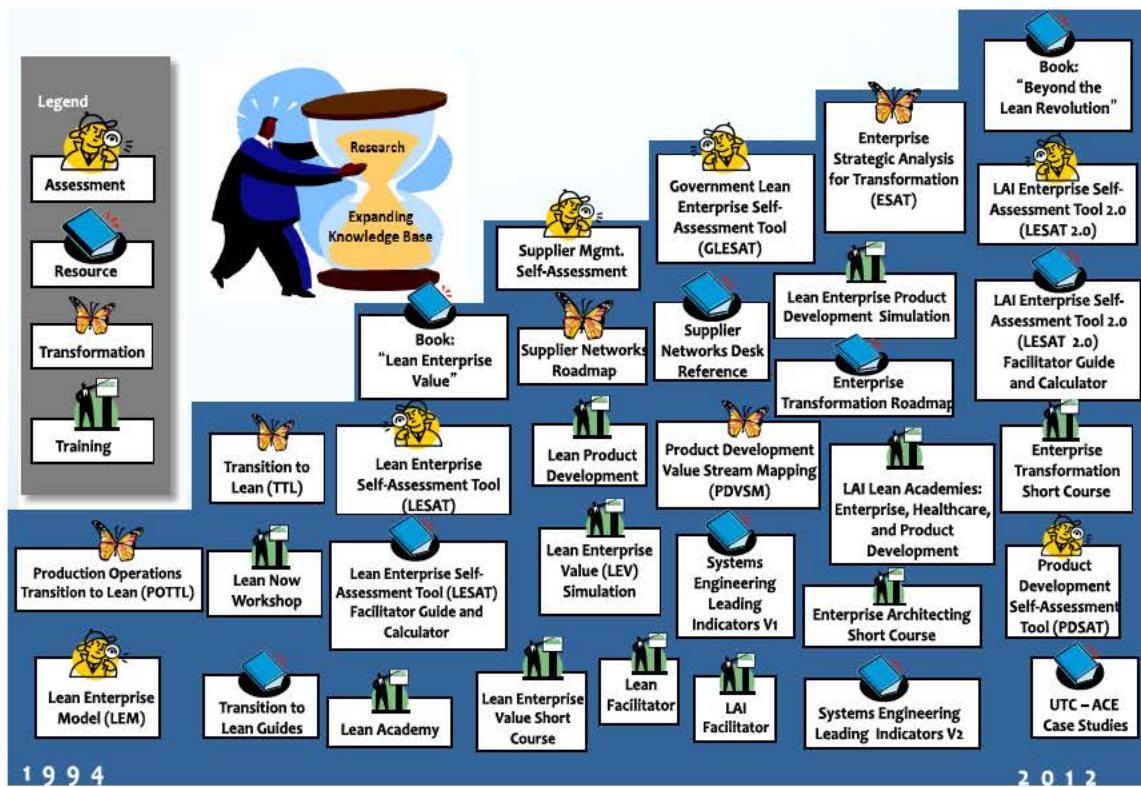


Figure 14. Summary of Co-Evolving Research, Products and Tools (from [93])

In summary, there are many tools and techniques found within LAI that offer promise to the RLV effort. Their basic methodology can be applied to virtually any program. The LAI technique that was identified in this thesis as most beneficial and thus could be tailored for suggested use by the Air Force and NASA RLV effort was the M&S and spiral development/incremental improvement approaches.

V. APPLICATION

With a basic understanding of the tools and techniques employed by the LAI, those tools can now be applied to the problem of RLV development and advance Air Force and NASA efforts. Because of the practicality and efficiency of Lean, infused with modern engineering teachings, many of the tools are already in place within the industry and government RLV efforts. Beyond the initial implementation, additional incorporation of LAI tools and techniques appears to offer considerable benefit in the quest for RLVs.

A. MODELING AND SIMULATION

Recommended in the LAI approaches, modeling and simulation (M&S) provides 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, such as Blue Origin’s rocket engine test-fire to simulate a suborbital mission, briefly discussed in Chapter II. The full-duration simulation, which occurred November 20, 2013, capped an 11-month series of tests during which the engine was powered up 160 times and operated for a cumulative total of more than 2.5 hours [94]. This was a very significant milestone for Blue Origin because the test simulation mitigated a major risk area for the New Shepard development, and it brought the company one step closer to flight testing; the company intends to begin orbital test flights in 2018 [94]. Utilizing M&S enabled Blue Origin to safely demonstrate the ability of the integrated engine to go throughout the throttle range without any dwell periods, restart, shut down, nor coast—the whole mission profile [94]. Also, it possibly allowed Blue Origin to re-evaluate and Lean processes to either improve performance or lower cost.

Here are three example programs where innovative M&S software is being applied to streamline RLV development processes and save hundreds of hours, permitting the allocation of resources elsewhere. Virgin Galactic, SpaceX, and Boeing developed these example programs.

Virgin Galactic uses the IDX 7000 image generator—an advanced six-channel, real-time image generator developed by Quantum3D, Inc.—to train pilots on spaceship

equipment and command. Quantum3D, Inc. develops and manufactures commercial off-the-shelf (COTS) visual computing solutions for government and commercial applications. The IDX 7000 offers enhanced performance and capabilities to deliver Virgin Galactic a versatile and powerful simulation and training platform that can be setup in a dedicated room or easily transported, to meet a range of onsite, on-location and mobile training needs [95]. Combined with real-time scene management software with geo-specific, worldwide synthetic environments, Virgin Galactic is able to train their pilots in a variety of simulations, from instrument/cockpit familiarization to a full range of special effects, sensors, weather, and lighting, along with mission-critical functions such as height-above-terrain and line-of-sight intersection testing [95].

SpaceX uses the Unigraphics modeling tool for its computer-aided design (CAD) and computer-aided manufacturing (CAM) work. Unigraphics allows for easier integration of all the vehicle subsystems. In the past, SpaceX utilized two-dimensional based drafts for their installation process. These two-dimensional model drawings included only part orientations and dimensions, which were found to be ambiguous and lack necessary information [96]. SpaceX decided to remove ambiguity of the two-dimensional models by moving all installation processes to three-dimensional CAD based models, in-turn providing real-time support in installing components on the launch vehicle [96]. The significance of real-time support meant timely feedback with exact locations, examples, and supporting parts; for example, prescribed torque values for bolts and washers. Three-dimensional models clearly show the location of the payload and its orientation with respect to the vehicle. For more granularity, the three-dimensional model allows the user to zoom in on any component in any orientation, and identify the proper part number, supplemental parts, and torque and connection values as needed. It also identifies if any special needs are required, such as the use of thermal grease, a grounding strap, or other supporting hardware or special requirements [96]. This innovative Lean M&S approach to SpaceX's installation process met the need for a more accurate and clearly understandable model for all the technicians and other engineers needing to perform any install on the Falcon 9 vehicle. By implementing this technique for

installation, all the waste (unnecessary processes) of installing components properly had been removed.

Finally, Boeing uses the Digital Mock-Up (DMU); it is a computer-aided design tool that utilizes the Computer Aided Three-dimensional Interactive Application (CATIA) software; a multi-platform 3-D CAD commercial software suite written in C++ programming language [97]. The DMU, composed of the CATIA-generated solid model, parts list, and requirements, is an electronic digital mockup that facilitates the development, integration, and management of complex systems. The DMU facilitates real time, synchronized design integration across all disciplines and provides electronic configuration control and single source of design control. The DMU provides integration of over 2500 CATIA solid models with resolution down to the fastener level [97]. Figure 15 is a typical representation of the utilization of the DMU.

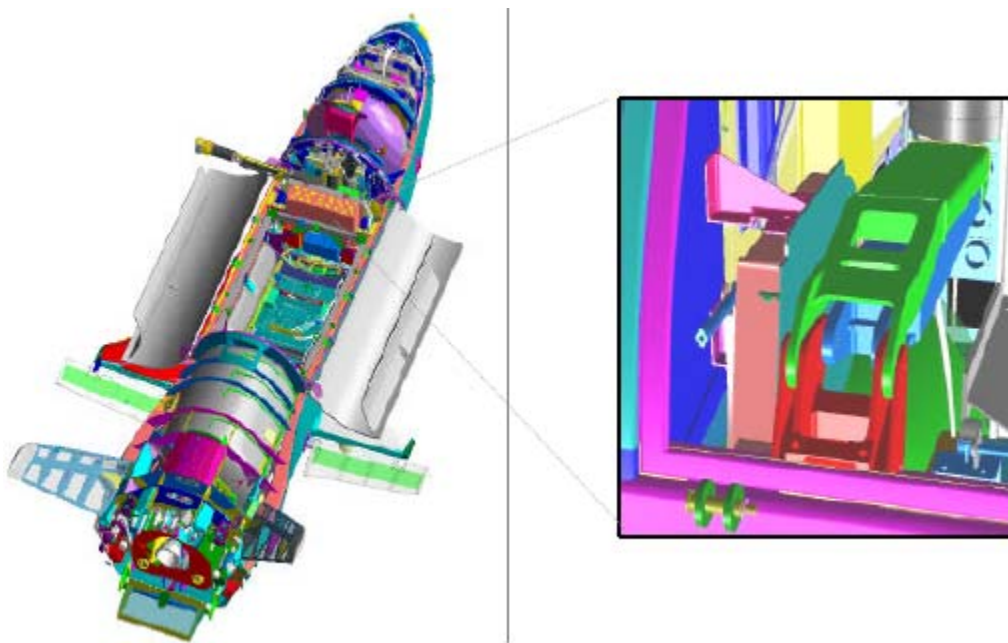


Figure 15. Digital Mockup Unit (DMU): X-37 Vehicle Solid Model
(with expanded view of mid-body battery pallet components)
(from [97])

B. INCREMENTAL IMPROVEMENT

As discussed earlier, LAI suggests an incremental or spiral approach to system development through LEM. This recommendation is being implemented within Blue Origin which has a Latin company motto that translates to “Step-by-Step, Ferociously.” Blue Origin’s stated objective is to develop vehicles and technologies “to dramatically lower the cost and increase the reliability of human access to space” [98]. Blue Origin’s incremental development approach uses suborbital tests to understand and characterize its system and retire development risks. Mentioned earlier in Chapter II, Blue Origin’s approach is to be able to separate the capsule from the propulsion module at any point to help ensure that the crew can return safely to the ground. (See Figure 10)

Furthermore, the Air Force’s X-37B RLV effort is a good example of the application of spiral development and incremental improvements technique advocated by LAI. For example, the X-37B is a 120 percent scale derivative of the X-40A, also built by Boeing for the Air Force (see Figure 16) [97]. The X-40A was a prototype design that did not utilize the advanced thermal protection materials, rocket engine and experiment bay found on the X-37B. From the X-37B standpoint, the X-40A testing was seen as a risk mitigation step [97]. The production of the X-37B is also an example of the combination of many sound techniques. As Dave Manly, Boeing Phantom Works X-37B program manager, stated in a 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 3-D modeling and simulation...to help us improve the quality and performance of this product. [99]

The X-37B program has a reasonable scope; for the most part it is on schedule and demonstrates the intended level of technology development. Lessons learned from the X-37B program provide additional guidelines for the use of this LAI technique: (1) the technologies demonstrated must be reasonably limited in scope, (2) must push the current boundaries of technology, and (3) a single program should not attempt to push too many technologies at once—a mistake seen in the X-33 and X-34 programs [97].



- Prior USAF Contract: Successful automated approach and landing flight in October 1998
- Modified for early atmospheric flights to support X-37 design

X-37 Design Risks Reduced Through X-40A Testing



- Advanced Technology Flight Demonstration Vehicle
- Linked to Space Maneuver Vehicle design

Figure 16. X-40A and X-37 Vehicles (from [97])

So, what happened to the two technology demonstration programs, the X-33 and X-34? Why did these programs fail? Recall from Chapter II, both the X-33 and X-34 promised to test advanced technologies that could be used in future RLVs, but encountered major problems and delays. The X-33 was developed to demonstrate the technology required for a future single-stage-to-orbit (SSTO) RLV [100] but failed from unsuccessful demonstrations of the composite fuel tanks and linear aerospike engine. The X-34 was developed to advance flight and data testing as well as ground operations. The program did not achieve its objectives; which included demonstrating new lightweight composites, a new thermal protection system, new avionics, rapid turnaround/re-flight capability, inclement weather landings, and performance of the engine [35].

Many were critical of the high-risk, high-payoff strategy employed on the X-33. In a 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” [101]. 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.”[101]

In order to meet the necessary weight limits to achieve SSTO, the X-33 would have needed new shaped composite fuel tanks and the un-flown linear aerospike engine. Both systems represented new technology developments, which led to considerable cost and schedule overruns [101]. The technology level at the time could not support these programs; but with a modest, steady incremental improvement approach, and partnerships with industry, such a RLV system can be realized. 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.

After years of trial and error, results revealed that overly ambitious projects like the X-33 and X-34 did not yield the benefits of manageable programs such as the X-37. The Air Force and NASA are capitalizing on LAI’s approach by anticipating many generations of RLVs—each subsequent system improving performance and reliability over the last. This will place capabilities that will allow them to benefit from technical advancements made for future generation RLVs while preserving some technological superiority over non-military systems.

C. INTEGRATED PRODUCT TEAMS

Strongly advocated within both LAI, the use of integrated product teams (IPTs) has become essential in the development of complex modern systems. The Boeing practice example stated below has been adopted by the Air Force to help improve support for space programs by taking advantage of the rapid communication shared knowledge and improved cooperation. In fact, the Air Force liaison to NASA on RLV issues, serves as the Deputy Program Manager for the X-37 [97]. These partnerships should continue

because they are an excellent step towards integrating the RLV effort within NASA, the Air Force and industry.

1. Integrated Management Structure

The integrated management structure for the X-37 project represents a tailored version of the overall integrated product/process development (IPPD) management approach Boeing has deployed on all programs in recent years. The principal attributes of the IPPD management approach include: (1) aligning the organizational structure with the work breakdown structure (WBS) to increase product focused accountability and clearly define responsibility; (2) blending functions into a seamless organization to eliminate barriers and enhance producibility and supportability during the design process; (3) defining product ownership in a multidiscipline team to foster communication and coordination and facilitate exchange of ideas; (4) integrating lead and support contractors into full participation in the IPT's; and (5) assuring full customer participation and insight to improve quality of the final product [97].

Thus, the X-37 program team is product focused and consists of a number of multidiscipline IPTs. These IPT's are centered on identifiable products with complete responsibility, accountability, authority, and the requisite resources (budgets, skills, knowledge, tools, and integrated information systems). Full partnership with the customer and suppliers is achieved, as they are working members of the IPTs [97].

2. Organization and Responsibilities

As mentioned above, the Boeing X-37 program organization is keyed to the program work base structure. The program manager has selected support staff and integrated product team leaders empowered with the appropriate responsibility, accountability, and authority for execution of their assigned WBS elements [97]. Government and major subcontractors are integrated into the IPT, as appropriate, to their functional involvement in the program.

IPTs corresponding to the eight major design elements of the X-37 project were formed [97]:

- Flight Sciences
- Airframe/Structures
- Mechanical/Thermal/Propulsion
- Avionics, Power, and Software
- GN&C
- Vehicle Assembly
- System Test
- Shuttle Integration

Each team has a lead and the individual teams have primary responsibility for maintaining their own subsystem specifications, change control baselines, subcontractor requirements and statements-of-work (SOW), material review boards, and risk mitigation activities. The Systems Engineering and Integration (SE&I) IPT, has responsibility for assuring appropriate integration of the individual subsystem IPT activities. The X-37 Deputy for Systems Engineering leads the SE&I IPT with membership comprised of the various subsystem IPT leads, in addition to representation from Configuration Management, Risk Management, Requirements and Analysis, Systems Integration, and Reliability, Maintainability, and Supportability [97]. Each individual IPT holds weekly technical interchange meetings (TIM). In addition, the IPT leads have their own weekly TIM.

3. Zone Managers

The X-37 vehicle has been divided into zones, each with a designated captain. Their primary responsibility is to assure that all components within their zone are properly integrated within the DMU. The zone captains hold three weekly simulation tests using the DMU [97].

4. Focused Tiger Teams

Tiger teams, smaller groups of engineers from across the IPTs, are formed to resolve specific multidisciplinary design problems when they arise [97].

D. BENCHMARKING

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 [83]. Today the Air Force operates the X-37B, but NASA's retired Space Shuttle is the first generation of RLVs and still offers a wealth of information for future RLV development. For example, as a benchmark the shuttle utilized 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 keep-out zones, which prevent the execution of other work and require costly infrastructure support [102].

As another example, in 2013 NASA's Office of Safety and Mission Assurance (OSMA) held its first quality benchmarking visits with two NASA prime contractors, Aerojet Rocketdyne and Boeing. These two companies were listed in the top five out of 100 total companies demonstrating continuous improvement and a commitment to quality by a Quality Magazine article [103]. These benchmarking meetings showcased some of Rocketdyne's and Boeing's quality best practices to representatives from NASA Headquarters, NASA centers and other space agencies. The Rocketdyne topics presented included "Risk-Based Corrective Action System," "Quality Clinic Process Overview," "Supplier Quality Portal" and their "Attention to Detail Program" [104]. The Boeing presentations included "Part Orientation Identification Navigation Tool (POINT)," "Supplier Quality Surveillance" and "Special Processor Controls" [104]. The highlights of the presentations included innovative techniques—such as Rocketdyne's Quality Clinic, where defective parts are removed from production and taken to a "clinic" to be assessed and treated—and new technologies, such as Boeing's integration of tablet computers on the production floor to streamline inspection and nonconformance control with future capabilities to include configuration control processes [104].

Brian Hughitt, a NASA Technical Fellow for Quality Engineering who coordinated the visits stated "in this demanding, challenging environment [of space], without collaboration no one organization can go it alone and succeed entirely on its own.

Tapping into the vast expertise, experiences and perspectives of other organizations is now an essential component of mission success...these meetings are high-leverage, improving quality across multiple organizations at a very low relative cost” [104]. This benchmarking program can be seen as a key component of a robust process by which NASA and its contractors collaborate and mutually enrich, educate and improve the aerospace quality community’s programs.

For the space industry, continuous improvement is essential for a quality organization. In these meetings, NASA disseminates selected practices to other stakeholders; as a result, NASA and other members of the space industry benefit from lessons learned and best practices. Benchmarking enhances quality across the industry and helps NASA reassess its current practices and incorporate leading-edge techniques and technologies, all at minimal cost to the agency [104].

These meetings are more than just educational tools; they also fill a hole in the aerospace quality industry during tough economic times. The Annual Conference on Quality in the Space and Defense Industries (CQSDI), serviced the industry for over 20 years, was cancelled for the first time this year due to budget cuts [104]. Similarly, NASA’s Quality Leadership Forum, which has been held for the past 15 years, was cancelled—due, in part, to budget tightening. During this one-year hiatus, the benchmarking visits will help sustain the spirit of collaboration and continuous improvement that has been a longstanding hallmark of the space industry [104].

Table 6 summarizes the findings of this thesis. The first column lists the four identified tools and techniques offering the most promise to RLV development. The second column briefly states examples of current tool-set use within the RLV development efforts. Finally, the third column recaps the recommendations for future use within the Air Force RLV efforts.

LAI Tools and Techniques	Current Examples	Recommendations
Modeling and Simulation	• Virgin Galactic's IDX 7000 image generator • Boeing uses the Digital Mock-Up • SpaceX's Unigraphics	• Apply to streamline RLV development processes and save man-hours • Continue Modeling and Simulation Efforts
Incremental Improvements	• Blue Origin's "Step-by-Step, Ferociously" motto • X-Vehicles	• Use tests to understand and characterize system and development risks • Technologies demonstrated must be reasonably limited in scope • Must push the current boundaries of technology • Single program should not attempt to push too many technologies at once
Integrated Product Teams	• Boeing X-37B Program • Industry/Air Force/NASA Relationship	• Integrated management structuring • Continue partnership between industry and government □
Benchmarking	• Shuttle Operations Benchmarking • NASA adopts benchmarking industry practices	• Continue to utilize shuttles' lessons learned as benchmark • Sustain the spirit of collaboration, education and continuous improvement

Table 6. Application Summary

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VI. CONCLUSION

This thesis identified techniques within LAI that are employed by market players today and also best suited for the RLV effort. Additionally, this thesis provided a historical perspective of both RLV development efforts within the government and industry, also origins of modern quality teachings to establish a universally accepted foundation of knowledge, upon which further examination can be based. This research addressed the commercial and governmental developments of RLVs. Reiterated below are the Research Questions provided with answers from the previous chapters:

1. What is a reusable launch vehicle (RLV)?

An RLV is a vehicle designed to launch into Earth orbit, and then return to Earth for subsequent launches. RLVs are designed to reduce launch costs by reusing the most expensive components of the vehicle rather than discarding them and building new ones for each mission, as is the case with the expendable launch vehicles (ELV). As of 2015, with the space shuttle already retired, the only operational RLV is the X-37B. A number of concepts are still being developed or studied, and thus far RLVs have been classified into two main types defined according to the mode of takeoff and landing. They can be horizontal or vertical takeoff vehicles with either horizontal or vertical landing capabilities. An RLV may be categorized further as being single-stage-to-orbit (SSTO) or two-stage-to-orbit (TSTO). Future RLVs also are expected to employ more advanced, reliable systems by utilizing novel SSTO vehicles and completely new launch methods, thus substantially decreasing the production and operating costs of current launch vehicles and making them safer than ELVs.

2. What is the current demand for RLVs and what advancements can commercial RLV development bring to the government?

The demand for RLVs has increased over the years. Recent activity aimed at developing and operating low-cost, RLVs have improved the prospects for sharply reducing launch costs. Which vehicles will be successful is still uncertain, as several different concepts are still in competition. NASA has been awarded \$17.7 billion in fiscal years 2013 and 2014 budgets with a clear aim of collaborating with commercial partners

to continue the development of RLVs that will provide cost effective access to space. R&D expenditures for new RLV technologies will be cheaper when combined with partnerships between private firms. In the context of previous manned space flight costs, it is obvious that the new era of manned space flight during the next decade or so must cost considerably less for commercialization of space to be successful with private funding. Therefore, the best way to reduce costs is by the development of new commercialized RLVs and novel technologies; they both will have to play a key role in meeting this goal.

3. What is Lean and what role does LAI quality initiatives play in commercial programs?

Lean is getting the right things to the right place at the right time, while minimizing waste. As a result, the use of Lean principles has been found to be very beneficial throughout almost the entire industrial enterprise. The Lean Advancement Initiative (LAI) is a unique research consortium that provides a forum for sharing research findings, lessons learned, best practices; and the newest thinking, products, and tools related to lean enterprise transformation with organizational members from industry, government, and academia.

LAI quality initiatives advocate, re-educate and otherwise offer a supporting framework for the use of quality techniques. LAI has succinctly presented quality tools and techniques for both commercial and government programs, thus saving potential users time and effort that would otherwise be spent on research. As seen in the many examples throughout this paper, the role LAI plays and the support it offers to commercial and government programs are tremendous. Many organizations, like the Boeing and the Air Force, have adopted LAI to shift the operational paradigm of their organization; because it has allowed them to solve operational/managerial problems and set a new tone of improved commitment to customer satisfaction and cost-savings.

In conclusion, this thesis began by introducing some background on the origins of RLVs (both government and commercial), demand for RLVs and LAI practices and tools like the Lean Enterprise Model (LEM), and the Lean Enterprise Transformation process. The applications of these tools to the Air Force and NASA RLV efforts have been found

to be highly effective. Modeling and simulation, benchmarking current systems, use of IPTs, and incremental improvements are already well utilized within the current RLV programs. The continued use of LAI and partnerships between industry and government will serve to advance the current state of RLV development and may one day lead to the realization of the long-standing goal of a fully operational RLV.

This thesis has explored the use of LAI teachings in the development of RLVs within the space industry and government. If possible, suggest that future research focus on the role quality initiatives play in government/commercial programs in other countries, like France or Japan. Exploring another country's advancements in RLV development would not only benefit the Air Force's and NASA's efforts, but it would allow a deeper investigation into the technical areas of RLV development and potentially offer many new applications of quality initiatives.

Finally, the application of LAI quality techniques to the commercial RLV efforts of the space industry has served as an example of ways to improve quality in the Air Force and NASA RLV efforts. Although, anyone seeking to improve their product or process would do well to examine multiple alternative approaches from a variety of fields gleaning the best techniques from each, before determining a course of action.

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