

Supply, Demand, and Entrepreneurial Ventures In the Space Launch Industry

by

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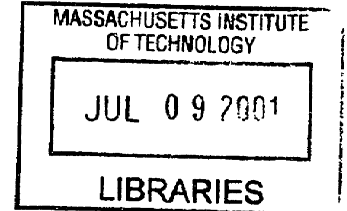
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Abstract

Responsive, affordable space transportation, using reusable launch vehicles (RLVs) to place payloads into orbit at a fraction of today's exorbitant costs, will become a reality within the next few decades. As the railroads unlocked the American West, and as the modern airplane shrank our planet, reusable launch vehicles will open space with vast scientific, commercial, humanistic, and military payoffs.

The large amount of financing required for commercial RLV development coupled with significant market risk, the employment of a myriad of high-risk technologies, the lack of Federal assistance beyond early stage RLV technology development, and numerous other barriers to entry have greatly undermined successful RLV system development. Historically, the U.S. government has stepped into the fray of past transportation technology and infrastructure development with investments and funding incentives. Over the past two decades, however, the U.S. government's record in RLV development has been dismal, characterized by repeated attempts to leapfrog critical technologies rather than applying a pragmatic, stepping stone, "build a little, fly a little" approach that was so successfully utilized in experimental aircraft development a few decades before. Despite a number of failed launch vehicle development endeavors since the development of the Space Shuttle, a wave of private entrepreneurial firms are currently attempting to develop innovative reusable launch vehicle concepts independently of the U.S. government. Originally bolstered by a late 1990s bullish low Earth orbit (LEO) market, the success of these endeavors may be destined to echo that of an analogous wave of failed entrepreneurial expendable launch vehicle development efforts from a few years before, especially now that the LEO market has declined so drastically.

This thesis addresses several aspects of the development of reusable launch vehicles. Demand for space launch is examined, with attention on commercial

satellite trends and emerging markets. Space launch supply is assessed, with discussion of the current situation of launch vehicle over-capacity and high global competition. Several reusable and expendable launch vehicle development programs are examined, including the efforts of both small entrepreneurial ventures and large national programs. An introduction to barriers to entrepreneurial RLV development is also presented, focusing on legitimacy issues and the problems of financing such high-risk ventures. Finally, technology and market entry competitive strategies for entrepreneurial RLV ventures are discussed and recommendations offered.

Thesis Supervisor: M. Diane Burton

Title: Assistant Professor of Management

Biographical Note

Born and raised in Maine, I moved to Ohio in 1984 after finishing my B.S. in aerospace engineering at Boston University. I have since worked for the Air Force Research Laboratory (AFRL) near Dayton, Ohio. I began my career in applied research and computer software contract management. Over the years I spent an increasing amount of time in project engineering and program management, and through mostly part-time study acquired an M.S. in astronautical engineering from the Air Force Institute of Technology, and a Ph.D. in aerospace engineering from the University of Cincinnati. My most recent position in AFRL was managing the Space Operations Vehicle Technology Office in the Air Vehicles Directorate while at the same time serving as deputy chief for its parent program, the Military Spaceplane Integrated Technology Thrust Program. The objective of these programs is to mature technologies that enable development of an Air Force space system consisting of reusable launch and space vehicles. The programs cover a very broad range of technologies spanning across all AFRL directorates and many external organizations, including NASA, industry, and academia.

One of my career highlights was managing the Mini Spaceplane Technology program with Boeing, which developed the X-40A Space Maneuver Vehicle flight test vehicle for the Air Force. This two year, intensive program culminated in a successful atmospheric flight test in 1998; under the subsequent X-37 program, NASA and Boeing will launch a derivative of the X-40a into space from the Space Shuttle in 2003 or 2004. I've also enjoyed acting as the AFRL focal point for reusable launch vehicle conceptual design and technology development over the last few years. This has allowed me to interact with nearly a dozen entrepreneurial reusable launch vehicle companies, primarily as an independent assessor of the technical maturity and viability of their designs, and occasionally as a research collaborator. These experiences provoked my curiosity about the business side of space launch, prompting the research contained in this thesis.

My research interests have been in trajectory optimization, hypersonic flight, and orbital mechanics. I studied the flight dynamics of planetary atmospheric entry with my M.S. thesis, and chaos and nonlinear dynamics of satellite attitude motion with my Ph.D. dissertation. Over the years my interest in research waned as my appetite for more applied work and management grew. Fortunately, this migration of interest was accompanied by increasing managerial responsibility; a desire for management knowledge led me here to the MIT Sloan School of Management.

My wife, Robin, took a year leave of absence from her audiology career to support my schooling and to spend additional time with our three-year-old daughter, Kylie, and our 18-month-old son, Ryan. In her somewhat less than bountiful spare

time, Robin is working hard to complete her coursework for her doctoral degree this year. In our pre-children days, Robin and I enjoyed hiking in the mountains and traveling. Today, we relive our own childhood with Kylie and Ryan on swing sets, playing with LEGOs, and drawing and painting. I'm also an avid beer brewer and love to fly-fish, wind surf, and attempt to play classical guitar.

Acknowledgement

I'll never forget one particular summer evening in my youth. It was my seventh birthday and my friend who lived across the street came over to celebrate. After dinner, cake and ice cream, and a bit of television, we camped outside under the stars in the open tree house my father had built in the apple trees behind our house.

I recall only one present from that birthday, some thirty-one years ago. It was a present not meant for me, but nonetheless a present of awe, of inspiration that has stayed with me ever since. That gift was seeing the live, grainy, riveting image on our television of Neil Armstrong taking the first human footsteps on the moon. Later I read that about half of the population of this planet either watched or listened to the landing.

Later that night in my sleeping bag I remember looking up and seeing the moon through leaves of the apple trees, wondering when I would be able to follow. I have gazed deep into the night sky many times since. The awe is still there.

I owe humble thanks for much of my inspiration to the courageous few - Armstrong, Aldrin, Glenn, Shepard, and the others - who risked everything to accomplish so much, and to the many who, like myself, have played but a small, modest role yet share the dream.

Most of all, however, I owe a great debt to my wife, Robin, and my toddlers, Kylie and Ryan, all who continually inspire me far more than the stars.

Many thanks also to Dr. M. Diane Burton for her gracious help and enthusiasm.

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1. Introduction

Transportation Revolution

Responsive, affordable space launch, using reusable launch vehicles (RLVs) to place payloads into orbit at fraction of today's exorbitant costs, will become a reality within the next two decades. As the railroads unlocked the American West, and as the modern airplane shrank our planet, reusable launch vehicles will open space with vast commercial, scientific, humanistic, and military payoffs. The nation that wins this economic space race will gain significantly through the growth of entirely new industries and new technological developments, reaping large financial rewards from increases in employment, corporate & personal tax revenues, and export revenues. Academia and industry will benefit immensely from routine, inexpensive access to a new laboratory environment, with likely advances in materials, communications, pharmaceuticals, and energy. Emerging markets such as space tourism, microsatellites, satellite maintenance and salvage, solar power, and others unimaginable today may flourish. Global package delivery in mere few hours could become the norm, making our current overnight delivery services the "snail mail" of the 21st century. Top Fortune 500 companies might someday own corporate RLVs to deliver VIPs to important meetings half way across the planet – and return them in time for dinner.

This transportation revolution will require responsive and affordable space launch costing an order of magnitude less than that of today's systems. The keys to responsiveness and low cost are operability, reusability, and their enabling technologies; the keys to a successful business case appear to be successful government involvement in technology development and financing.

The Development Challenge

RLV development is probably the most difficult technical challenge the aerospace industry has ever faced. Success in this endeavor will require an immense engineering refocus from subsystem optimal performance to overall launch vehicle

system operability, and a merging of the currently, widely divergent aircraft and spacecraft engineering worlds. Success is also dependent upon leadership that challenges and changes many current space launch practices and paradigms from both operations and technology development perspectives. Rather than the current expensive and time-consuming practice of extensively modifying a launch vehicle for its every payload, for example, a future RLV may have standardized payload interfaces, analogous to an F-15's standardized weapon racks. Rather than the 18,000 - 30,000 hours required to refurbish the Space Shuttle's thermal protection system tiles between launches, an operability-focused technology push will invent a thermal protection system for an RLV with reductions in turn-around-time of two orders of magnitude, trading vehicle flight performance for large gains in operability.

The large amount of financing required for commercial RLV development coupled with significant market risk, the employment of a myriad of high-risk technologies, the lack of Federal assistance beyond early stage RLV technology development, and numerous other barriers to entry have greatly undermined successful RLV system development. Historically, the U.S. government has stepped into the fray of past transportation technology and infrastructure development with investments and funding incentives. Over the past two decades, however, the U.S. government's performance in RLV development has been deficient, characterized by repeated attempts to leapfrog critical technologies rather than applying a pragmatic, stepping stone, "build a little, fly a little" approach that was so successfully utilized in experimental aircraft development a few decades before.

The Space Launch Industry

Worldwide commercial space spending was over \$70 billion in 1997 and is projected to grow to nearly \$140 billion by 2005.¹ The space launch industry's portion of this grew significantly in the 1990s, averaging about 20% growth per year, with worldwide revenues exceeding \$6.7 billion in 1999. The total impact on the

¹ "Lockheed Martin Sees Commercial Space Market Doubling by 2005," *Aerospace Daily*, Vol. 187, No. 21, July 31, 1998.

United States economy of the U.S. commercial space launch industry and of the industry sectors it enables (launch vehicle manufacturing, launch services, satellite and ground equipment manufacturing, satellite services, remote sensing, and related distribution) was recently calculated to be \$61.3 billion for 1999 by the Federal Aviation Administration Associate Administrator for Commercial Space Transportation (FAA AST).² In this report, the U.S. commercial space transportation industry is held directly and indirectly responsible for nearly 500,000 jobs and \$16.4 billion in employee earnings in the United States in 1999. The contribution to these figures by the launch vehicle manufacturing and launch services sector is about 28,600 jobs and \$3.5 billion of economic activity, or only about 6% of the total. This result suggests, according to AST, that the launch vehicle industry is an effective enabler of other industries, with a cascading impact to the U.S. economy.³

The space launch industry is characterized by a very high degree of risk, high costs, and very large barriers-to-entry, so large that nearly every successful launch system in use today was originally sponsored by its respective government.⁴ Barriers to entry into the launch service market include development of vehicles requiring very complex, risky, and costly technologies, large expensive infrastructure investments, and high market risk. Governments and their large aerospace contractors consequently dominate the industry.

The riskiness of space launch is legendary; the historical launch vehicle success rate over the past 40 years is only about 85%, and over the past decade, about 95%. Launch failures are unforgiving and almost inevitably result in loss of both the launch vehicle and its payload, the latter either catastrophically (usually when range safety personnel are forced to destroy an errant rocket) or by being deployed in an uncorrectable orbit. Losses from a single launch can amount to more than a billion of dollars, and in case of the relatively rare manned flight, to loss of life as well. In

² Associate Administrator for Commercial Space Transportation (AST), *The Economic Impact of Commercial Space Transportation on the US Economy*, Federal Aviation Administration, February 2001, <http://ast.faa.gov>.

³ Ibid.

1999, launch vehicles had only a 90% success rate over 77 attempts worldwide, and the payloads they successfully inserted into orbit experienced a 94% success rate of their own.⁵

Space launch costs are extremely high, with an industry average price tag in the range of \$5,000 - \$7,000 for placing one pound of payload into low Earth orbit. The prices charged by many launch services are competitively influenced by direct or indirect government subsidies, including investments in research and development, and launch infrastructure.

Initial outlays to develop a new generation launch vehicle are enormous and the development process itself is risky and time consuming. Rather than developing a completely new launch vehicle, manufacturers in the past have instead almost always incrementally upgraded the performance of their current rockets. After about half of a century, the result is a launch vehicle industry that exhibits many characteristics of a mature industry – incremental change, competition based primarily on price, focus on manufacturing and process technologies rather than product technologies, etc.

Over the years the satellite industry has matured significantly as well. Payloads, once few in number, unique, temperamental, and technologically complex, have become routine, less risky, more robust, and increasingly fabricated using standardized, commercial off-the-shelf technologies. Ground-based support for space launch and on-orbit assets has also become more routine. Increased competition and, in some cases, technology maturation have caused both launch and payload costs to decline to the degree that small satellites, once the pride of nations, have become commonplace and owned by universities and even clubs.

⁴ Many were derived from ballistic missiles developed during the Cold War.

⁵ Cáceres, Marco, "Why Space Mishaps Are On The Rise," *Aerospace America*, July 2000.

Reusable Launch Vehicles

Except for the partially reusable Space Shuttle system, every orbit capable rocket today is an expendable launch vehicle (ELV). Reusable launch vehicles (RLVs) promise vastly increased reliability and lower costs over ELVs,⁶ and thus they have been earnestly pursued in research and development programs for more than 30 years. Yet even with R&D investments exceeding tens of billions of dollars, no developmental RLV program has succeeded. Despite this dismal record, in the last decade more than 15 small entrepreneurial RLV companies have formed, all vying to do what governments and the aerospace giants such as Lockheed Martin and Boeing have failed to do - develop a commercially viable RLV. This, in the face of a Space Shuttle total development bill of about \$40 billion, the failure of the National Aero Space Plane program to the tune of over \$3 billion, the recent failures of the X-33 and X-34 programs at over \$1.5 billion, and a host of deterrents too numerous to mention here. And this, despite the fact that the past is littered with failed ELV entrepreneurial efforts, a much less challenging development effort than that posed by an RLV.

Financial markets have not favored commercial RLV ventures. A number of entrepreneurial RLV development businesses were started in the mid-1990s, bolstered by the then bullish, even exuberant, low Earth orbit (LEO) communications satellite market that appeared to underestimate the threat of fiber optics. With the bankruptcies or deep financial straits experienced by Iridium, ICO, Orbcomm, Globalstar and others in the last two years, the LEO market has since declined. It appears several RLV entrepreneurial ventures will likely soon follow.

The enthusiasm, creativity, and commitment of the RLV entrepreneurs are truly fascinating. It is unfortunate, however, that technical design viability eludes several of their designs, especially considering the other daunting barriers to entry they face. Most, perhaps even all, of the current entrepreneurial RLV development efforts will

fail.⁷ Still, there is a real, albeit small, chance of success for a few of the leading entrants. And, as noted above, the potential payoff is huge – a successful (cost effective and reliable) RLV would be a disruptive product, turning the entire launch industry on its ear. And the company that finally pulls off this feat will be compared in history books to the likes of the Wright brothers. The RLV entrepreneurs thus form a fascinating sub-industry within the overall conservative aerospace sector, a very dynamic sub-industry whose time scale has yet to be determined, but with potential to someday be gainful to the academic studying the dynamics of disruptive technologies in the vein of Utterback, Christensen, and others.⁸

Thesis Scope

The commercial space industry is composed of three primary segments - satellite manufacturing, ground support and services, and space transportation. The focus of this thesis is on the latter segment, which encompasses rocket manufacturing, integration, and launch services.

This thesis addresses several facets of the space industry that affect the development of reusable launch vehicles. Chapter 2 discusses the development of the space launch industry to set a framework for exploring the industry in more detail in subsequent chapters. The demand for space launch vehicles is examined in Chapter 3, focusing on the projected satellite market, since this sector drives derivative demand for launch vehicles. Emerging markets are also investigated in addition to other factors influencing demand such as substitutes for satellites and launch services.

⁶ Most studies claim an order of magnitude reduction in launch costs is obtainable, along with an increase in reliability of several orders of magnitude. Reliability of the Space Shuttle system, for example, is quoted to be 0.993.

⁷ Note that in addition to the hurdles mentioned here, statistically very few new business starts succeed.

⁸ See: Utterback, James, M., *Mastering the Dynamics of Innovation*, Harvard Business School Press, 1994; and Christensen, Clayton, M, *The Innovator's Dilemma*, Harvard Business School Press, 1997.

The supply of expendable (conventional) launch vehicles is examined in Chapter 4. This section concentrates on new entrants to the launch vehicle market over the past few years as well as numerous failed entrepreneurial development efforts, primarily from the 1980s. Chapter 5 presents a number of reusable launch vehicle concepts under development by the United States government, foreign nations, and small, private, entrepreneurial firms. The focus of this chapter is on the efforts of these entrepreneurial ventures which are attempting to adapt to the changing LEO market.

Several RLV technology development programs are discussed in Chapter 6, accompanied by discussion of observations from these technology programs and from technology strategies employed by ELV and RLV developers. An introduction to barriers to entrepreneurial RLV development is also presented, focusing on legitimacy issues and the problems of financing such high-risk ventures. Finally, technology and market entry competitive strategies for entrepreneurial RLV ventures are discussed and recommendations offered. The thesis closes with Chapter 7's summary and conclusions.

Caveats

The scale and scope of this thesis effort did not allow me to examine all of the ELV and RLV development efforts available in the literature. I thus was forced to down-select from a larger population the programs and concepts I found most interesting or relevant to this work as a whole. In particular, with respect to the small, entrepreneurial RLV ventures, I attempted to select the most mature concepts from the literature. Inclusion or exclusion of certain concepts does not in any way imply a systematic assessment of their technical or business viability or an endorsement of any concepts.

Unless otherwise cited, the assessments and opinions expressed in this work are the author's only and should not in any manner be construed as those of the United States Air Force or the Massachusetts Institute of Technology.

2. Development of the Space Transportation Industry

Even a basic understanding of the space launch industry is elusive without an examination of its development over the past half century. This chapter presents a brief overview; interested readers are urged to refer to any of several good sources for more detailed information.⁹

The Early Days

An Austrian engineer by the name of Professor Eugene Sänger is generally credited as the first to design rocket-powered suborbital and orbital aircraft in his book called *Raketenflugtechnik* in 1933¹⁰ Sänger's later work during World War II included a design of a suborbital bomber aircraft that would use rocket engines to skip in and out of the atmosphere. The intent was spaceplane to achieve intercontinental ranges in order to be able to bomb New York City from Germany. Although never built, his reusable launch vehicle design was remarkably modern, and it has graced a number of books since, inspiring generations of aerospace engineers and a modern European spaceplane design named for him.

An intensive German rocket development program during World War II resulted in major advancements in the field. In addition to rocket-powered aircraft, Germany developed the first ballistic missile, the V-2. The V-2 had a maximum speed of about Mach 4 and was used against the British in 1945. In essence, the U.S. and Soviet space race effectively began at the end of World War II with their respective acquisition of many German rocket engineers and scientists from Peenemünde who had designed and built the V-2 ballistic missile. The V-2 technology and its German developers formed the foundation for American and Soviet intercontinental ballistic missile (ICBM) development during the Cold War, which in turn formed the basis for many of the expendable launch vehicles (ELVs) still used today.

⁹ See, for example, www.ksc.nasa.gov/history/rocket-history.txt, or the excellent collection, "The Last Frontier: Archives and History," at the University of Sydney's web site, www.edfac.usyd.edu.au/staff/souters/space/archives.html#archsh.

¹⁰ Ashford, David and Collins, Patrick, *Your Spaceflight Manual – How You Could Be A Tourist in Space Within Twenty Years*, Headline Book Publishing Plc, London, U.K., 1990.

For many years, from the close of World War II until the late 1950s, national defense concerns dominated many governments' focus on space, creating a race to develop effective, accurate ICBMs with nuclear warheads. This defense focus provided the impetus for governments – especially for the Soviet Union and the United States who eyed one another with no small amount of trepidation - to spend huge amounts of capital to develop high performance ELVs. Physics dictates that the maximum velocity required to launch an ICBM to the other side of the planet is only one to two percent less than the total velocity required to reach orbit. Thus the first ICBMs were a close, evolutionary step from the first orbit capable expendable launch vehicles.¹¹ This phase of international competition to develop ICBMs was overtaken in the late 1950s by the popularly termed “space race.”

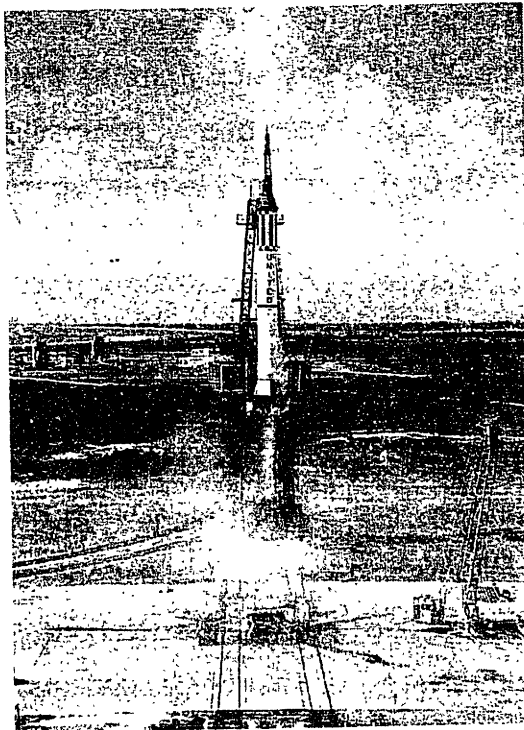
The Space Race

The space race began in earnest 1957, with the Soviets' unexpected insertion of Sputnik, the world's first artificial satellite, in low Earth orbit. This event was a shock to most of the world, and particularly to the United States who had thought its own technology to be superior to the Soviet Unions'. The U.S. answered the Soviet challenge by hurriedly establishing the National Aeronautics & Space Administration (NASA) that year, constructed out of the National Advisory Committee for Aeronautics (NACA) and other government organizations, and charging it to execute a civilian space program. The well-publicized race to put men in space was on, driven largely by national prestige as well as defense concerns.

Throughout the late 1950s and most of the 1960s the space race drove a very rapid acceleration of technological progress in space launch. Some highlights pertinent to the development of ELVs are:

¹¹ As this thesis focuses on space launch from the Earth's surface to low Earth orbit (LEO), from here on I use the term “ELV” to mean an *orbit capable* expendable launch vehicle. Technically, a small class of ELVs designed for suborbital flight exists (e.g. sounding rockets) but are ignored here.

- The U.S.'s Juno Launcher, derived from the Redstone ballistic missile of 1953, put the first American satellite into space in 1958.
- Soviet cosmonaut Yuri Gagarin was the first human in space and the first to orbit the Earth in April 1961.
- The first American in space (suborbital flight) was Alan Shepard in May 1961 using the Redstone Mercury launcher (Figure 1), derived from the ballistic missile of its namesake.
- The first American to orbit the Earth was John Glenn in 1962 using an Atlas rocket.



**Figure 1 Mercury-Redstone 3 Rocket Carrying Alan Shepard
in First U.S. Manned Spaceflight, May 5, 1961**
(Photograph compliments of NASA)

The Atlas rocket was the first American ICBM, first operational in 1960; a modification of it is still in production today, more than forty years later. Likewise, the Thor intermediate-range ballistic missile from the 1950s led to the Thor-Agena and then the Delta II ELVs. Today's Titan ELV is yet another example of a first generation U.S. ballistic missile developed in the late 1950s of which an ELV derivative is still in use today. In fact the Evolved Expendable Launch Vehicle

(EELV) program,¹² a partnership between the United States Air Force, Lockheed Martin Corporation, and The Boeing Company, is currently developing new versions of some of these launch vehicles, the Atlas V and the Delta IV, to replace existing Atlas, Titan, and Delta ELV fleets.

The space race took a momentous twist with John F. Kennedy's famous challenge to put man on the moon before the end of the 1960s. Suddenly, launching men and spacecraft to low Earth orbit (LEO) wasn't enough; the Soviet – American race to the moon had begun. Mankind intended to stretch his reach from LEO operations, of only 100 miles or so above the Earth's surface, to the Moon some 220,000 miles away. The Apollo lunar program required the development of the Saturn 1B and the Saturn V rockets, the latter the largest launch vehicle ever built. Together the Saturn rockets had 22 successful launches with no failures.

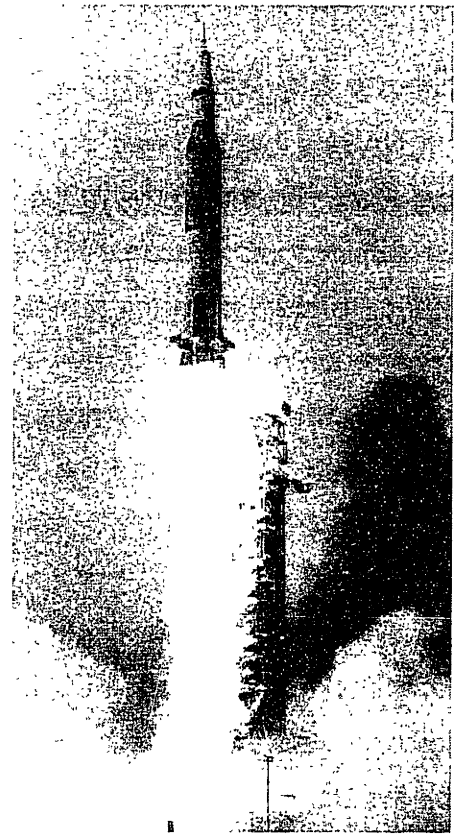


Figure 2 Apollo 13 Saturn V Launch, April 11, 1970
(Photograph compliments NASA)

The United States and the Soviet Union had the only launch capability throughout the first 12 years of the space age, from 1957 to 1969, while engaging in the space race and the race to the moon. In those days space commercialization was much more stymied than today by the strict prohibition of rocket technology transfer due to national security efforts to limit the spread of ballistic missile technology. In 1970, however, Japan and China completed the initial development of their own launch systems, although with limited success and only infrequent launches throughout the 1970s. Effectively then, the U.S. and the U.S.S.R. had a launch duopoly through the 1970s. The end of the 1970s saw additional space

¹² The EELV program is discussed in Chapter 4.

launch proliferation. In December 1979 the European Space Agency (ESA) first successfully launched their Ariane rocket. India soon followed, launching its first satellite into orbit in July 1980.¹³

Space Shuttle Program

NASA's budget was drastically reduced at the end of the Apollo lunar-landing program. In the early 1970s under the Nixon administration, however, the Space Shuttle program became NASA's priority. In the early years of its development, the Space Shuttle program promised far lower launch costs than existing ELVs as well as a much more responsive launch capability. Total cost in fiscal year 2000 dollars for the design, development, and acquisition of the first four Space Shuttles was about \$40 billion,¹⁴ and the first shuttle orbital flight occurred in 1981. Test flights were completed on July 4, 1982, marking the start of commercial operations.

While the Shuttle (Figure 3) was being developed, the Nixon administration specified that all existing ELV programs were to be terminated when the Shuttle fleet became operational, since every U.S. satellite from that point on would be launched by the Space Shuttles. The United States government's decision to phase out ELVs not surprisingly led to a drastic reduction in research and development of expendable launch vehicles. Furthermore, companies were encouraged by the government to produce their ELVs in a very slow, continuous production mode. Production slowdowns in concert with Shuttle development delays hurt manufacturing economies of scale, causing ELV production costs rise, a situation encouraged by the government so that expendable launch vehicle prices would be more competitive with those charged for the Space Shuttle.¹⁵

¹³ Papp, Daniel S, and John, McIntyre, R., Editors, *International Space Policy*, Greenwood Press, Inc., Westport, Connecticut, 1987, p. 5.

¹⁴ Mulville, Daniel, Statement of Daniel Mulville, Chief Engineer, Office of the Administrator, NASA, at the "Space Transportation Architecture Studies: The Future of Earth-to-Orbit Spaceflight" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 27 October 1999, www.house.gov/science/.

¹⁵ Hertzfeld, Henry R, "Economic, Market, and Policy Issues of International Launch Vehicle Competition," in *International Space Policy*, Papp, Daniel S, and John, McIntyre, R., Editors, Greenwood Press, Inc., Westport, Connecticut, 1987.

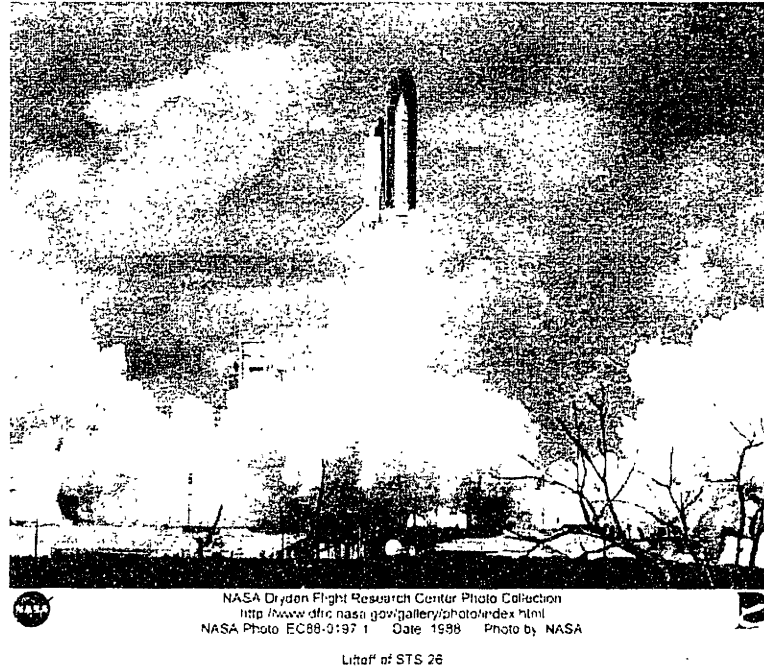


Figure 3 Space Shuttle Launch
(Photograph compliments of NASA)

It wasn't long after the Shuttle became operational before it became blatantly obvious that launch costs and flight frequency were in practice far from ideal, the former more than an order of magnitude higher than predicted. Regardless, NASA continued with its highly political commitment to launch all payloads with the Shuttle. The United States government's hesitancy and long delays in eliminating ELVs in the early 1980s contributed much uncertainty in the marketplace, delaying commercial investment in new ELV systems. The Air Force, long unhappy about what it saw as too much dependency on a sole source space launcher, repeatedly criticized NASA's insistence on using only the Shuttle to launch all U.S. payloads. Finally, in 1984 over NASA protests the Air Force requested proposals for a new ELV system that could launch Shuttle class payloads. In 1985 the Air Force contracted with Martin Marietta to develop ten "complementary" (to the shuttle) ELVs

or “CELVs” for the 1988 – 1992 time period. Martin Marrieta’s winning CELV was the Titan 34D7, later known as the Titan 4.^{16, 17}

In vein with its general policy of deregulation, the Reagan administration began to encourage privatization and commercialization of space transportation in 1982.¹⁸ This encouragement was manifested in the administration's 1982 National Space Policy and the National Security Council's 1983 policy for ELV commercialization.¹⁹ The latter policy statement fully endorsed commercialization of expendable launch vehicles by the private sector, and encouraged commercial use of government launch ranges. The policy also called for indirect subsidies for commercial ELVs in the form of lower prices for use of government facilities, equipment, and services. The aerospace industry reacted very cautiously, however, primarily due to the difficulties competing in a market entirely composed of government-owned or subsidized launches. One exception was Starstruck, Inc., a small entrepreneurial ELV development venture that began operations in 1981 and conducted a flight test in 1984 shortly before folding.²⁰ Another exception was Space Services, Inc. (SSI). One of the earliest private ELV ventures, SSI carried out the first successful privately funded rocket launch by a private U.S. company in September 1982.²¹ In order to conduct the launch, however, SSI had to suffer a difficult process to gain approval and a license, through seventeen different United States government offices.²² As a result of this difficulty, Reagan delegated responsibility for the process to the Department of Transportation, which set up its Office of Commercial Space Transportation in December 1983.

¹⁶ From: Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989; and Pace, Scott, *U.S. Access to Space: Launch Vehicle Choices for 1990 – 2010*, RAND Project AIR FORCE, RAND Corporation, Santa Monica, California, March 1990.

¹⁷ The number of CELVs ordered by the Air Force was more than doubled after the Shuttle Challenger disaster.

¹⁸ Brooks, Timothy A, “Regulating International Trade in Launch Services,” Berkley Technology Law Journal, Volume 6:1, Spring 1991, www.law.berkeley.edu/journals/btlj/articles/vol6.html.

¹⁹ Ibid, Brooks.

²⁰ See Chapter 4 for more information on this and other ELV entrepreneurial development efforts.

²¹ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989.

The Reagan administration continued its efforts to privatize the commercial launch industry, and Congress cooperated with the Commercial Space Launch Act in 1984, which encouraged entrepreneurial space transportation investment by establishing launch vehicle licensing and insurance regulations and allowing use of government facilities. After President Reagan's announcement, U.S. companies entered the private launch services market, somewhat cautiously due to concern that a later U.S. administration might revoke this policy, McDonnell Douglas Astronautics Company with its reliable Delta ELV, Martin-Marrietta Corporation with its Titan 3 originally made by the Martin Company for the Air Force,²³ and General Dynamics Corporation with its Atlas ELV. Numerous other aerospace companies, such as Boeing Aerospace Company and Hughes Aircraft Corporation, invested in R&D for new ELV systems.²⁴ In response to the Shuttle fleet's inability to meet demand, the Reagan administration finally restored allowance for use of commercial ELVs in 1985.²⁵

Curiously, while the Reagan administration promoted commercialization of ELVs, NASA was doing the opposite, using its multi-billion dollar annual expenditures in the aerospace industry to discourage aerospace contractors from developing ELV systems that would compete with NASA's Shuttle.²⁶ NASA also constructed another massive barrier to entry to potential private ELV ventures – low, subsidized launch prices with which only other nationally subsidized offers such as Arianespace could compete.

NASA had a monopoly of the commercial space launch market for the Western world for more than the first two decades of the space age. The European

²² Ibid.

²³ www.ast.lmco.com/company_history.shtml. The American-Marietta Corporation and Glenn L. Martin Company merged in 1961.

²⁴ Papp, Daniel S, and John, McIntyre, R., Editors, *International Space Policy*, Greenwood Press, Inc., Westport, Connecticut, 1987, pp. 6 – 7.

²⁵ Sietzen, Frank, Jr, "Air Force Evolved Rocket May Restore U.S. Launch Leadership," Space.com, 12 July 1999.

²⁶ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989.

consortium Ariespace entered the space launch commercial market by first launching their Ariane launch vehicle in 1980, breaking NASA's monopoly on Western commercial space launch. Ariane, however, was still experimental until 1982, and had limited capacity through the mid-1980s. Competition between Ariespace and NASA changed the game, with demand increasing for lower cost and higher reliability launch services. Both the Ariane and Shuttle launches were, and still are today, heavily subsidized. Competition grew in the mid-1980s when China began offering commercial launch services and the Soviet Union renewed its attempts to attract Western payloads, raising questions of security, economics, and national prestige. Security aspects of technology transfer were then, and are still today, hotly debated and sometimes limited some payloads from using launch services from restricted nations. Economic issues included domestic and foreign government subsidies for their respective launch services, and ability of Eastern launcher services to attract launch insurance.

Post Space Shuttle Challenger Disaster

The space shuttle Challenger tragedy occurred in January 1986. A primary cause was attributed to intense schedule pressure due to NASA's attempt to increase launch frequency from five flights in 1984, to nine in 1985, and to fifteen in 1986.²⁷ The disaster was followed shortly by the second consecutive failure of a Titan launch in an Air Force launch that April, and then a NASA Delta launch accident in May. Thus, within a span of a few weeks in 1986, all three of the U.S. major launch systems were grounded for extended periods of time. This left the United States with almost no capability to launch commercial and military satellites, which began to accrue waiting for an available launcher. Confidence in the U.S. space program was severely shaken and NASA's space strategy sharply criticized. NASA's Advisory Council complained in August 1986 that NASA seemed to lack

²⁷ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989.

long-range objectives and had allowed its space technology base to deteriorate.²⁸ Reagan's order for the fourth shuttle and his announcement ordering NASA to stop launching commercial payloads also occurred the same month.

In 1986 the Reagan administration effectively banned the Shuttle launch of commercial payloads beyond 14 prioritized ones, in an attempt to encourage privatization of launch services in the United States. Before this point U.S. aerospace firms had been reluctant to enter the space launch business, acknowledging the fact that they could not profitability compete with NASA's and ESA's ability to heavily subsidize launch costs.²⁹ The Challenger disaster in 1986 forced even greater ELV demand. However, for the reasons discussed above, U.S. ELV fleets had changed very little since the 1970s; they were still based on retrofitted old 1950's ballistic missile technology and still extremely expensive.

While the United States was reviewing fundamental national space policy and strategy and conducting accident investigations on its grounded fleet,³⁰ the rest of the world did not sit still. The Soviet Union launched their Mir space station only three weeks after the Challenger accident, and continued to accumulate valuable experience from its fantastic pace of launches. In 1985, for example, the Soviet Union had 98 launches compared to only 17 for the United States, a difference primarily due to the far shorter life span of the average Soviet satellite.³¹ The Ariane also had a launch failure in 1986 that grounded the rocket into 1987. However, Arianespace took advantage of the break down in U.S. launchers in 1986 to aggressively expand their capability by upgrading the Ariane 3 and pushing the

²⁸ Kranzberg, Melvin, "The Top Line: Space as Man's New Frontier," in *International Space Policy*, Papp, Daniel S, and John, McIntyre, R., Editors, Greenwood Press, Inc., Westport, Connecticut, 1987, p. 16.

²⁹ Papp, Daniel S, and John, McIntyre, R., "Introduction: Space... the Final Frontier," in *International Space Policy*, Papp, Daniel S, and John, McIntyre, R., Editors, Greenwood Press, Inc., Westport, Connecticut, 1987.

³⁰ The Challenger disaster grounded the Shuttle fleet for about 2 ½ years, as well as canceling the shuttle-based liquid hydrogen / liquid oxygen propelled Centaur upper stage due to shuttle safety concerns.

development of the Ariane 4, which was first launched in 1988.³² Nonetheless, due to the scarcity of launch resources and Reagan's announcement and subsequent deletion of a large portion of the Shuttle's manifest, demand for space launchers rose sharply. Many American payloads as well as many foreign ones that were cut from the shuttle manifest flocked to overseas launch service providers. Ariane continued to launch, and launch frequently, significantly undercutting American launch prices, especially for American commercial satellites needed by private firms. Consequently, Arianespace's business boomed and the market share owned by U.S. launch vehicle companies dropped. China, which had started marketing its launch services to foreign commercial customers in 1984, substantially increased their marketing efforts in early 1987, and began booking contracts with the West in earnest.³³ Chinese launch prices were generally even lower than Arianespace, but their reliability record was somewhat spotty.

The same 1984 U.S. administrative directive that allowed the Air Force to pursue alternative space launch to the shuttle also directed the Department of Defense (DoD) and NASA to jointly study national space launch system architectures for the 1995 – 2010 timeframe. Recommended was development of a very heavy lift (100,000 lb of payload to LEO) ELV system, followed by an even heavier lift (150,000 lb) partially reusable launch system, and a two stage fully reusable Shuttle II, the latter to be operational around 2005.³⁴ While these recommendations were not acted upon, through the end of the twentieth century this investigation was followed by numerous other national launch system studies as well as by several cancelled launch vehicle development efforts. Among these development efforts

³¹ Kranzberg, Melvin, "The Top Line: Space as Man's New Frontier," in *International Space Policy*, Papp, Daniel S, and John, McIntyre, R., Editors, Greenwood Press, Inc., Westport, Connecticut, 1987, p. 17.

³² Suriano, Robyn, "Florida's Future in Space: Arianespace is Big Threat to The State," *Florida Today*, 1997, www.flatoday.com/space/explore/special/floridasfuture/.

³³ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989.

³⁴ Pace, Scott, *U.S. Access to Space: Launch Vehicle Choices for 1990 – 2010*, RAND Project AIR FORCE, RAND Corporation, Santa Monica, California, March 1990.

were the Advanced Launch System (ALS) and the National Aero Space Plane (NASP) programs, both joint NASA and DoD efforts.

Post Cold War Development

The end of the Cold War with the dissolution of the U.S.S.R. changed the launch vehicle market significantly. The 1990s saw major consolidation in the U.S. of the large space industry firms, or “primes”, in response to large reductions in United States government defense spending and globalization of core technologies. Boeing acquired Rockwell International and its Space Shuttle program in 1996, and McDonnell Douglas and its Delta family of launchers in 1997. Similarly, Lockheed Martin acquired General Dynamics and its Atlas family of launchers in 1994. Consolidation led to a corresponding increase in global competition, a shift in reliance towards commercial programs, downsizing, and difficulties in attracting and retaining quality employees. Gained were some advantages in efficiency, and maintenance of core technology, engineering competencies, and manufacturing facilities. Many firms worked hard to convert defense research and development (R&D) to commercial use.

Consolidation continued into the turn of the century with last year’s \$3.75 billion merger between the U.S. space industry giants, The Boeing Company and Hughes Space and Communications. Labeled by Space Business News as “by far, the most significant highlight to hit the commercial sector in 2000,” this merger resulted in a new space company, Boeing Satellite Systems.³⁵ Lockheed Martin, Boeing’s main U.S. competitor, also made a major gain in 2000, with its acquisition of Comsat Corporation.

Major European Union consolidations involving rocket manufacturers also took place in 1999 and 2000. EADS (European Aeronautic Defense & Space Company) was formed from a merger of France’s Aerospatiale Matra SA, Germany’s DASA

³⁵ “SBN’s 2000 Year-In-Review Special Issue,” *Space Business News*, Vol. 18, No. 25, December 6, 2000.

aerospace (part of DaimlerChrysler), and Spain's Construcciones Aeronauticas SA, making EADS the world's third largest aerospace and defense company behind Boeing and Lockheed Martin Corporation.³⁶

The 1990s saw a large increase in global launch service competition as efforts stepped up to market new international ELVs. The economic hardship suffered by Russia and Ukraine after the break up of the Soviet Union also prompted these countries to commercialize former Soviet ELVs, offering reliable launches at very low prices. A number of multinational alliances were formed between the East and the West to launch and market these ELVs and create new ventures, such as Sea Launch, Eurockot Launch Services GmbH, and International Launch Services.

Significant changes occurred in U.S. space policy as well. After the Challenger accident, NASA was directed to move commercial payloads from the shuttle to ELVs in Reagan's 1988 directive. And until the Launch Services Purchase Act of 1990, NASA continued to manage ELV launches for civil space customers.³⁷ President George Bush signed the Launch Services Purchase Act into law in November 1990. This act effectively prohibited NASA from launching satellites into space, a dramatic reversal of United States space policy since before that point NASA held a monopoly on U.S. civil space launch, launching almost every U.S. civil spacecraft before 1990. Pricing guidelines were established in the 1993 Launch Services Trade Agreements with Russia and Ukraine to limit the negative effects of their subsidized offerings on U.S. companies.³⁸ In 1994 the Clinton Administration ordered that hereafter NASA would be the lead government agency for RLV development and the Air Force the lead government agency for ELV development. The 1994 National Space Transportation Policy (NSTC-4) also called for "government and private sector decisions by the end of this decade on development of an operational, next-

³⁶ Friedman, Robert E., "Standard & Poor's Industry Surveys: Aerospace & Defense," August 10, 2000.

³⁷ Anderman, David, "The Launch Services Purchase Act, 10 Years On – A Personal View Of The Campaign To Enact The LSPA," www.cwo.com/%7Edavida/index.html.

³⁸ Thompson, David W, "Commercial Space Policy Needs to be Reviewed in the U.S.," *Space News*, January 22, 2001, pp. 19 - 20.

generation reusable launch system.”³⁹ Responding to a number of RLV development efforts that began in the mid-1990s, U.S. Congress responded with the Commercial Space Act of 1998, which gave FAA's AST full authority to license RLVs in the United States. A rash of export control legislation in the wake of unauthorized satellite technology transfer to China also occurred in the late 1990s.

Over the years, much work has been accomplished in upgrading ELV performance to increase lift capability in order to meet demand for heavier commercial satellites. Heavier lift capability also allows a launch vehicle to carry more satellites, an economic means of providing launch services for LEO and MEO communication satellite constellations. However, relatively little work has been accomplished in actually decreasing launch costs. The United States Air Force is addressing this problem by currently funding development of two EELV (Evolved Expendable Launch Vehicle) families, one by Lockheed Martin and the other by Boeing. The new EELV systems are expected to aid the U.S. in recapturing global market share by reducing costs by roughly 25% over the current generation of ELVs.

Increased global competition is evident in the RLV arena as well. Reusable launch vehicle development programs are currently underway in the United States, Japan, France, and several other nations. The vast majority of these programs, however, reside in the U.S. in small entrepreneurial RLV firms. Bolstered by the very hot LEO market a few years ago, Kistler Aerospace, Kelly Space & Technology, Pioneer Rocketplane, Universal Spacelines, Space Access LLC, Rotary Rocket, and other entrepreneurial companies formed to develop privately funded RLVs.⁴⁰ These firms are challenging the paradigm in the aerospace industry that only the traditional aerospace giants such as Lockheed Martin and Boeing can possibly successfully develop reusable launch vehicles.

³⁹ Mulville, Daniel, Statement of Daniel Mulville, Chief Engineer, Office of the Administrator, NASA, at the “Space Transportation Architecture Studies: The Future of Earth-to-Orbit Spaceflight” hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 27 October 1999, www.house.gov/science/.

3. Demand for Space Launch

In this section I present an overview of the demand for space launch, focusing on demand for low earth orbit (LEO) launch vehicles and two emerging markets, microsattellites and space tourism. Demand for space launch vehicles is a derived demand, from the uses of payloads in space.

Demand Overview

The space transportation industry grew significantly in the 1990s, averaging about 20% growth per year, with worldwide revenues exceeding \$6.7 billion in 1999.⁴¹ The outlook over the next few years looks dim, however, as demand for satellite launches drops and more launch systems come on-line. An article in *Military Space* predicts total revenues from the launch and launch insurance markets to grow from \$7.6 billion in 1994, peak at almost \$11 billion by 2001, and decline to \$6.7 billion by 2004.⁴² Standard & Poor's predicts that although worldwide orbital launches with on-line systems in 1997, 1998, and 1999 numbered 74, 82, and 128, respectfully, space transportation industry revenues will likely remain constant or even slightly decline over the next few years.⁴³ A recent *Space News* article is even more grim, predicting that the global launch capacity for commercial satellites will "dwarf demand over the next 10 years, putting heavy downward pressure on prices and perhaps driving some players out of the market altogether."⁴⁴

Worldwide commercial space spending was over \$70 billion in 1997 and was projected by Lockheed Martin in 1998 to grow to nearly \$140 billion by 2005.⁴⁵

⁴⁰ From: Cáceres, Marco, A, "Too Many Launch Vehicles for the Market?" *Aerospace America*, February 1999, p. 26; and Iannotta, Ben, "Small Start-ups Vie for Big Business," *Aerospace America*, August 1998, p. 34.

⁴¹ Friedman, Robert E., "Standard & Poor's Industry Surveys: Aerospace & Defense," August 10, 2000.

⁴² "Forecast Sees Growth in Launch Market," *Military Space*, Vol. 15, No. 7, March 30, 1998.

⁴³ Friedman, Robert E., "Standard & Poor's Industry Surveys – Aerospace & Defense," August 10, 2000.

⁴⁴ Ferster, Warren, "Launch Supply Could Exceed Demand for Next Decade," *Space News*, January 22, 2001, p. 8.

⁴⁵ "Lockheed Martin Sees Commercial Space Market Doubling by 2005," *Aerospace Daily*, Vol. 187, No. 21, July 31, 1998, p. 174.

Such predicted high rates of growth were fueled primarily by large projected increases in numbers of LEO telecommunications, Internet broadband, and Earth imaging satellites. The 1997 satellite forecast by the FAA's Office of Commercial Space Transportation predicted about 1,063 LEO payloads would need to be launched in the subsequent decade, driving demand for launches way up.⁴⁶ Entrepreneurs and launch industry incumbents both reacted to these favorable forecasts from the mid- to late 1990s by implementing development programs either alone or in alliances. But within two or three years after that 1997 forecast, Iridium and ICO had gone bankrupt, and Globalstar and Orbcomm were struggling to remain solvent. The 2000 satellite forecast by the FAA's Office of Commercial Space Transportation projects that 522 LEO payloads will be deployed in the ensuing decade, almost exactly half of the 1997 prediction.⁴⁷ In contrast to the upheaval in the demand for LEO launches, the GEO market has remained relatively steady over the few years, with the FAA forecasts for demand for GEO launches fluctuating only by about 10% over the past three years.⁴⁸

Launcher Segmentation: Orbit Reach and Lift Capability

Selection of a space launch provider is based on a number of decisions: launch cost, reliability, system performance / payload capacity, availability and schedule, availability of and cost of insurance, regulatory constraints, political and technical risk, national security and technology transfer, and working relationships between the payload company's and launch firm's technical and managerial staffs. Selection of a launcher is also a function of desired final orbit. The vast majority of commercial satellites are placed either into low Earth orbit (LEO) or geostationary orbit (GEO); only occasionally is a Medium Earth orbit (MEO) utilized. Low Earth orbit is generally defined as orbits with altitudes ranging from about 150 miles to 1500

⁴⁶ Moring, Frank, Jr, "LEO Failures, Shuttle Investment Seen as Obstacles to New RLV," *Aerospace Daily*, Vol. 197, No. 25, p. 214, February 8, 2001.

⁴⁷ Associate Administrator for Commercial Space Transportation (AST), *2000 Commercial Space Transportation Forecasts*, Federal Aviation Administration, May 2000, <http://ast.faa.gov>.

⁴⁸ *Ibid.*

miles,⁴⁹ typically using orbital inclinations between 0 degrees (for equatorial coverage) and 101 degrees (polar and sunsynchronous orbits), and is used for communications, scientific payloads, imaging, and data services. More recently, commercial remote sensing satellites, long the domain of governments, are starting to be deployed in LEO as well. Space Imaging's Ikonos, launched in September 1999, was the first of these to become operational.⁵⁰

Geostationary satellites use a specific orbit, about 22,300 miles directly above the equator, where they revolve around the Earth at the same angular rate as the Earth spins on its axis. Satellites in GEO thus remain relatively fixed over the same spot on the equator, providing an ideal location for communications and Earth observation satellites. MEO are all orbital altitudes between LEO and GEO. To achieve GEO requires considerable more energy for the same payload mass than LEO, and thus requires larger, more powerful and expensive launch vehicles. GEO launchers loft heavy upper stage boosters into space that insert the payloads into a geosynchronous transfer orbit (GTO). Because of the high cost of GEO capable launch vehicles, government involvement in defraying development costs has always been required in the past and will likely to be necessary for some time. LEO capable launch vehicles, with payloads ranging from a few hundred pounds to ten or twenty thousand pounds, are therefore usually the focus of private company development.

Space launchers are also segmented based on lift capability, the payload weight delivered into LEO. Light, medium, and heavy lift payload classes are generally taken to mean payloads in the ranges of less than 10,000 pounds, 10,000 to 20,000 pounds, and more than 20,000 pounds, respectively.

⁴⁹ Just to complicate matters, not all LEOs are created equal. A launch vehicle's performance generally degrades with increased orbit inclination. A launch vehicle's payload capability to an orbital inclination of 28.5 degrees (launching due east launch out of Kennedy, for example) would be significantly less than its payload capability to the International Space Station's orbital inclination of about 51.6 degrees.

The Satellite Industry

The satellite industry drives the derivative demand for launch vehicles. Satellite manufacturing businesses generated revenues of \$11.3 billion in 1999, about 1.7 times that of the launch business.⁵¹ Like the launch business, satellite manufacturing is capital intensive, with very large initial development costs for RDT&E as well as production. Unlike current launch vehicles, however, satellites can rather quickly become technically obsolete, especially in more recent times as technology maturation times decrease. While the development cycle time for a new generation satellite can take from five to seven years, an evolutionary, incremental upgrade can be developed in about one year.⁵² It takes about 18 months, on average, to build a satellite.⁵³

Launch costs are often a significant percentage (typically roughly 50% or more) of the total cost of designing, fabricating, and placing a satellite into Earth orbit. Due to the very high cost of space launch, satellite designers and owners must trade-off the costs of adding double or triple redundancy to critical subsystems to increase the satellite's on-orbit reliability with the costs of having to build and re-launch a replacement satellite. Increasing redundancy increases the cost and weight of the satellite. If launch costs can be greatly reduced, however, some of this redundancy may not be necessary, causing payload costs to also decrease.

Some of the variance in the literature of prospects for the space launch industry over the next decade is likely due to differing assessments of the separate government and commercial launch markets. Only very recently did commercial launch payloads outnumber government ones.⁵⁴ In 1999 commercial customers accounted for 60% of the launch service market versus 40% by government.

⁵⁰ Associate Administrator for Commercial Space Transportation (AST), *2000 Commercial Space Transportation Forecasts*, Federal Aviation Administration, May 2000, <http://ast.faa.gov>.

⁵¹ Friedman, Robert E., "Standard & Poor's Industry Surveys: Aerospace & Defense," August 10, 2000.

⁵² Ibid.

⁵³ Ibid.

Government Demand

A significant percentage of total demand for launch services is by the United States government for Department of Defense weather, surveillance, early warning, GPS (global positioning system), communications and other satellites. Security regulations for these payloads restrict the launcher to U.S. companies. Other United States government agencies such as NASA (National Aeronautics & Space Administration) and NOAA (National Oceanic and Atmospheric Administration) are also large buyers and also exclusively employ U.S. launch companies. Even with costs much higher than those of competitors, NASA's own Space Shuttle is locked-in as the launch vehicle for many NASA payloads. For missions and payloads that require a human presence in space, however, the Space Shuttle holds nearly a worldwide monopoly with unparalleled capability and versatility.

Future United States government launch demand is expected to rise over the next decade due to projected modest increases in NASA science and space exploration needs and in DoD satellite needs.

International Space Station Servicing

Construction of the International Space Station (ISS) will be carried out using Space Shuttles, requiring a number of launches over the next five or so years. Due to the very high cost of the Shuttle, however, launch of supplementary construction materials or, once online, ISS regular re-supply missions have potential for a significant market value. The costs of using the Space Shuttle to re-supply the International Space Station over its ten-year design life, as currently planned by NASA, is estimated at \$25 billion.⁵⁵

While at first glance a lucrative market, current ISS operational characteristics and constraints may require extensive, perhaps even prohibitively expensive, RLV

⁵⁴ Most references attribute this crossover to have occurred either in 1997 or 1998.

⁵⁵ Cowing, Keith, Editor, "Space Transportation Architecture Studies: Future of Earth-to-Orbit Spaceflight," Hearings before the House Committee on Science's Subcommittee on Space and Aeronautics, *NASA Watch*, 27 October 1999.

design modifications. RLVs proposing to service the International Space Station must meet very stringent performance and interface requirements given by the *Interface Definition Document for ISS Visiting Vehicles, SSP 50235*.⁵⁶ A few very abbreviated example requirements from this document that may seriously impact RLV designs are:⁵⁷

- RLV Docking with ISS Options - specific hardware, software, and communications interface requirements, the capability of (essentially) maintaining a holding position for up to 34 hours outside the ISS approach ellipsoid, compatibility of the environmental control and life support system, and pressurization for the mating compartment. Safety considerations on-dock at ISS also may affect design, such as the ability to withstand micrometeoroid and orbital debris impacts and readiness for emergency departures. The time required to transfer material from a docked RLV or an RLV based transfer vehicle can be in excess of 9 days, a relatively long dwell time influencing RLV consumable requirements.
- RLV Not Docking with ISS Options (Space Station Remote Manipulator System is used to remove and replace payload module inside the RLV's payload bay) - specific hardware, software, and communications interface requirements, high RLV navigational accuracy, and low error tolerances on attitude control.

NASA Space Shuttle Replacement

NASA currently plans to replace its current, partially reusable, Space Shuttle with either a new, Shuttle-derived launch vehicle or a "clean sheet designed" RLV, developed and operated by industry.⁵⁸ NASA has targeted 2012 for initial operations of this system and has already invested heavily in RLV technologies and experimental flight demonstrators, including the X-33, X-34, and X-37 programs. NASA has spent more than a billion dollars in this area over the last few years and

⁵⁶ Letchworth, Janet F, and Letchworth, Gary F, "Second Generation Reusable Launch Vehicle Servicing of the International Space Station," AIAA Paper 2000-5141, AIAA Space 2000 Conference and Exposition, Long Beach, CA, September 19 - 21, 2000.

⁵⁷ Ibid.

intends to spend more than \$4.5 billion over the next six years under its Space Launch Initiative program to continue this work and to initiate the Space Shuttle replacement program. One objective of this effort is to promote development of a commercially viable launch vehicle. That is to say NASA does not wish to own the RLV but rather to only purchase launch services at a reasonable price. NASA's requirement for manned spaceflight, however, may make it impossible to develop a commercially viable system for two reasons. First man-rating a system involves huge expenses that are not required for unmanned systems, the vast majority of all launch vehicles. Second, the performance penalty required to design a launch vehicle to hold humans is also huge, both in terms of additional vehicle mass, systems and subsystems, and thus cost, as well as seriously reduced performance.

Air Force Military Spaceplane System

Due to a number of key deficiencies in its current space operational capabilities, the Air Force Space Command component of the United States Air Force (USAF) has documented draft needs for the capability for a militarized RLV system. In response, the Air Force Research Laboratory in concert with NASA is currently developing critical technologies for its Military Spaceplane System, a reusable space system architecture to perform a wide range of missions including launch-on-demand, reconnaissance, surveillance, satellite orbit transfer, and space defense. As currently conceived, the Military Spaceplane System includes the Space Operations Vehicle, a militarized reusable launch vehicle, the Space Maneuver Vehicle, a reusable upper stage / reusable satellite bus, the Orbital Transfer Vehicle for on-orbit asset relocation, and the Modular Insertion Stage, a low cost expendable upper stage. From a user perspective, the Space Operations Vehicle would be ideally as different from a civil or commercial RLV as an F-111 is from a Boeing 737, with emphasis on operational characteristics such as mission flexibility, rapid launch, rapid turn around, and all weather operations, rather than minimum cost launch.

⁵⁸ I believe the former is more likely due to the inevitable political backlash to the recent failures of NASA's X-33 and X-34 programs as well as the International Space Station program development woes.

Table 1 summarizes some of the differences between the desired attributes for a military reusable launch vehicle versus NASA's RLV requirements.

Table 1 Military Versus NASA Commercial / Civil RLV Attributes

Military Spaceplane RLV Requirements	NASA Commercial / Civil RLV Requirements
Light - Medium Lift	Heavy Lift
Military Missions	Spacelift, On-Orbit Support
High Sortie Rate and Surge	Limited Sortie Rate/No Surge
Large Crossrange	Limited Crossrange
Military Operability	Increased Operability (vs. Shuttle)
All-Weather Operations	Some Weather Limits
All Azimuth Launch	Limited Azimuth Launch
Full Alert Capability	No Alert Capability
Dispersed Operations	One Operations Site

Development of the military spaceplane system, even at the relatively low levels of funding the program has received, has been controversial, both inside and outside of the Air Force. In 1996, for example, President Clinton Administration line item vetoed military spaceplane funding, an act later ruled unconstitutional and rescinded. Curiously, the same Administration incorporated a new DoD Space Policy in July 1999 calling for "assured, cost-effective, responsive access to space," critical asset protection, effective surveillance of space, timely constellation replenishment and reconstitution, and space system protection, all hallmarks of the military spaceplane system.⁵⁹ The 1999 DoD Space Policy also gave a new U.S. perspective of space, analogous to the high seas and international airspace, where purposeful interference with U.S. space systems (either commercial or government) will be viewed as an infringement of United States' sovereign rights, and may be responded with use of force.

⁵⁹ From: Department of Defense Directive 3100.10, *Space Policy*, and PDD-NSC-49/NSTC-8, *National Space Policy*, July 9, 1999; and Cohen, William, Secretary of Defense Memorandum, *Memorandum on Department of Defense Space Policy*, July 9, 1999

A recently concluded congressional study warned about the vulnerability of the United States' critical space assets, of the potential for a "Pearl Harbor in space."⁶⁰ This report from the Commission to Assess U.S. National Security Space Management and Organization, recommended "development of the capability to interdict foreign satellites with minimum preparation time, i.e. military spaceplane and reusable, maneuvering upper stages."⁶¹ The commission was established last year and headed by Donald Rumsfeld, now the new Bush Administration's Secretary of Defense. This increased emphasis in acquiring a military RLV capability might be fueled in part by recent reports that China, Russia, and other nations have accelerated their development of anti-satellite technology and jamming capabilities.⁶² This perceived need may have also been strengthened by a May 1998 temporary failure of a commercial communications satellite, which caused nearly 90% of the 45 million pagers in the United States to go dead for almost a day.⁶³ As the worst failure in space communication history, this incident provided only a hint of what an attack on U.S. space assets could offer yet serves as a valuable extrapolation point.⁶⁴

Commercial Demand

Technology Transfer Limitations

In 1999 four satellite manufacturing companies held nearly 80% of the world market: Hughes (37%), Lockheed Martin (18%), France-based Alcatel/Aerospatiale (11%), and Loral Space & Communication Ltd.'s SS/L unit (11%).⁶⁵ However, strict U.S. export controls on space technology have, according to some reports, severely

⁶⁰ Stone, Andrea, "USA's Dependence on Satellites Places Nation at Risk," *USA Today*, January 11, 2001, p. 5A.

⁶¹ Sietzen, Frank, Jr, "Spacelift Washington: Commission to Recommend Military Space Boost, New Programs," January 10, 2001, www.spaceref.com.

⁶² From: Sietzen, Frank, Jr, "Spacelift Washington: Chinese and Russian Space Researchers Designing Anti-Satellite Systems; Who Will Direct The Future of U.S. Space Policy," February 8, 2001, www.spaceref.com; and Sietzen, Frank, Jr, "Spacelift Washington: National Security Space Needs May Drive Bush Space Policy – A Special White Paper Background Report," January 28, 2001, www.spaceref.com.

⁶³ Stone, Andrea, "Space Assets' Face Threat," *USA Today*, January 11, 2001, p. 1A.

⁶⁴ Canan, James W, "An Aerospace Force Takes Shape," *Aerospace America*, February 2001, p. 33.

⁶⁵ Friedman, Robert E., "Standard & Poor's Industry Surveys: Aerospace & Defense," August 10, 2000.

hurt U.S. satellite manufacturer competitiveness over the past year or so. The Strom Thurmond National Defense Authorization Act of fiscal year 1999 was the Administration's response to allegations that a U.S. aerospace company had transferred space technology to the Chinese in violation of U.S. export controls, and that this technology had helped improve Chinese missile capability. The Strom Thurmond National Defense Authorization Act transferred licensing jurisdiction over commercial communications satellite exports from the Commerce Department to the State Department, and also levied several special space technology export controls.⁶⁶ This legislation resulted in commercial communications satellites being treated by the United States government as more like missiles, military aircraft, or munitions for export purposes. Export license applications for these satellites have been subjected since early 1999 to increased scrutiny, and contract-killing delays. This has greatly affected the entire space industry, and has seriously harmed the competitiveness of U.S. satellite manufacturers.⁶⁷ A recent article in *Aerospace America* by Pamela Meredith and Sean Fleming notes,⁶⁸

"There have been reports that U.S. commercial satellite sales have declined by approximately 40% since the licensing jurisdiction transfer. For example, DaimlerChrysler Aerospace (now part of EADS) indicated that it would reduce its dependency on U.S. suppliers in the wake of the transfer."

Of course, how much of that 40% can be attributed to a naturally slumping market regardless of export policy is unknown. Subsequent industry complaints prompted the Foreign Relations Authorization Act, FY00 that expedited license application processing for export of commercial communication satellites and related equipment to NATO countries and certain non-NATO U.S. allies.⁶⁹ Industry

⁶⁶ Meredith, Pamela L, and Fleming, Sean, P, "The Year in Review: Legal Aspects," *Aerospace America*, December 2000.

⁶⁷ Thompson, David W, "Commercial Space Policy Needs to be Reviewed in the U.S.," *Space News*, January 22, 2001, pp. 19 - 20.

⁶⁸ Meredith, Pamela L, and Fleming, Sean, P, "The Year in Review: Legal Aspects," *Aerospace America*, December 2000.

⁶⁹ *Ibid.*

complaints also prompted the Clinton Administration to introduce the Defense Trade Security Initiatives in May 2000, to further alleviate the licensing bottleneck to certain foreign countries.

Recent LEO Constellation Woes

The uncertainty in growth in the space launch industry is primarily due to uncertainty in the commercial space industry as a whole. Telecommunications, digital television, radio, paging, tracking, telephone, earth observing, and Internet services satellites provided high demand for satellites and launches throughout much of the 1990s. Demand for telecommunication satellite launches has slowed considerably in the last couple of years, however. A recent trend is the downsizing in number and scope of planned Earth communication satellite constellations due to lower cost competition using alternative, conventional technology such as fiber optic and copper telecommunication lines. This trend was instigated by the financial failures of several satellite data communication ventures over the past few years. The most infamous failure of these was also the first - Motorola's Iridium, a \$5 billion, 66 satellite low Earth orbit constellation for hand-held, dual mode phones, fixed phones, paging, and low speed data services. Many satellite telecommunications companies like Iridium underestimated the speed far less costly land-based wireless phone systems spread around the planet in the 1990s. Iridium handsets that provided global coverage but costing \$3,000 couldn't compete with very inexpensive, more compact, cellular telephones that worked almost anywhere business people traveled. This resulted in Iridium failing to acquire an adequate subscriber base; the company filed for protection from its creditors under Chapter 11 United States bankruptcy code in August 1999.⁷⁰ Other industry failures followed soon after. ICO Global Communications filed for Chapter 11 about two weeks after Iridium after failing to secure \$600 million in financing commitments it had expected.⁷¹ ICO had planned to build a \$3.7 billion medium Earth orbit (MEO) telecommunication constellation composed of 10 satellites, for portable and fixed

⁷⁰ "Satellite Firm Faces Bankruptcy," Reuters, August 27, 1999, www.wired.com/news/business.

⁷¹ Ibid.

telephones.⁷² Some analysts blamed Iridium's failure for the lack of investor confidence in financing ICO and other telecommunication satellite constellation ventures as well as the primary cause for lack of investment capital in new reusable launch vehicle ventures, referring to this as the "Iridium Effect."⁷³

With the first two dominos down, other ventures began to topple. Orbcomm Global LP, who has been operating under Chapter 11 bankruptcy protection since September 1999, is reportedly requesting permission to auction off its business.⁷⁴ Orbcomm was founded in 1990 to provide two-way data communications services for individuals, tracking of barges and truck trailers, and industrial asset monitoring. Orbcomm currently employs a constellation of 35 satellites in low Earth orbit (LEO). The cost of the system was estimated at \$330 million in a 1997 report.⁷⁵ Likewise, Globalstar LP stopped servicing its debt in January 2001, after having found great difficulty in acquiring subscribers. Globalstar was initially designed as a 48-satellite constellation to provide hand-held, dual mode telephone and other communication services for an initial investment of \$2.5 billion.⁷⁶ In the fourth quarter of 2000, Loral Space & Communications Ltd. reported a loss of about \$1 billion, corresponding to their 38% stake in Globalstar.⁷⁷ Orbital Imaging Corporation (Orbimage) has also run into financial difficulty, working with an investment-banking firm to restructure its debt, and planning on missing a March 2001 scheduled interest payment to bondholders.⁷⁸

Still, some forecasts see the multimedia, remote sensing, weather, and navigation portions of the satellite market significantly increasing over the next decade. Spaceway, a geostationary (GEO) constellation of 8 satellites, currently

⁷² Cook, William J, "1997 A New Space Odyssey," *U.S. News & World Report*, March 3, 1997.

⁷³ "The Year in Review: Space Systems," *Aerospace America*, December 2000.

⁷⁴ Magnuson, Stew, "Orbcomm May Be Bound For Auction Block," *Space News*, February 11, 2001, www.spacenews.com.

⁷⁵ Cook, William J, "1997 A New Space Odyssey," *U.S. News & World Report*, March 3, 1997.

⁷⁶ *Ibid.*

⁷⁷ Silverstein, Sam, "Loral Declares Billion-Dollar Loss on Globalstar," *Space News*, February 15, 2001, www.spacenews.com.

⁷⁸ Bates, Jason, "Orbimage to Miss Payment, Restructure Debt," *Space News*, February 15, 2001, www.spacenews.com.

provides fixed telephone service for developing areas, fax, and broadband multimedia, and is thought by some to have a good shot at capturing a reasonable Internet broadband subscriber base.⁷⁹ And Teledesic, the “Internet of the Sky,” the most blatantly ambitious LEO constellation project of all those planned in the 1990s, still remained in a planning mode as of last year.⁸⁰ Teledesic had originally planned a \$9 billion, 840 satellite, broadband multimedia LEO constellation with backers of the ilk of Bill Gates and Craig McCaw.⁸¹ Plans for the future include a merger of Teledesic with New ICO, formerly ICO Global Communications.

Satellite Size Trends

Marco Cáceres, a well-published space industry analyst with Teal Group, summed up recent and predicted satellite trends in a recent article in *Aerospace America*.⁸² He noted that the first wave of satellite constellations was the “mobile wave,” composed of small, commercial, mobile communications satellites for LEO constellations weighing less than 1,000 kg (2,200 lb). This wave occurred during 1997 - 1999 and was composed of about 150 satellites in the Iridium, Globalstar, and Orbcomm constellations discussed above. The sizes of these satellites were significantly smaller than most commercial satellites in the past – each Iridium satellite weighed in at about 1,500 lb, Globalstar at about 1,000 lb, and Orbcomm at approximately 100 lb. Cáceres also described the first “broadband wave”, anticipated from 2002 to 2004. The broadband satellites will typically be much larger sized than the mobiles; the SkyBridge, Astrolink, and Spaceway networks will be composed of satellites weighing about 2,200 lb, 7,000 lb and 10,000 lb, respectively.⁸³

One satellite broadband system is already up and running. StarBand Communications began its direct-to-home broadband Internet service in November

⁷⁹ Cook, William J, “1997 A New Space Odyssey,” *U.S. News & World Report*, March 3, 1997.

⁸⁰ “New ICO Emerges from Bankruptcy Protection,” May 17, 2000, www.teledesic.com/newsroom/articles.

⁸¹ Ibid.

⁸² Cáceres, Marco, “The Emerging Nanosatellite Market,” *Aerospace America*, February 2001.

⁸³ Ibid.

2000, with download speeds up to 500 kbps and upload speeds up to 150 kbps. Their website asserts that the StarBand antenna can accommodate both their Internet service as well as EchoStar's DISH Network satellite TV programming, a convenient bundling. StarBand uses one geostationary satellite to cover virtually the entire continental United States, with Alaska, Hawaii, and Puerto Rico to be added soon.⁸⁴

Although most broadband satellite networks are planned for geosynchronous orbit (GEO), at least one will be a low Earth orbit (LEO) constellation. The SkyBridge broadband system will employ a constellation of 80 satellites at an altitude of 913 miles to provide national and regional telecommunications operators and service providers with broadband capacity, enabling them to offer high-speed, highly-interactive multimedia services to businesses and residential users anywhere on the planet.⁸⁵ This use of LEO instead of traditional GEO for broadband is notable as it enables SkyBridge to offer highly interactive, real-time multimedia services due to the much shorter signal propagation time (about 30 milliseconds for SkyBridge versus about ½ second for GEO satellites). Alcatel Space, Europe's leading satellite exporter, will build SkyBridge satellites. Alcatel has contracted Starsem to launch 32 SkyBridge satellites on 11 Soyuz/ST-Fregat launch vehicles, beginning in 2002. The Boeing Company, through Delta Launch Services, will launch 40 of the satellites with two Delta III rockets, each carrying four satellites, and four Delta IV rockets, each carrying eight satellites.⁸⁶

The \$1.4 billion North American network portion of the Spaceway global broadband satellite network is scheduled to begin operations in 2002. Spaceway will provide two-way, high-data-rate applications such as Internet services, desktop video conferencing, and interactive distance learning. The North American network

⁸⁴ www.starband.com.

⁸⁵ www.skybridgesatellite.com/news/.

⁸⁶ www.skybridgesatellite.com/system/.

will be composed of two active Spaceway HS 702 geosynchronous orbit satellites and an in-orbit spare, all built by Boeing Satellite Systems (formerly Hughes).⁸⁷

While Starband was the first to market for a two-way high-speed Internet service, DirectPC service, a subsidiary of DirecTV, has offered a hybrid service for a few years, using a high-speed downlink in concert with a standard dialup phone line for the uplink.⁸⁸

A host of other firms are entering or have already entered the direct-to-home and small business satellite Internet services market, including Helius Inc., Inmarsat, WildBlue, NetSat28, Tachyon, TeleCrossing, Ultimate Satellite, EuropeOnline, and SeaTel, Inc.⁸⁹

Some industry experts think the business prognosis for the broadband Internet services wave looks quite positive, following the lead of GEO based direct-to-home television services, which have been doing very well and are serving more than 10 million households in the United States.⁹⁰ Video and audio streaming, especially for live events such as sports or movies, may be a large future market. PayForView.com, for example, has recently announced acquisition of the Internet broadcast rights to International Soccer games, as well as agreements to offer future live web casts of three Ultimate Fighting Championship bouts.⁹¹ A recent survey found that a satellite Internet broadband broadcasting system appears to be the optimal method for future digital distribution of movies from studios directly to theaters, if pirating concerns could be mitigated. The value of a digital versus celluloid movie distribution system to the consumer is primarily better image and sound quality, more options for future special effects and supporting aids, and more variety in non-movie offerings. The value of such a system to the movie studio is a

⁸⁷ www.hns.com/news/pressrel/.

⁸⁸ Lindsay, Clark S, Editor, Space Investing Web Site, www.hobbyspace.com/Investing/index.html.

⁸⁹ Ibid.

⁹⁰ Ibid.

vast reduction in distribution and manufacturing costs, higher profit margins due to disintermediation, the ability to hold premiere showings simultaneously in many different geographical areas, and possibly a reduction in piracy. The value to the movie theater is primarily better leverage of fixed assets by creating additional revenue streams, as the Internet streaming capability could be applied for revenue generating broadcasts of distance learning courses, business meetings, sports offerings, and other pay per view events. However, while direct costs of the system would be low to the consumer and movie studios, costs to the movie theater to transition to digital projection and distribution would be large, perhaps even prohibitively so.⁹²

A number of industry experts predict that the wave following the broadband wave will be composed of constellations of very small satellites or perhaps clusters of these microsattellites, nanosatellites, or picosatellites. This emerging market is discussed in a subsequent section.

Substitutes for Space Transportation Products & Services

"The degree of success the communications-satellite industry achieves in competition against fiber-optic cable will be the single most-important determinant of the future of a commercial launch industry."

*- Bob Cole, 1989*⁹³

Substitutes for Satellites

Fiber-optic cable, copper telecommunication lines, and cellular telephone microwave towers are the greatest threat as substitute products to the communications satellite industry, and thus to demand for low Earth orbit launch

⁹¹ Karasopoulos, Harry, Lazo, Horacio, Sibley, Bo, and Bee Teck Tan, Christopher, "Digital Distribution of Motion Pictures," Research Paper for 15.567 Introduction to E-Commerce, Massachusetts Institute of Technology, December, 2000.

⁹² Ibid.

services. As discussed in the prior section, a number of satellite telecommunications companies like Iridium underestimated the speed far less costly land-based wireless phone systems could be implemented in many different world markets in the 1990s. Many satellite telecommunications firms probably also did not predict the degree of cost reduction in creating this infrastructure enabled by such large-scale network construction and technology innovation. The result was a nasty black eye for the space industry, causing a large drop in projected LEO launch demand over the past year and into the next few years. Even though terrestrial networks won the first battle, they have not won the war.

Fiber optic networks offer several advantages besides some cost aspects over satellite systems, such as higher bandwidth capacity, lower susceptibility to electromagnetic interference (either from nature or by jamming) and tapping, and higher overall reliability (coupled, however, with a higher susceptibility to natural disasters or physical man-made disruption).⁹⁴ Satellites offer the advantages of higher flexibility with respect to reconfiguring the system to address changing needs as well as applications; telecommunication satellites can fulfill a multitude of different missions such as point-to-point, point-to-multipoint, mobile, remote, direct broadcasting, and private networks. In addition, satellites can be more cost-effective or even the only provider for many mobile, remote, and point-to-multipoint communications. Examples of point-to-multipoint communications include direct broadcasting of cable and network television, radio, and business broadcasts. Remote telecommunications applications are especially important for satellite systems. For example, even with the increasing availability to consumers of ground-based Internet services using cable and telephone links, an estimated 30 million households in the U.S. located outside of urban and suburban areas will not have this offering for many years, if ever.⁹⁵

⁹³ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989, pp. 98-103.

⁹⁴ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989, pp. 98-103.

One advantage often touted of ground-based networks over satellites is the lack of transmission delay (approximately ½ second) experienced by GEO satellites. This delay was once considered a showstopper for Internet service protocols, but this problem has been solved with sophisticated packet routing processors, and a number of companies are successfully offering Internet broadband services today. The transmission delay is not significant to most Internet users since it is of the same order of magnitude of other system time lags. However, it can be a problem for real-time, highly interactive applications such as multi-user gaming.⁹⁶

Aside from competing with conventional, ground-based technologies such as fiber optics and microwave transmission towers, there are few other potential substitutes for satellites that the space launch industry relies on. High altitude, high endurance aircraft are being developed that might be used to loiter over large cities for long periods of time – perhaps even multiple days between landings – substituting for a telecommunications satellite over a relatively small land area. One such concept is Scaled Composites' Proteus aircraft, developed primarily to serve as a wireless transmission station with a 12-hour loiter capability. Blimps have also been studied for these applications.

Substitutes for Launch Vehicles

Most technology research and development conducted today is directed for launch vehicles employing liquid, solid, or hybrid liquid-solid rocket engines. Advanced airbreathing hypersonic propulsion systems, including airbreathing and rocket combined cycle engines are also being vigorously studied, as well as technologies required to incorporate them into a reusable launch vehicle system. In addition, work is also underway in developing launch assist technologies, such as in-flight air collection and liquefaction systems, takeoff-assist sleds, in-flight propellant transfer, etc. Although these studies could drastically alter the configuration,

⁹⁵ Lindsay, Clark S, Editor, Space Investing Web Site, www.hobbyspace.com/Investing/index.html.

⁹⁶ Ibid.

performance, and operational characteristics of a resultant launch vehicle, they do not contribute to an actual substitution for launch vehicles in general.

There are few substitutes even being considered for conventional and advanced launch vehicles, and none are generally expected to be operational anytime soon. In fact, the commercial and technical viability – or at least technical maturity - of some of these concepts is hotly debated today. Only a few concepts will therefore be discussed here.

One of the more interesting concepts is a laser-propelled launch vehicle concept that uses a pulsed laser beam from a ground-based laser to heat the air on the specially shaped underside of the “Lightcraft.” The rapidly heated air creating a blast wave that propels the Lightcraft upwards. Numerous flight tests of subscale models have been conducted in New Mexico, with an altitude of 233 feet reached by a 1.8 ounce Lightcraft model using a 10 kW pulsed carbon dioxide laser.⁹⁷ The firm Lightcraft Technologies was formed in February 2001 to commercialize this technology, and plans to launch nanosatellites into orbit within 5 years,⁹⁸ a very ambitious schedule considering the formidable challenges remaining to be worked out.

Electromagnetic powered rail guns have been examined for either rocket launch assist or as an independent launch system for small payloads having the very unique capability of surviving 30-50 g accelerations and very high heating.

Even more ambitious ideas have been pursued such as a tower spanning from the earth’s surface beyond geosynchronous orbit altitudes (some 22,500 miles away!), and tethers of like magnitude that either reach down into the Earth’s atmosphere to grab a payload and pull it into orbit, or are anchored to the Earth’s

⁹⁷ www.lightcrafttechnologies.com/news.html.

⁹⁸ Lindsay, Clark S, Editor, Reusable Launch Vehicle News Web Site, www.hobbyspace.com/Links/RLVNews.html.

surface and employ some sort of elevator-like system to carry payloads into orbit.⁹⁹ Buckytubes, tubular microscopic strings made of carbon atoms, and having an extremely high strength-to-weight ratio, have been considered as a viable future construction material for the anchored tether concept.

NASA, universities, and private citizens have also studied some theoretical physics concepts that may someday replace launch vehicles or more efficiently utilize existing space vehicles. These concepts include quantum teleportation, wormholes in space, and the elimination of momentum.¹⁰⁰

Emerging Markets

Motivated especially by the recent souring of the LEO communication satellite market, reusable launch vehicle developers are carefully scrutinizing other facets of the launch market. Several yet untapped commercial markets may increase demand for space transportation services in the future. Space tourism, for example, has been extensively studied with some supply and demand forecasts showing a potentially lucrative market – but only enabled by launch costs of a fraction of those of today's systems. Micro-, nano-, and picosatellites may offer a relatively inexpensive architectural option to the satellite industry in the future, perhaps enabling a resurrection of demand for LEO launches. Another area of high market potential is in very fast freight services where a company would provide nearly global package delivery in a mere few hours rather than overnight using RLVs with suborbital trajectories. Such an offering could obviously be extended to a suborbital passenger service. Other possible markets for RLVs are to launch payloads for space solar power, space-based manufacturing, satellite-aided agriculture, and even advertising and entertainment. Two of these emerging markets for launch services, microsats and space tourism, are examined in more detail below.

⁹⁹ Don't hold your breath.

¹⁰⁰ Beardsley, Tim, "The Way to Go in Space," *Scientific American*, February 1999.

Microsatellites

In addition to the trends of LEO communications satellites becoming smaller and GEO satellites becoming larger, an emerging market in pico-, nano-, and microsatellites has appeared. Although in the paragraphs below I'll take some license in sometimes referring to all three classes of very small satellites (micro-nano- and picosatellites) simply (and unimaginatively) as "very small satellites", these satellite classes are differentiated by their mass, often as: picosatellites < 1 kg (2.2 lb), nanosatellites < 20 kg (44 lb), and microsatellites < 200 kg (440 lb).¹⁰¹

Miniaturization technologies have enabled commercial satellites to shrink considerably. Instead of the traditional few thousand pounds per satellite, constellations of microsatellites today are made up of individual satellites weighing less than a few hundred pounds each. One good example is Orbcomm that, as discussed above, currently employs a constellation of 35 satellites in low Earth orbit to provide commercial communications and monitoring services. Each Orbcomm satellite weighs in at a little less than 100 pounds. And however as impressive this was when first deployed just a few short years ago, Orbcomms may seem like behemoths relative to some future communication and imaging satellite constellations.

According to Cáceres,¹⁰² launches of 24 nanosatellites into Earth orbit have been attempted since 1990, with nearly half of these launched in 2000 alone. Some of the builders and/or owners are Weber State University, Air Force Academy, Orbital Sciences, Interferometrics, GE Americom, Amateur Radio Satellite organization, Amsat-North America, Japan's Institute of Space and Astronautical Science, National Autonomous University of Mexico, Technical University of Berlin, German Space Agency, Santa Clara University, Arizona State University, Stanford University, China's Tsinghua University, University of Rome, and many others. More than half a

¹⁰¹ There doesn't appear to be a clear consensus in the literature over the exact value of these masses, but the order of magnitude is consistent.

¹⁰² Cáceres, Marco, "The Emerging Nanosatellite Market," *Aerospace America*, February 2001.

dozen additional nanosatellites built or owned by eight other American universities will likely be launched in 2001 or 2002.¹⁰³

While miniaturization has made micro-, nano- and picosatellites feasible, another reason for the recent growth in nanosatellite numbers is the recent availability of relatively low cost ELVs. One of these is the United States Air Force's Minotaur, which offers orbital and suborbital versions, and is made of its stockpiled Minuteman II ICBM engines and components of Orbital Science's Pegasus XL booster. The Minotaur had its first two launches, both successful, in 2000. Another is Ukraine's Dnepr, which is based on an adaptation of the SS-18 ICBM, a good use of the 150 missiles otherwise scheduled for destruction as part of the START Treaty.¹⁰⁴ Russia is also offering new low cost launchers, the Shtil and Start 1.¹⁰⁵ At essence, converted ballistic missiles (many slated to have been destroyed as a result of treaties), some of these new low cost ELVs are capable of launching a number of nanosatellites in addition to a larger primary payload for total per launch cost of about \$10 million.¹⁰⁶ This is far less than the costs of older, more established launchers such as Orbital Science's Pegasus or Taurus ELVs, and it enables launch fees for some nanosatellites of roughly a few hundred thousand dollars or less.

Besides universities, clubs, and well-established national space programs, past microsatellite successes coupled with new low launch costs are opening the doors for new customers to enter the space marketplace. Vietnam's National Center for National Science and Technology recently announced that, working with the British Surrey Space Research Center, it would build its own microsatellites within the decade to monitor Vietnam's natural resources and environment.¹⁰⁷ Algeria is also

¹⁰³ Ibid.

¹⁰⁴ www.kosmotras.ru/welrus2.htm.

¹⁰⁵ Cáceres, Marco, "The Emerging Nanosatellite Market," *Aerospace America*, February 2001.

¹⁰⁶ Ibid.

¹⁰⁷ "Vietnam Working With Surrey To Build Microsats," *SPACEDAILY*, February 14, 2001, www.spacer.com/news/vietnam-01a.html.

entering the microsatellite arena, working with the Surrey Space Research Center, to design, build, launch, and operate an Algerian microsatellite.¹⁰⁸

With the ranks of small satellite manufacturers growing, small satellites will likely become more and more inexpensive. Not long after successfully orbiting and operating an imaging microsatellite, the Tsinghua University Aerospace Center announced their intent to initiate a commercial enterprise. The primary revenue stream for the new business would be sales of microsatellites and a secondary revenue stream would come from selling images from its own orbiting microsatellites.¹⁰⁹ In doing so Tsinghua University will compete with the growing ranks of small satellite manufacturers such as AeroAstro, Amsat, Surrey, and Orbital Sciences. Tsinghua University also plans to develop and launch its first nanosatellite this year.

Very small satellites have been traditionally launched as secondary payloads “piggybacked” onto the primary payload, in an economical exploitation of a launcher’s excess capacity. A recent trend in the microsatellite market, however, is for a number of pico-, nano-, or microsatellites to be combined with a “host platform” or “mothership” that transports each satellite to its preferred orbit insertion point. This host platform may either be a mothership satellite or a special bus or expendable orbital transfer vehicle. This approach is particularly useful for constellations where neighboring orbits are nearby. There are some efforts to standardize these low cost host platforms to be compatible with a number of different launch vehicle interfaces. One such host platform is the Multiple-Payload Adaptor (MPA) built by the One Stop Satellite Solutions Company that integrates multiple satellites of 23 kg (50.6 lb) mass or less. AeroAstro’s SPORT (Small Payload Orbit Transfer) is a competing host but with considerable more on-orbit maneuverability and hence mission flexibility. Last year Aerospace Corporation

¹⁰⁸ “Surrey Wins Algerian Microsatellite Contract,” *SPACEDAILY*, August 17, 2000, www.spacer.com/news/microsat-00t.html.

¹⁰⁹ Long, Wei, “China Microsat Performs Well; Nanosat is Next,” *SPACEDAILY*, August 22, 2000, www.spacedaily.com/news/microsat-00u.html.

orbited two picosatellites, each about the size of a cigarette pack and weighing 0.25 kg (0.55 lb), using the Orbiting Picosat Automated Launcher (OPAL) constructed by students at Stanford University.¹¹⁰ SpaceDev Inc. has also announced their intent to develop a prototype orbital Maneuvering and Transfer Vehicle (MTV), test firing a small hybrid liquid-solid rocket engine in November 2000.¹¹¹

As these host platforms integrated become more available and more widely used, we may see a future trend of these integrated satellite payload packages becoming the primary payloads for ELVs rather than the usual current practice of smaller numbers of very small satellites being secondary, piggybacked payloads. Industry expert Marco Cáceres from the Teal group asserts that these developments will ease the deployment of pico-, nano-, and microsatellites in a very important way.¹¹²

“These (host platforms) could well be revolutionary types of technologies, in terms of the way they may expand both the number of satellites that could be launched and the number of players who compete in the satellite market. They could enable nanosatellite launches to increase from the current ten or so satellites per year to hundreds. If this happens, nanosatellites, along with microsatellites and picosatellites, could be the next major driver of the satellite market, perhaps during 2005 - 2010.”

In his article Cáceres states further that:¹¹³

“Under ‘conventional’ satellite market forecasts, which largely do not account for nanosatellites, the number of satellites projected to be built and launched over the next 10 years is roughly 1000, or an average of 100 satellites per year. With such low numbers, it is difficult to justify investing in costly and somewhat risky reusables.”... “With an

¹¹⁰ “Picosatellites: Small is Beautiful,” *The Economist*, February 4, 2000.

¹¹¹ “SpaceDev Successfully Fires First Rocket Motor,” *Business Wire*, November 16, 2000.

¹¹² Cáceres, Marco, “The Emerging Nanosatellite Market,” *Aerospace America*, February 2001.

¹¹³ *Ibid.*

energized micro-, pico- and nanosatellite market, the number of satellites could conceivably grow exponentially and create the kind of launch volume needed to make RLVs both profitable and affordable.”

The above assessments are important. Cáceres observes that the host platforms for very small satellites could very well be a disruptive product, a product that triggers revolutionary changes by greatly increasing the number of very small satellites launched as well as the number of competitors in the satellite marketplace. He also contends that this disruptive product may enable RLV commercial viability. Thus, host platforms may bring disruptive changes to both the satellite and the launch services worlds. A capable¹¹⁴ RLV is itself a disruptive product, one that will revolutionize the space launch industry. Thus, we may find that in this situation one disruptive product enables a second, and perhaps a third as outlined below.

Microsatellite Clusters

The Space Vehicles Directorate of the Air Force Research Laboratory (AFRL) and the Air Force Office of Scientific Research have both invested heavily in microsatellite technology development, and are especially interested in missions involving clusters of microsatellites that fly in formation in nearby orbits. AFRL plans to place a cluster of three experimental microsatellites in orbit in either 2003 or 2004 under the Technology Satellite of the 21st Century, or “TechSat 21”, program.¹¹⁵ This program will examine the feasibility of using clusters of small, independent satellites (about 120 kg or 264 lb each) to replace larger, single satellites for both military and commercial applications. Basic research is being conducted under TechSat 21 in such areas as precision formation flying, collaborative control, sparse aperture sensing, advanced thermal management, micropropulsion, and microelectro-mechanical systems (MEMS). MEMS technological progress is a particularly big driver of micro-, nano-, and picosatellite development in general, and is currently receiving much attention by space researchers.

¹¹⁴ One that delivers the promised single order of magnitude decrease in launch costs and multiple orders of magnitude increase in reliability and safety.

¹¹⁵ Wilson, J. R, “Satellite Clusters Reshape Space Plans,” *Aerospace America*, November 2000.

Replacing large single satellites with microsatellite or very small satellite clusters is analogous to the migration from mainframe to networked computers, according to AFRL program managers, and has the potential to significantly reduce mission costs and significantly increase flexibility. Microsatellite¹¹⁶ clusters could theoretically provide high versatility in communications and sensing applications, allowing large changes in aperture by merely changing spacing between the satellites. This would enable on-demand, reconfigurable missions for the military, providing valuable mission flexibility. Microsatellite clusters should also be far less vulnerable than their single satellite cousins; if one fails for whatever reason its function could be replaced either by an on-orbit spare, a quickly launched spare, or the remaining elements in the cluster. The latter option might result in somewhat degraded performance due to decreased aperture size yet the system would remain functional.¹¹⁷ Microsatellite clusters may also offer a much less expensive opportunity for performing upgrades. Engineers imagine a highly adaptable, networked system that can be reprogrammed with the replacement of only one or a few microsatellites rather than the entire system. Last, but perhaps most significantly, microsatellite clusters may result in large cost reductions for both users and satellite manufacturers due to economies of scale. Microsatellite clusters thus have the potential to be a disruptive technological innovation.

Space Tourism

The concept of high volume space tourism has been studied extensively.¹¹⁸ Many studies have shown vast, untapped national and world markets, with tens of

¹¹⁶ Or nanosatellite or picosatellite clusters.

¹¹⁷ Wilson, J. R., "Satellite Clusters Reshape Space Plans," *Aerospace America*, November 2000.

¹¹⁸ See for example:

Mueller, Hartmut, and Elingshausen-Bluhm, Martin, "Space Tourism - New Business Opportunities or a Remaining Fiction?" IAF Paper 98-1503, 49th International Astronautical Congress, Melbourne, Australia, September 28 - October 2, 1998;

Penn, Jay P, and Lindley, Charles A, "Space Tourism Optimized Reusable Spaceplane Design," Conference on Next Generation Launch Systems, Space Technology & Applications International Forum, STAIF-97, Albuquerque, NM, January 26-30, 1997;

Ashford, David and Collins, Patrick, *Your Spaceflight Manual – How You Could Be A Tourist in Space Within Twenty Years*, Headline Book Publishing Plc, London, U.K., 1990;

millions of potential space tourists all willing to pay significant percentages of their yearly income for the trip of their lifetime. In several of these imaginative studies giant fleets of RLVs whisk tourists hourly to giant orbital hotels, complete with space-based sports arenas, in scenes reminiscent of *The Jetsons*.¹¹⁹ Other studies portray a more modest level of consumer demand, yet sufficient to create a lucrative industry. All, however, are enabled only with RLV launch costs of a fraction of those of today's systems.

Of all the possible emerging markets for RLVs, space tourism is the most prominent and perhaps the most controversial. Receiving fervent support from a number of private citizens, professional associations, and Internet web sites, space tourism is heralded by many as the key emerging market segment that will create enough demand to enable profitable RLV development. With an investment of many billions of dollars, an orbit capable reusable launch vehicle could conceivably be developed, allowing orbital space tours to be offered from the start of commercial operations. However, due to the more probable evolutionary nature of vehicle performance capability due to both technology development and investment constraints, a more likely scenario is for a gradual expansion of space tour offerings from suborbital to orbital. In this model the first commercial offerings will be brief suborbital tours with duration of perhaps just a few minutes. As the launch vehicle's reliability and safety becomes established, media attention and word of mouth will increase demand and RLV service growth. Increases in revenues will allow for additional capital investments in research, development, and hardware, which in turn will increase RLV performance resulting in longer and longer suborbital tours. Eventually demand for orbital tours will prompt enough investment to develop an orbit capable RLV that is a derivative of the successful, proven suborbital version.

Reynerson, C, "A Space Tourism Platform Model for Engineering and Economic Feasibility," AIAA Paper 2000-5218, AIAA Space 2000 Conference, Long Beach, CA, 19-21 September 2000;

Fukada, Takahiro, "Japan Plans to Make Space Tourism Science Fact," *Houston Chronicle*, January 4, 2001.

¹¹⁹ A popular children's cartoon series that first aired in 1962.

Expansion in the on-orbit market will take place from initial multi-orbit tours each of a few hours¹²⁰ to extended stays, perhaps in some sort of space hotel.

Mueller and Elingshausen-Bluhm¹²¹ propose a similar incremental, long-term development of the space tourism industry in a 1998 conference paper, a rational and relatively conservative approach compared to some industry advocates. First, a suborbital RLV is developed, tested, and then used to open the suborbital tourism market. The RLV is later developed further into an orbit-capable system. While in its initial operational stage, a hotel module is attached to the International Space Station in the 2015 – 2020 timeframe, allowing for multi-day on-orbit stays of limited capacity. A separate 4000 unit orbital hotel is concurrently constructed and completed in 2020, accompanied by a large increase in “spaceliner” fleet size. Subsequent enlargements to the hotel increase its size and capacity, leading to a mature space tourism industry by 2030.¹²²

In the same work, Mueller and Elingshausen-Bluhm¹²³ also summarize and examine the results of a number of prior market research studies of space tourism. Past surveys and market analyses have estimated worldwide market potential for space tourism as high as \$25 to \$50 billion annually, corresponding to hundreds of RLVs transporting several million passengers to and from orbit each year. Price estimates in these studies range from on the order of \$5,000 per trip to over \$100,000. Segmentation of the market indicates consumers with high and very high incomes are the most likely to be able afford the steep initial prices for space tours. Wealthy space enthusiasts, extreme outdoor adventurers, and experiential adventurers will likely be the lead users. Later, as the reliability and safety record is established and the RLVs are made more comfortable, they will be followed by luxury tourists. Mueller and Elingshausen-Bluhm note that current luxury cruise

¹²⁰ It takes about 90 minutes for a spacecraft to circle the planet in a low Earth orbit.

¹²¹ Mueller, Hartmut, and Elingshausen-Bluhm, Martin, “Space Tourism - New Business Opportunities or a Remaining Fiction?” IAF Paper 98-1503, 49th International Astronautical Congress, Melbourne, Australia, September 28 - October 2, 1998.

¹²² Ibid.

¹²³ Ibid.

tours today successfully charge nearly \$100,000, and that about half that amount is sometimes charged today for certain extreme adventures.

One likely error in some prior market research studies of space tourism is the implicit assumption that just because a polltaker responds that she would hypothetically pay, for example, \$20,000 for a ticket for a three-hour space tour, it may be unlikely she would actually do so when offered the opportunity. In reality, perhaps only a fraction of respondents would actually do so, especially in the formative years of space tourism where vehicle reliabilities and safety risks are still being established. It seems that many people consciously or subconsciously enjoy considering themselves as adventurers, particularly in the hypothetical context of a poll.¹²⁴

A number of factors will challenge space tourism market diffusion, perhaps slowing it more than many advocates believe. First, the service is unfamiliar and unlike any other tourism offering. Although sure to pique the imagination, the concept of leaving the Earth's atmosphere behind may provide a psychological stumbling block for some consumers, especially, perhaps, the older generations who experienced the Apollo program, and equate spaceflight as a unique and risky occupation for an elitist astronaut corps. Then too, knowing that the deadly vacuum of space resides only a breached hull away may be frightening; movie and television productions have often shown us such dire consequences. Several times each year the U.S. public is exposed to real televised images of expensive, complex, and modern expendable launch vehicles exploding on their television screens. People "know" launch vehicles are experimental, risky, and hazardous. I still hear the old phrase, "It doesn't take rocket science to do this," almost every week. These beliefs are even more firmly entrenched by those recalling the disturbing, unforgettable visual scenes of the Space Shuttle Challenger disaster.

¹²⁴ Indeed, much of American advertising exploits this tendency. Consider, for example, commercials for sport utility vehicles (SUV) that exclusively depict these vehicles off-road, conquering mountains and undertaking other outdoor adventures. Yet it is well known that less than a couple of percent of all SUV owners in the U.S. actually ever leave a paved road with their vehicles.

Because of this attitude, market diffusion of space tourism is critically dependent upon the industry's safety and reliability records, not only for customer demand but also for financing. Note it is the industry's record, rather than merely one particular company's, that is so crucial for swaying public opinion. Hence it may be in the best interests of the industry to somehow establish and police some sort of industry safety and reliability standards, even beyond those imposed by the Federal Aviation Administration's licensing and certification processes. Such restrictions should be considered for even unmanned experimental RLV concepts that will be later evolved into passenger variants. One important study on space tourism stated that the requirement for overall safety will need to be at least 0.9999, that is to say a maximum of one accident involving fatalities out of every 10,000 flights. This overall safety is roughly 100 times that of the Space Shuttle (usually attributed to be 0.993, or 7 catastrophic accidents for every 1000 flights), and the same target NASA has set for its 2nd generation reusable launch vehicle, which intends to develop a Space Shuttle replacement with initial operations in 2012.¹²⁵ As a comparison, current expendable launch vehicles typically have demonstrated reliabilities ranging from only .90 to .98 (or from 2 to 10 catastrophic accidents for every 100 flights). The eventual goal is for at least the safety of a modern passenger jet with its demonstrated reliability of about .9999995 (1 catastrophic accident for every 2 million flights).

Public acceptance of a new space tourism business based on a new RLV concept will be obviously heavily influenced by the reputation of the company offering the service. As noted above, this reputation is influenced by the company's, as well by the overall industry's, safety and reliability records. Legitimacy concerns could also be a factor, particularly if a small entrepreneurial firm with no established brand image and little manufacturing or integration experience developed the RLV. Some legitimacy concerns could be mitigated if the small entrepreneurial firm

¹²⁵ "2nd-Generation Rocket Program Opens Doors at Marshall Center," *Federal Technology Report*, January 25, 2001.

contracts to established industry figureheads for at least all critical systems and subsystems, if not integration as well. RLV developer Kistler Aerospace is currently following this strategy, contracting with Northrop Grumman, for example, to fabricate vehicle structures. Other legitimacy issues that could also be significant are discussed in Chapter 6.

Space tourism enthusiasts acknowledge the existence of the “giggle factor” when discussing space tourism with the general public, but even more so with industry insiders. However, predicting the availability of advanced technology is notoriously difficult, often much to the amusement of hindsight observers. Sometimes it less amusing than disappointing; I, for one, had been looking forward to having androids clean my house, cook my meals, and do my laundry while I “tooled around” the skies in my convertible plane-car, all by the turn of the century. This, and many, other remarkable innovations were promised by innovators and various technology seers just a few decades ago. Under-exaggerations of technology advance are as common as over over-exaggerations it seems. “If man was meant to fly, he would have wings” so goes the common colloquial saying. In 1900, your great-grandfather may have uttered this and laughed at the thought of man being able to fly, yet in 1903 the Wright Brothers shattered that paradigm with their first and subsequent successful powered flights at Kittyhawk, North Carolina. As Ashford points out in *Your Spaceflight Manual*,¹²⁶ if your great-grandfather had observed the Wright Brothers’ more than 100 experimental flights in 1904, not one with a flight times lasting more than five minutes, your great-grandfather may have laughed again, this time at the thought of a commercial airline passenger service being established within his children’s lifetimes. Yet 10 years later the world’s first scheduled airline passenger service was established to fly customers from St Petersburg to Tampa, Florida.

Drastically lower launch costs than those of today are also critical for this industry to go far. According to NASA’s 1998 *General Public Space Travel and Tourism*

report, precursory business models show that profitability of large-scale space tourism businesses require launch costs in the range of \$1 to \$2 million per flight.¹²⁷ This is 200 to 500 times less than current Space Shuttle launch costs and even a factor of ten less than NASA's goals for its 2nd generation reusable launch vehicle, currently planned for initial operations in 2020.¹²⁸ Many critics of space tourism point out this level of costs may be unattainable for another 30 or more years; after all, launch costs have not decreased even a fraction of this amount over the past 20 or 30 years. On the other hand, this imposing problem doesn't mean a smaller-scale tourism business couldn't be profitable, particularly if the vast majority of any required technology maturation happened to be funded by the government.

Of course a plethora of other challenges too numerous to mention here would have to be overcome for RLV space tourism to become mainstream (e.g. RLV or space hotel design for protection from solar flares, micrometeorites and other space debris, artificial gravity and/or space sickness mitigation, certification, regulation, insurance, and environmental policy).

A common denominator in many of these studies is the very low estimated development cost for a very reliable, passenger carrying, orbit capable RLV, and in some cases for the space hotel facilities as well. Some studies assume the entire development costs including technology R&D (research and development) is accomplished by commercial enterprises alone, while others assume the government would pay for any required R&D. Many studies argued for venture profitability assuming a cost of capital of around 6%, approximately the rate of a government-backed loan. Eilingsfeld and Schaezler argue persuasively that these assumptions are not necessarily valid, that with the past history of government sponsored RLV development programs, the private sector is essentially on their

¹²⁶ Ashford, David and Collins, Patrick, *Your Spaceflight Manual – How You Could Be A Tourist in Space Within Twenty Years*, Headline Book Publishing Plc, London, U.K., 1990.

¹²⁷ O'Neil, Daniel Compiler, et al., *General Public Space Travel and Tourism - Volume 1: Executive Summary*, NASA Report NP-1998-3-11-MSFC, March 1998.

own.¹²⁹ In their study, Eilingsfeld and Schaetzler applied the standard financial CAPM (Capital Asset Pricing Model) to an example space tourism venture that had assumed a 6% cost of capital. Calculating the business risk index using recreational and luxury goods industry comparables led to an estimated cost of capital of 17.6% and economic infeasibility of the venture. Even this rate, I believe is intuitively low, perhaps out of sync with real and perceived technological, programmatic, and market risk. Regardless, Eilingsfeld and Schaetzler's work makes the following three valuable points:

- The cost of capital for a RLV space tourism venture is likely to be much higher than the frequently assumed cost of capital range of 6 - 7%.
- Several past space tourism studies showing emphatic profitability are actual negative net present value investments.
- Smaller, incremental space tourism projects (suborbital RLV tours) with their relatively small initial investment requirements are much more likely to be profitable.

A number of space tourism reusable launch vehicle concepts also suffer from design integrity or incorporate unrealistically ambitious, unprecedented technology maturation schedules. Penn and Lindley,¹³⁰ in contrast, present an excellent synopsis of a two-stage-to-orbit RLV design, focusing on the true critical design drivers – operability and operational costs, reliability, safety, and vehicle turnaround time - all via significant up-front, designed-in robustness and margin at the expense of performance and development cost. With an excellent overview of the technological drivers and with estimates for research, development, testing, and evaluation of \$10 billion in 1997 dollars, Penn and Lindley appear to have one of the most realistic designs in the literature.

¹²⁸ This date varies in the literature, quoted as 2012 as recently as December 2000 by NASA Marshall Space Flight Center program managers. This latest date is from "2nd Generation Rocket Program Opens Doors at Marshall Center," *Federal Technology Report*, January 25, 2001.

¹²⁹ Eilingsfeld, F, and Schaetzler, D, "The Cost of Capital for Space Tourism Ventures," IAA Paper IAA-00-IAA.1.4.02, Symposium on Economics and Commercialization of Space Activities, 51st International Astronautical Congress, Rio de Janeiro, Brazil, October 2-6, 2000.

Suborbital RLV Space Tourism Ventures

The Civilian Astronauts Corps (CAC, also known as Advent), located near Houston, Texas, wanted to build a floating RLV, tow it out into the Gulf of Mexico, tether it to the bottom of the sea, and launch it on a suborbital trajectory with a maximum altitude of 70 miles. Recovery of the reusable launch vehicle would have also been in the ocean, horizontally in the manner of a seaplane. CAC attempted to find 2,000 people willing to place a deposit for the four-minute suborbital flight at \$5,000 each, to help finance system development.¹³¹ The company succeeded in collecting about \$200,000 from 62 prospective passengers but went out of business in April 1999.¹³² Another entrepreneurial RLV developer, Vela Technology, is working with Seattle-based Zegrahm Expeditions to attempt to find customers willing to pay a \$5,000 deposit for suborbital flights costing \$98,000 per seat.¹³³ Interestingly, both companies acquired full-paying customers without even a vehicle to show them. An even more ambitious space tourism venture is being planned by the Japanese Rocket Society, a private organization that intends to establish a joint venture to develop a prototype RLV in 2004 with the help of a number of prominent Japanese entities, including Mitsubishi Heavy Industries Ltd, Sharp Corporation, Fujitsu Ltd, and Nissan Motor Company, Ltd. The Japanese Rocket Society plans to construct a fleet of 52 reusable launch vehicles and complete more than 1,200 test flights by 2015.¹³⁴

More "down-to-Earth" companies include SpaceX of Orlando, Florida, and Space Adventures of Fairfax, Virginia, who intend to offer short, zero gravity airplane flights similar to those used by NASA to train astronauts. Two well-known, experienced

¹³⁰ Penn, Jay P, and Lindley, Charles A, "Space Tourism Optimized Reusable Spaceplane Design," Conference on Next Generation Launch Systems, Space Technology & Applications International Forum, STAIF-97, Albuquerque, NM, January 26-30, 1997.

¹³¹ "Mayflower Sells Out Seven Flights," October 27, 1998, *SPACEDAILY*, www.spacer.com/spacecast/news/mayflower-98c.html.

¹³² "Space Tourism Company Shuts Down," *SpaceViews*, April 13, 1999, www.spaceviews.com/1999/04/13a.html.

¹³³ Hagood, Kathy, "Florida's Future in Space: Tourism Companies Ready to Go," *Florida Today*, 1997, www.flatoday.com/space/explore/special/floridasfuture/.

adventure travel companies, Omega World Travel and Quark Expeditions, back the latter company, who also offers rides on a Russian MiG-25 fighter aircraft.¹³⁵ A number of other similar adventure travel companies (e.g. Spacetopia, Incredible Adventures)¹³⁶ exist today that offer a combination of terrestrial adventure trips, zero gravity airplane flights, and future suborbital space tours.

Space Station Tourism

Space tourism has been featured prominently recently in the media. United States businessman and former NASA rocket scientist, Dennis Tito, had intended to visit the Mir space station sometime in 2001, negotiating a deal worth about \$20 million through MirCorp, a Holland-based firm established to initiate commercial ventures on board Mir. (According to CNN, two tourists paid millions of dollars each to visit Mir a number of years ago when the Soviet government controlled it.¹³⁷) Tito's trip to Mir was cancelled in late 2000, however, upon the decision to abandon Mir and initiate a destructive reentry into the Earth's atmosphere in February of 2001. Undeterred, the Russians have offered Tito a trip instead to the Russian module attached to the Alpha segment of the International Space Station in 2001 as a tourist. The price: about \$20 million to Russian coffers. Reactions to this announcement have varied considerably although U.S. Representative Ralph Hall, member of the House Science Committee, recently complained to NASA about NASA's apparent open consideration of the trip.¹³⁸ Citing the increased risk to the ISS of having a private citizen aboard, Hall called for NASA to clarify its position. Some argue that the precedent has already been set by the trips Ohio Senator John Glenn, Utah Senator Jake Garn, and Florida Congressman Bill Nelson have taken aboard the Space Shuttle at the cost to U.S. taxpayers of millions of dollars. Although sooner than intended, NASA chief Dan Goldin has more than once stated

¹³⁴ Fukada, Takahiro, "Japan Plans to Make Space Tourism Science Fact," *Houston Chronicle*, January 4, 2001.

¹³⁵ Hagood, Kathy, "Florida's Future in Space: Tourism Companies Ready to Go," *Florida Today*, 1997, www.flatoday.com/space/explore/special/floridasfuture/.

¹³⁶ www.spacetopia.com & www.incredible-adventures.com/dearadv.html.

¹³⁷ "U.S. Tourist Plans to Visit Mir by 2001," CNN.com, June 19, 2000.

¹³⁸ Berger, Brian, "Senior Democrat on House Science Committee Sounds Note of Opposition to Tito Flight," *Space News*, February 8, 2001.

NASA's intent to eventually turn the International Space Station over to private enterprises, even to be utilized as a space hotel.¹³⁹

Mr. Tito is not MirCorp's only customer eyeing the ISS. NBC also had plans with MirCorp – a television program called, "Destination Mir," where contestants were to compete for a visit to the Mir space station. Brainpower TV, a German television company, is also working with MirCorp for the International Space Station visits for winners of their own competition.¹⁴⁰

"Fast Freight" or Fast Package Delivery

"Fast Freight" or Fast Package Delivery refers to the nearly global delivery of packages in a mere few hours rather than overnight, a high-speed extension to today's one- and two-day delivery services that employ conventional jet aircraft. Candidate goods for this market include biological specimens and transplant organs, urgent and original documents, fresh delicacies, high-value inventory items, and critical manufacturing and assembly-line components.

Fast Package Delivery first appears in the literature in the 1994 NASA - Industry Commercial Space and Transportation Study that claimed the fast freight market could in itself economically justify development of an RLV system.¹⁴¹ This study proposed customer fees ranging from \$100 to \$1,000 per pound and market volumes ranging from 10 to 50 million pounds per year. Some follow-on studies have supported the economic viability of a suborbital RLV system to carry fast freight, although emphasizing the large uncertainty in market size.¹⁴² In a 1999 study, however, Martin et al. showed a bifurcation exists in the market and system requirements for Fast Package Delivery, with two separate flight system solutions

¹³⁹ "NASA Chief Calls for Space Commercialization," *Reuters*, 25 September 1999.

¹⁴⁰ Young, Kelly, "MirCorp Giving Up on Russian Station, Concentrating on Alpha," *Florida Today*, December 13, 2000.

¹⁴¹ Commercial Space Transportation Alliance, *Commercial Space and Transportation Study Final Report*, April 1994, NASA Report No. N95-25747.

¹⁴² Personal discussions with representatives from The Boeing Company and Econ, Inc., Kirtland Air Force Base, New Mexico, 1997.

best serving the market's and customers' needs.¹⁴³ The first system, for routine scheduled service, would be a Mach 2 – 3 aircraft similar to the recently cancelled High Speed Civil Transport. The second system, for on-demand chartered flight, would either be an RLV or a hypersonic cruise vehicle (presumably, a scramjet-powered Mach 6 aircraft) having the capability for operating out of conventional airports, with subsonic loiter, and quick turn around times. Furthermore, Martin et al. state that the business case for Fast Package Delivery can not support development of the RLV or hypersonic cruise vehicle due to the low production level and high amortization costs, suggesting instead joining the Fast Package Delivery and space transportation markets.¹⁴⁴

Initial introductions to the concept of Fast Freight Delivery often provoke vigorous skepticism. While the mere few, small studies on this subject to date should not be interpreted as concrete proof that a viable Fast Freight business case exists for RLVs or hypersonic cruise vehicles, they certainly point to an interesting potential that needs further study. It is an error, however, to dismiss this market out of hand; in its conceptual form, many also dismissed Federal Express's overnight delivery service,¹⁴⁵ yet it produced revenues exceeding \$8 billion per year by the mid-1990s.

Solar Power

Space based solar power generation offers a vast potential for an alternative, "clean," effectively inexhaustible energy source. Unlike a ground based solar power system that is limited by night and inclement weather, a space solar power system would have the capability to generate energy continuously. In addition, without the filtering effects of the atmosphere a space-based solar power system would receive significantly more solar energy than a ground based system. A large-scale solar power plant on Earth would furthermore be restricted to land availability, whereas a

¹⁴³ Martin, Jared, et al., "Scheduled vs. On-Demand Service for a Fast Package Delivery System," Conference on Next Generation Launch Systems, Space Technology and Applications International Forum, STAIF-99, Albuquerque, NM, January 31 - February 4, 1999.

¹⁴⁴ Ibid.

¹⁴⁵ Indeed, if one believes the legendary story circulating in graduate management schools today, the founder of Federal Express, Frederick W. Smith, Jr., received a "C" grade in his MBA business plan course for the overnight delivery concept due to a "nonexistent market".

space-based system would not. One key issue that may affect the feasibility of space based solar power plants is the transfer of power to the Earth's surface. Most studies have examined either microwave or laser beaming. The jury is still out, however, on the feasibility of either option due to atmospheric attenuation and the possibility that this attenuation could contribute to pollution or even global warming. A second key issue is the extremely high cost of space transportation for proposed solar power systems, some of which are several orders of magnitude heavier than today's satellites. The literature indicates that reducing launch costs to at least 1/20th of today's prices will be necessary to enable economic viability of a very technologically advanced, orbit-based, solar power system.¹⁴⁶

Satellite Salvage: Recovery, Repair, Maintenance, and Repositioning

While not likely to be a large market, satellite salvage may nonetheless be an important future market. Salvage operations might begin with the on-orbit recovery of a satellite, followed by repair or maintenance, and then either the return to Earth or the reinsertion of the satellite into a new orbit. An RLV working in concert with a reusable orbital transfer vehicle (ROTV) would probably provide the most effective means of conducting such operations: the ROTV would be able to transport satellites to and from the higher LEOs as well as MEOs and GEOs that the RLV would not be able to reach. One such ROTV concept is the Boeing Solar Orbital Transfer Vehicle concept currently being examined in the Air Force's Military Spaceplane Program.

NASA has successfully conducted commercial satellite salvage on a few occasions. Salvage operations conducted during two separate 1985 NASA Space Shuttle missions resulted in a partial recovery for insurers of over \$280 million in claims paid out for three satellites that had been stranded in low Earth orbit due to perigee-kick stage malfunctions.¹⁴⁷

¹⁴⁶ See, for example: Alpert, Mark, "Making Money in Space," *Scientific American*, March 1999.

A number of studies have also looked beyond satellite salvage to a state of routine, on-orbit, autonomous satellite maintenance including refueling and updating modular electronic black boxes. Such endeavors are apparently not financially viability, and are enabled only by a large drop in launch costs.

Space Based Manufacturing

The literature holds numerous promises of great wealth to be made by corporations using sizable manufacturing plants in space, especially for pharmaceuticals and certain materials. The only problem is that so far none of these promises have come true. A 1983 report for NASA by a panel of the National Academy of Public administration on encouraging business ventures in space technologies recommended more emphasis on all facets of NASA's program on materials processing in space due to its "large potential for commercialization."¹⁴⁸ Hertzfeld¹⁴⁹ notes that detailed business studies completed in 1978 predicted full-scale manufacturing operations in space as quickly as 1984. Seventeen years later we still don't manufacture anything in space. More importantly, no key products appear on the horizon.

The past few years have seen an increasing interest once again in manufacturing in space. The enthusiasm seems to build as the International Space Station takes form. Billed in the 1980s and 1990s as an ideal laboratory for commercial materials processing, proponents for ISS have claimed that research in space will lead to vast scientific and commercial payoffs. Yet little evidence for this can be seen from assessing the reams of scientific data obtained from research in space from the mid 1980s to the mid-1990s.¹⁵⁰ Beardsley¹⁵¹ observes that as of the 1996 no large

¹⁴⁷ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989, p. 97.

¹⁴⁸ National Academy of Public Administration, *Encouraging Business Ventures in Space Technologies*, Washington, DC, 1983.

¹⁴⁹ Hertzfeld, Henry R, "Economic, Market, and Policy Issues of International Launch Vehicle Competition," in *International Space Policy*, Papp, Daniel S, and John, McIntyre, R., Editors, Greenwood Press, Inc., Westport, Connecticut, 1987.

¹⁵⁰ Beardsley, Tim, "Science in the Sky," *Scientific American*, June 1996.

¹⁵¹ Ibid.

companies are planning major research or manufacturing projects on the ISS, an interesting fact considering the ISS had been under development since 1984. Alpert makes a compelling argument against the likelihood of competitive space-based manufacturing as follows:¹⁵²

“For a number of years NASA promoted the idea of space-based manufacturing, claiming that certain pharmaceuticals, semiconductor materials and other products could be manufactured with better quality in an orbital station than in an Earth-based factory. High launch costs have prevented most companies from considering the idea. But even if cheaper vehicles become available, very few products could be manufactured in orbit and sold profitably on Earth. Most products made in space simply would not be competitive with products made on the ground – in part because Earth-based manufacturing techniques are continually improving.”

The situation may be different now, however, due to significant NASA funding sponsorship of ISS research. Of current interest to some researchers are applications of crystal growth in space, particularly of proteins, as well as extremely thin coatings of polymers or semiconductors.

Other Markets: “Spontaneous Space”

Perhaps the most forward, “outside the box” thinking about emerging markets for space transportation can be found in the writings of Rick Fleeter, CEO of AeroAstro. Fleeter’s “Spontaneous Space” essay presents a number of interesting potential offerings including:¹⁵³

“- Loft a satellite to image an event on earth – an earthquake, volcano, or maybe a big traffic jam or rock concert in time for the evening news

¹⁵² Alpert, Mark, “Making Money in Space,” *Scientific American*, March 1999.

¹⁵³ Fleeter, Rick, “Spontaneous Space,” www.mindspring.com/~rfleeter/OLDSpontaneousSpace.htm.

- *Provide extended solar illumination to your farm in Florida or California's central valley, after sunset or before dawn, to speed harvesting for two days before a forecast frost*
- *Take a picture of traffic in a New Jersey neighborhood every five minutes during rush hour to figure out where to locate a new Dunkin Donuts*
- *Create a diversion before a critical military operation*
- *Make detailed photographic records of southern Florida the day before, and the day after, passage of a hurricane to verify that insurance claims are for actual storm damage"*

Certainly, a myriad of additional emerging market opportunities would appear if the price for launching payloads into low Earth orbit were to be reduced one or two orders of magnitude. Some of these applications will no doubt seem blatantly obvious to our children, or perhaps their children, and even provoke their chuckles that we were so oblivious.

Summary

In summary, there is an opportunity for explosive growth in the numbers of micro-nano- and picosatellites launched in the future due to (1) today's prevalence of relatively low cost, small ELVs, (2) the emergence of host platforms (or essentially small orbital transfer vehicles), (3) a multitude of new applications for small satellites flying in formation or clusters. In addition, this explosive growth may enable the commercial viability of RLVs, which if successfully developed should further fuel the growth in small satellites by providing much reduced launch costs. This positive feedback loop, or virtuous cycle, could be a major driver in growth in small satellites and RLVs.

A number of other emerging markets could also drive demand for reusable launch vehicles, perhaps even enabling development. Among these are space based manufacturing, satellite salvage or maintenance, solar power, space tourism, fast package delivery, or one or more of Fleeter's futuristic, but entirely plausible,

spontaneous space missions. Space tourism is one of the key missions for several current RLV entrepreneurial ventures. In fact, a common premise in the literature is that the demand for space tourism will be so high it will drive development of successive generations of lower and lower cost RLVs, breaking the current paradigm that space travel is only the venue of governments and their large aerospace contractors. Upon inspection, however, projected demand for space tourism seems very uncertain (some would even say dubious) and likely very sensitive to trip prices, launch costs, and other factors such as consumers' confidence in the service provider's competence and the safety of the firm's RLV fleet. Perception of the attractiveness of a space tour is possibly very unstable. One could imagine a venture-enabling portion of the market to vanish overnight – in the event of one or more disasters early on with one of the commercial ships or even with another launch vehicle, such as another shuttle disaster like the Challenger. Or perhaps advances in virtual reality or other entertainment technologies increase other entertainment options to the degree that interest in space wanes considerably. Despite its risk, space tourism could be a potent emerging market for reusable launch vehicles. In his study on design and market synthesis for space tourism, Kendrick ¹⁵⁴ concludes that space tourism will prompt development of a RLV system that will reduce launch costs to less than fifty dollars per pound to low Earth orbit. While typically derived from very optimistic data and often greeted by great skepticism, such predictions may indeed be eventually proven valid: space tourism could be the key to opening up low cost access to space.

Of course, market elasticity is a key economic factor driving future space launch demand. In their study on the macroeconomic benefits of low-cost RLVs, Shaw et al.¹⁵⁵ found that the low prices promised by future RLVs, of less than \$1000 per pound to LEO, may elicit a large elastic response from the marketplace, opening the doors for the entry of a number of new space-based businesses, such as space

¹⁵⁴ Kendrick, Rodney, "A Design & Market Synthesis for Space Tourism," AIAA Paper 2000-5161, AIAA Space 2000 Conference and Exposition, Long Beach, CA, September 19 - 21, 2000.

manufacturing and satellite servicing which are not profitable at today's launch prices. Market elasticity seems to be predicted to be especially large in this study and others for launch prices of around \$500 per pound to LEO.

¹⁵⁵ Shaw, Eric J, Hamaker, Joseph W, and Prince, Frank A, "Macroeconomic Benefits Of Low-Cost Reusable Launch Vehicles," IAF Paper 98-1403, 49th International Astronautical Congress, Melbourne, Australia, September 28 - October 2, 1998.

4. Space Transportation Supply: Expendable Launch Vehicles

This chapter presents an overview of current expendable launch vehicle development programs as well as recent entrants to the ELV market over the past few years. The chapter also examines a number of small, private, entrepreneurial ELV ventures that failed, as well as an overview of the supply of expendable launch vehicles.

Supply Overview

Especially at the beginning of the space age, the primary motives for countries to engage in space exploration have been national security and national prestige. Other factors, such as keeping a skilled labor force employed and maintaining an advanced scientific and engineering research and development capability, were also considered and perhaps have become more important with time. From exclusively public beginnings, space launch has only gradually and partially become commercialized and privatized; many launchers remain today under the control of their governments which offer commercial launch services at heavily subsidized rates. Thus, the supply-side of space launch transportation has to date been dominated by the public sector, and due to the existence of numerous daunting barriers to entry there is no reason to believe this will change in the near future. Public sector research and development investments in current space launch systems are sunk costs, and they will be incurred over and over again by nation after nation as new governments strive to acquire their own space launch capability. As nations competed for military might and prestige based on naval fleet size hundreds of years ago, so do some countries today strive to belong to the "elite" club of space-faring nations. North Korea, for example, alarmed much of the world in August 1998 with their launch of the Taepo Dong 1 ballistic missile, claiming to have orbited the country's first satellite. (Interestingly, a number of Western analysts and satellite experts debated the validity of this claim, noting the launch but neither able to find evidence of a satellite in the orbital parameters given by the North Koreans, nor able

to hear any of the satellite's audio transmissions - revolutionary hymns and Morse code signals).¹⁵⁶

Since the public sector developed the systems, it is important to realize that making a profit is not the most important consideration for many suppliers of space launch vehicles. Indeed, making a profit may be impossible for most launch systems, especially if development and infrastructure costs need be amortized (see this chapter's Ariane 5 discussion). Direct and indirect government subsidies are therefore a way of life in this business, not a temporary manifestation. In the future additional governments will almost certainly develop their own space launch capacity and will probably offer commercial services regardless if a profit can be had. Market economics will therefore drive the number of launcher types and quantities but not below a certain minimum capacity. Only very recently have ELV services offered by private enterprises provided substantial competition to government owned launch vehicle systems. Even so, every operational space launch system to date was developed at least in part in part through government subsidies. The current wave of private ELV and RLV entrepreneurial development efforts are attempting to challenge this paradigm.

Key Players & Rivalry

Global Competition & Overcapacity

Major players in the space launch industry are The Boeing Company, Lockheed Martin Corporation, Orbital Sciences Corporation, Arianespace (a France-based consortium of 50 companies), Russia's Kunichev, Russia's Starsem, Ukraine's Yuzhnoe, and China's Great Wall Industries Incorporated. Several minor players also exist who have the potential to substantially increase their market share, such as Japan and India.

¹⁵⁶ "North Korean Space Guide," World Space Guide, FAS Space Policy Project, www.fas.org/spp/guide/dprk/index.html.

The number of launch systems offered today is higher than at any other time in history. Recent growth in the number of new launch vehicles is also historically large. In last decade or so many new vehicles have arrived on the international market including, Arianespace's Ariane 5, Lockheed Martin's Athena, LMLV-1, Titan IV-B, and Atlas III, Eurockot's Rockot, Boeing's Delta III, Japan's H-2 and M-5, China's Long March CZ-3B, Orbital Science's Pegasus XL, Russia's Proton M, and Sea Launch's Zenit 3SL.¹⁵⁷ Market entry of Russian, Ukrainian, and Chinese ELVs was accompanied by United States government restrictions on the number and prices of their launches. Presumably, this was to limit predatory pricing that could limit U.S. firms from investing in development of new launch vehicles or upgrades to existing ones.¹⁵⁸

The space transportation industry is currently suffering from heightened global competition and overcapacity. The high level of international competition is obvious by a quick scan of a compilation of the vehicles launched last year with their respective providers, as seen in Table 2, from the Space Transportation Association's Complete Launch Log for 2000.¹⁵⁹

Table 2 Space Launch Vehicles Launched During Year 2000

Vehicle Provider	Launch Vehicles (and variants) Launched in 2000
Lockheed Martin	Atlas 2, 2A, 2AS, 3
Starsem	Soyuz-Fregat
Arianespace	Ariane 4, 42L, 44LP, 505, 506, 508
China Great Wall Industry Co.	Long March 3A, 3, 4B
Orbital Sciences	Minotaur, Taurus, Pegasus XL
Russia	Soyuz-U, Proton, Proton K, Eurockot Rockot, Cosmos 3M, Soyuz-U, Start-1, Tsiklon 3
Ukraine	Zenit-2
Boeing	Delta 2, 3
Japan	M-5

¹⁵⁷ Cáceres, Marco, "Why Space Mishaps Are On The Rise," *Aerospace America*, July 2000, p. 18.

¹⁵⁸ World Technology Division, *Global Satellite Communications Technology and Systems*, International Technology Research Institute, December 1998.

¹⁵⁹ The Space Transportation Association, "Complete Launch Log for 2000," www.spacetransportation.org.

NASA	Space Shuttles (Endeavour, Atlantis, Discovery)
International Launch Services	Proton, K, DM
Sea Launch	Zenit 3SL
USAF	Titan 2, 4B, Delta 2, Atlas 2AS
Russian Ministry of Defense	Proton
China	CZ-4B
ISC Kosmotras	Dnepr

United States satellites and launch services are purchased by many foreign countries, making this U.S. industry a large contributor to the U.S. trade balance. In the free world, the United States had nearly a monopoly in launch services for decades and still controlled the world's commercial launch business as late as the mid-1980s. Today, however, the U.S. portion of the world's commercial market has been eroded to somewhere between 30 - 50%, roughly equal to that held by Arianespace's Ariane rocket system alone. Although the literature is not entirely consistent on market shares, a recent industry analysis attributes market share as follows: Arianespace - 30%, Boeing - 20%, Krunichev - 18%, and Lockheed Martin – 15%.¹⁶⁰ (Others give Arianespace's share in 2000 at 50%).¹⁶¹ Thus, approximately 83% of the world's market share is controlled by only 4 organizations. This competition is only heating up. Ukraine, Russia, China, Japan, Israel, Brazil, and India already have, or are in the process of developing, expendable launch vehicles of which many are offered commercially. In addition, at least 15 entrepreneurial firms are also diligently working to develop their concepts, hoping to enter the fray in the next few years. Almost all of these concepts are reusable launch vehicles, which the entrepreneurs generally claim will reduce launch costs by 25% to 90% compared to current systems. Overall, competition has increased dramatically in the commercial launch market, reducing industry profits substantially.

With some of the highest launch fees in the world, the U.S. space launch industry has retained significant market share in the face of lower price foreign competition.

¹⁶⁰ Friedman, Robert E., "Standard & Poor's Industry Surveys: Aerospace & Defense," August 10, 2000.

¹⁶¹ Pirard, Théo, "Conversations with Françoise Bouzitat," *Aerospace America*, November 2000.

Some attribute this to the United States having historically higher launch vehicle reliabilities, an important competitive advantage in an industry that experiences a very high launch failure rate.¹⁶² A rash of U.S. launch vehicle catastrophes over the past few years coupled with lower launch prices and vast improvements in many foreign systems has seriously eroded this advantage, although very recent U.S. and foreign partnerships might be reversing this trend.

The challenge to the space transportation industry on the current global overcapacity of space launch services was noted by Francois Auque, the executive vice president of EADS (European Aeronautic Defense and Space company) in a recent interview with *Aerospace America*.¹⁶³ Auque noted the need to “streamline the global European system to make it more efficient” and that “the general trend is clearly to reduce costs...” Interestingly, Auque added that EADS is “convinced there is room for transatlantic cooperation” in the launch services arena. This was a curious comment in so much that Europe and the United States currently have a very high level of rivalry in space launch, and highly competitive and not easily absorbable launch vehicle families. In contrast, a recent interview with Françoise Bouzitat, secretary general of Arianespace, mentions the possibility of further European cooperation in the ELV arena to increase global competitiveness. Last year, for example, the Arianespace board agreed to pursue the strategy of arranging joint ventures with Starsem and Eurokot in order to acquire the ability to market a full range of launch services, all under a European label.¹⁶⁴ Arianespace currently offers only heavy lift launch services with its Ariane 4 and Ariane 5 ELVs. France-based Starsem, established in 1996, is a European-Russian company that provides reliable and proven Russian Soyuz rocket launch services to the commercial market, while Eurokot Launch Services GmbH is a joint venture of Germany’s Astrium GmbH and Russia’s Khrunichev State Research and Production Space Center to launch

¹⁶² Friedman, Robert E., “Standard & Poor’s Industry Surveys: Aerospace & Defense,” August 10, 2000.

¹⁶³ David, Leonard, “Conversations with Francois Auque,” *Aerospace America*, January 2001.

¹⁶⁴ Pirard, Théo, “Conversations with Françoise Bouzitat,” *Aerospace America*, November 2000.

commercial ELV derivatives of the highly reliable Russian SS-19 ICBM.¹⁶⁵ In response to the interviewer's question of who is Arianespace's most serious, current rival, Bouzitat responded,¹⁶⁶

"Arianespace's most challenging (current) competitors are the U.S. companies that are marketing competitive rockets produced in Russia and Ukraine."

As another sign of the current competitive climate, both ILS and Boeing reportedly have announced their goal of each acquiring 50% of the worldwide market for launch services, a direct challenge to Arianespace.¹⁶⁷

The revenue model for launch services has also changed, reflecting the increased competition in the industry as well as the trend away from single satellite customers and towards satellite constellations. Instead of the traditional ordering of a single launch at a time, the trend over the past few years has been for satellite manufacturers and service providers to purchase blocks of options, a much more lucrative option for many launch companies.

New Entrants into the ELV Market

A number of new expendable launch vehicles have entered the market over the past few years, helping to create the greatest overcapacity of launch services ever. This section takes a brief look at some of these new ELV entrants.

United States Air Force, Boeing, & Lockheed Martin - EELV

The Evolved Expendable Launch Vehicle (EELV) program is a partnership between the United States Air Force (USAF) and industry to develop two new national launch systems, the Atlas V with Lockheed Martin Corporation and the Delta IV with The Boeing Company, to replace existing Atlas, Titan, and Delta ELV

¹⁶⁵ www.starsem.com & www.eurockot.com.

¹⁶⁶ Pirard, Théo, "Conversations with Françoise Bouzitat," *Aerospace America*, November 2000.

¹⁶⁷ Pirard, Théo, "Conversations with Françoise Bouzitat," *Aerospace America*, November 2000.

fleets. Consistent with its name, EELV development is evolutionary, focusing on standardizing or consolidating launch vehicle manufacturing processes, procedures, support equipment, and infrastructure, leveraging many existing, well-proven technologies and system components. The overall goals of the program are to provide medium and heavy lift expendable launch vehicle families that will reduce launch costs by at least 25% from current levels, as well as to strengthen the U.S. space launch industry.

The reduction in launch costs should be realized by the EELV program largely by means of two significant design innovations: standardization of launch vehicle-payload integration interfaces and standardization of the booster cores. The former includes standardized specifications for environmental, mechanical, and electrical launch vehicle-payload interfaces, greatly reducing the effort of integrating payloads into the launch vehicles, as well as allowing for rapid switching of payloads between the EELV boosters. These design innovations should significantly reduce manufacturing, assembly, payload integration, and launch operations costs, and helped the program office win the 1999 Defense Standardization Program National Honorary Award. Largely due to these innovations, the EELV program is expected to save DoD an estimated \$5 to 7 billion in launch costs over the next two decades.¹⁶⁸

The USAF began the first phase of the EELV program in 1995, funding competitive preliminary design and risk reduction demonstrations by Alliant Techsystems, The Boeing Company, Lockheed Martin Corporation, and McDonnell Douglas Aerospace. These four \$30 million contracts were completed by late 1996, and the program down-selected into the second program phase, retaining Boeing and Lockheed Martin to conduct \$60 million, 17 month efforts to refine their launch system concepts and complete a detailed system design.¹⁶⁹ The program initially intended to select one of the two competing contractors and fund the development of

¹⁶⁸ Summerall, Tonya, 1st Lt., "EELV Program Saves Money," *SPACEDAILY*, July 3, 2000.

¹⁶⁹ www.laafb.af.mil/SMC/MV/eelvhome.htm.

their new launch system. Due to the very positive market outlook in 1997, however, and in order to take better advantage of competition, the EELV program was restructured mid-stream, resulting in USAF cost sharing on both new launcher developments rather than acquiring only one, to the tune of about \$500 million each to Lockheed Martin and Boeing for engineering and manufacturing development.¹⁷⁰

The EELV program was again modified in 2000 due to the rapidly changing launch market. Reacting to last year's waning commercial launch market, the EELV program released Lockheed Martin from its commitment to build an Atlas V launch pad on the U.S. Western Range at Vandenberg Air Force Base, California. Under the new plans, Boeing will launch its medium and heavy lift Delta IVs from both the Eastern Range (Cape Canaveral Air Force Station, Florida) and Western Ranges, but Lockheed will only launch medium lift Atlas Vs from the Eastern range. In addition, Lockheed agreed to complete qualification of its heavy lift Atlas V, but does not intend to fly unless called upon by the Department of Defense (DoD) to back up Boeing's heavy lift EELV.¹⁷¹ When online, the EELVs will constitute DoD's sole source of medium to heavy lift expendable launch vehicles.

The first (demonstration) launches of the medium lift and heavy lift EELVs are scheduled for 2002 and 2003, respectively.¹⁷² In order to help reduce risk the USAF will fund the first heavy lift Delta IV launch, paying Boeing \$141 million to launch a simulated payload.¹⁷³ Reportedly, a Broad Area Review into past launch accidents recommended the Air Force consider using commercial launch insurance for some future EELV flights.¹⁷⁴ The Air Force has never utilized commercial launch insurance in the past, but could adopt the practice depending on the success of the first few EELV launches. A possible complication is the typical requirement by the

¹⁷⁰ McKinney, Col. Richard W, et al. "EELV Meets CAIV." *Aerospace America*, May 1999, p. 68.

¹⁷¹ Mason, James, "Launching Into," *Flight International*, December 19, 2000, p. 32.

¹⁷² www.laafb.af.mil/SMC/MV/eelvhome.htm.

¹⁷³ Mason, James, "Launching Into," *Flight International*, December 19, 2000, p. 32.

¹⁷⁴ Wall, Robert, "EELV Outlook Impacted by Weakness In Commercial Launch Market," *Aviation Week & Space Technology*, July 3, 2000.

insurer for both launch vehicle and payload information data; the security classification of some of the EELV missions would not allow this information to be given to insurers, particularly since they are generally foreign firms.

India – PSLV, GSLV

India entered the commercial launch service marketplace in May 1999, launching small research satellites for South Korea and Germany with the Indian Space Research Organization's (ISRO) Polar Satellite Launch Vehicle (PSLV).¹⁷⁵ The PSLV is a four stage ELV that uses a combination of solid and liquid-propellant stages as well as several strap-on boosters. ISRO also plans to soon enter the geosynchronous orbit commercial launch market with their Geostationary Satellite Launch Vehicle (GSLV), scheduled for a first launch in 2001. ISRO stated recently that they would eventually offer commercial launch services at a cost about 25% lower than available anywhere else.¹⁷⁶

Arianespace – Ariane 5

Arianespace is arguably the most dominant player in the space launch industry and their new Ariane 5 heavy lift launcher should continue this trend. Currently in a transitional phase between the Ariane 4 and the fully operational Ariane 5, Arianespace was very successful in wresting market share from U.S. launch service providers in the 1980s and 1990s and is currently a very tough competitor. In 1997, for example, Arianespace owned over 50% of the world's commercial market versus the U.S.'s 30% share. The first commercial launch of the Ariane 5 occurred in December 1999. The Ariane 5 ELV is capable of launching up to about 40,000 lb into LEO, and 15,000 lb into GTO.

The Ariane ELV family was the first ever designed purely for commercial operations. As a result, Arianespace's efficiency of launch operations is impressive.

¹⁷⁵ "India Marks First Commercial Launch," *SpaceViews*, May 26, 1999, www.spaceviews.com/1999/05/26a.html.

¹⁷⁶ "Indian Space Research Organization (ISRO)," *Aerospace Daily*, Vol. 197, No. 24, p. 208, February 7, 2001

While each Ariane is integrated and launched in roughly three weeks, for example, American competitors habitually take four to six weeks, and in many cases use about twice as many personnel in doing so. Arianespace also typically launches a dozen or more times per year, a pace unmatched by any other competitor in the world and a fundamental reason why Arianespace is so successful. More frequent launch opportunities provides more schedule freedom for customers who may otherwise have to pay many months of interest on huge capital investments before being served. More frequent launches also translates into higher manufacturing and operational economies of scale.

As a heavy lift launch vehicle of GTO services, Arianespace has the competitive advantage of a launch facility located in Kourou, French Guiana, near the equator. (Equatorial launches to GTO are far more efficient than those from higher latitudes due to their maximum utilization of the Earth's rotational speed). This allows an Ariane ELV to carry heavier payloads, a boon to the communication's industry that has consistently demanded bigger and more capable GEO satellites over the last few decades. Unlike the U.S.'s two primary launch sites, the Eastern Range out of Cape Canaveral Air Station in Florida, and Vandenberg Air Force Base in California, Kourou is a commercially constructed and commercially operated spaceport. By not sharing the spaceport with other companies, Arianespace must pay a higher fee per launch to pay for the facilities. However, unlike the primary American spaceports that are owned by the United States government, Ariane does not suffer high costs associated with launch pad logjam. Demand to use the launch facilities at Cape Kennedy is so high at times if a launch is cancelled due to technical problems or bad weather, its two-day launch slot might expire, forcing the launch vehicle to be removed from the launch pad and delaying the launch for days or even weeks before another slot can be scheduled.¹⁷⁷

¹⁷⁷ Suriano, Robyn. "Florida's Future in Space Arianespace is Big Threat to The State." *Florida Today*, 1997. www.flatoday.com/space/explore/special/flordasfuture/

ESA's cost to develop the Ariane 5 ELV for Arianespace, including required spaceport infrastructure, has been estimated at \$9 billion. Fortunately for Arianespace, ESA's investment is free and thus is essentially a large subsidy. As pointed out by the WTEC (World Technology Division, International Technology Research Institute) panel in their *Global Satellite Communications Technology and Systems*, December 1998 report,¹⁷⁸ such a large investment would likely exclude purely commercial companies from competing in the heavy lift segment of the space launch industry; amortization of these funds even with a very low cost of capital of 10% or 15% would add roughly \$90 to \$110 million per launch, causing the system to be unaffordable to customers. Furthermore, it took about twelve years for ESA to develop, test, and make the Ariane commercially operational. Such a long development time without revenue streams may be prohibitively costly for private ventures.

The upgrade from Ariane 4 to Ariane 5 was almost entirely a performance improvement, an increase in payload mass capability, rather than a cost reduction. This focus on increasing performance instead of reducing costs appears to be the normal growth strategy for ELVs. WTEC observes further that if it is necessary to depend on government subsidies to fund performance enhancements via development of derivative heavy lift ELVs, it is almost even more certainly required to fund a more heavily modified ELV variant that incorporates significant operational cost reductions.¹⁷⁹

In a recent interview Françoise Bouzitat, secretary general of Arianespace, was asked why Arianespace was pressing ESA member states for additional investments to upgrade Ariane 5's performance in the near future, especially with Ariane 5's already impressive performance. Her response was that Arianespace sees stable future GEO market of about 25 to 30 satellites annually. However, due to current growth trends in GEO satellite weight, Arianespace expects to eventually need the

¹⁷⁸ World Technology Division, *Global Satellite Communications Technology and Systems*, International Technology Research Institute, December 1998

capability to place 7 (metric) ton satellites into GTO. Thus, in order to continue their cost effective practice of launching two or more satellites at a time, the company is already working on Ariane 5 upgrades to 10 tons to GTO by 2002 and 12 tons by 2005 - 2006 timeframe.¹⁸⁰

Brazil - VLS

Brazil established a space program in the early 1960s and over the last four decades has developed four sounding (suborbital) rockets and one small, orbital ELV, the Satellite Launching Vehicle (VLS). The VLS is designed to orbit payloads of up to approximately 840 pounds. Both test flights of the VLS have failed, the first in November 1997, and the second in December 1999. A 1997 report said that the VLS's price tag was only \$6.5 million, which would be very competitive if system problems can be corrected.¹⁸¹ Like the Ariane, the VLS also takes advantage of a well-situated launch site near the equator.

Japan - H-2A

Japan's NASDA (National Space Development Agency) is trying to build a viable commercial launch business with their development of the H-2A system, a derivative of their problematic and very costly H-2 ELV. Before the H2 program was cancelled following a catastrophic launch failure in late 1999, each flight cost about \$170 million. In order to successfully compete in today's market, it is estimated that the H2A will have to be able to offer launches for \$100 million or less.¹⁸² Despite NASDA's efforts to reduce costs, however, H2A launches are expected to be expensive due to the relatively high value of the yen compared to the dollar, low production volumes, and mixed success of several cost reduction programs. One cost cutting option being considered by NASDA is to purchase components from U.S. companies rather than produce them domestically. This option might not be

¹⁷⁹ Ibid.

¹⁸⁰ Pirard, Théo, "Conversations with Françoise Bouzitat," *Aerospace America*, November 2000.

¹⁸¹ "Brazil's First Space Rocket Falls Into Sea," CNN, November 3, 1997, www.cnn.com/TECH/9711/03/brazil.rocket/.

¹⁸² Kelly, Emma, "Engine Problem Forces H2A Launcher to Delay First Flight," *Flight International*, December 5, 2000, p. 35

exercised, as it is against Japan's prior strategy of trying to independently develop a self-sufficient, indigenous launch business.¹⁸³

Hughes (now Boeing Satellite Systems) and Loral have each placed orders for 10 H-2A rockets to launch large communications satellites, in order to diversify their suppliers of launch services.¹⁸⁴ Since then, technical problems with the Mitsubishi LE-7A first stage engine have delayed the first flight of the H2A from February 2001 until at least summer.¹⁸⁵

Sea Launch, Inc. - Zenit-3SL

Sea Launch, the only ocean-based launch service company, provides commercial heavy lift launch services with the Zenit-3SL ELV from an equatorial launch platform in the Pacific Ocean. Sea Launch is an international partnership composed of Boeing Commercial Space Company, Russia's RSC Energia, Ukraine's SDO Yuzhnoye/PO Yuzhmash, and Norway's Anglo-Norwegian Kvaerner Group.¹⁸⁶ Boeing, with 40% ownership, is responsible for overall integration and operations management. RSC Energia has a 25% share and provides an upper stage as well as launch vehicle integration and mission operations. SDO Yuzhnoye/PO Yuzhmash holds a 15% share and provides the first two rocket stages, launch vehicle processing and operations. Kvaerner Group, with a 20% share, provides operational services for the launch platform it converted from an oil-drilling rig and for the assembly and command ship. Although Sea Launch's equatorial launch site provides a competitive advantage for the company, it may be offset somewhat by the significant logistics and transportation challenges.

Sea Launch's inaugural flight took place in March 1999, and its first commercial flight occurred in October of that year. Although both flights were successful, Sea

¹⁸³ Ibid

¹⁸⁴ Davis, Neil, "Japan Strives to Fix Space Program," *Aerospace America*, June 2000

¹⁸⁵ Kelly, Emma, "Engine Problem Forces H2A Launcher to Delay First Flight," *Flight International*, December 5, 2000, p 35

¹⁸⁶ www.sea-launch.com

Launch's third flight in March 2000 ended in failure. Subsequent commercial launches in July and October 2000 and March 2001 were successful.

USAF - Orbital Suborbital Program Space Launch Vehicle (Minotaur)

The Orbital Suborbital Program Space Launch Vehicle (also known as the "Minotaur") was developed for the USAF to provide a low cost, reliable space launch capability to support United States government small-satellite launches.¹⁸⁷ The four-stage Minotaur is made of a combination of the Minuteman II ICBM and the Orbital Science Corporation's Pegasus XL launch vehicle, with the M-55A1 and SR-19 Minuteman II rocket motors forming the first two stages, and the Orion 50 XL and Orion 38 Pegasus XL rocket motors forming the third and fourth stages, respectively. A Pegasus payload fairing is also utilized.¹⁸⁸

The Minotaur is integrated by Orbital Science Corporation, and can launch as much as 750 lb into LEO. The development of the Minotaur was designed to incorporate most of the development risk in the first mission, to be followed by lower cost, routine launch operations. The cost of the first Minotaur launch was \$23 million; follow-on launches are estimated to cost about \$13 million.¹⁸⁹ To date, there have been two successful launches, the first in January 1999, and the second in July 2000. The first Minotaur launch was reportedly the first ever U.S. rocket launch from a privately-owned commercial spaceport in the United States (operated by Spaceport Systems International, a limited partnership of ITT Industries, Inc. and California Commercial Spaceport.)¹⁹⁰

Eurockot Launch Services GmbH - Rockot

Eurockot Launch Services GmbH is a joint venture of Germany's Astrium GmbH and Russia's Khrunichev State Research and Production Space Center, with 51%

¹⁸⁷ USAF Fact Sheet, The OSP Space Launch Vehicle ("Minotaur"), www.losangeles.af.mil/SMC/PA/Fact_Sheets/minotaur_fs.htm

¹⁸⁸ Ibid

¹⁸⁹ Serra, Jean-Jacques, "Minotaur," *The Satellite Encyclopedia*, www.tbs-satellite.com/tse/online/lanc_conestoga.html

¹⁹⁰ Ibid

and 49% shares, respectively. The Rockot is an adaptation of the highly reliable Russian SS-19 ICBM, which has been flight-tested over 140 times, according to the company's web site, and can launch about 4200 pounds to LEO.¹⁹¹ A "Commercial Demonstration Flight" in May 2000 was a success, and the first commercial flight is scheduled for fall of 2001.

Starsem - Soyuz

France-based Starsem, established in 1996, is a European-Russian company that provides reliable and proven Russian Soyuz rocket launch services to the commercial market. Starsem is responsible for commercial marketing, sales, and operations of the Soyuz ELV family, and its first six commercial launches were all conducted in 1999. In June of 2000 Starsem shareholders were Aerospatiale Matra (35%), Ariespace (15%), the Russian Aeronautics and Space Agency (25%), and the Samara Space Center (25%). That month Starsem and Eurockot Launch Services announced they had formed a strategic partnership coordinating their marketing and development activities. This alliance followed the establishment of the European Aeronautics, Defense, and Space Company (EADS), formed by the merger of several European companies including Aerospatiale Matra, a 35% stockholder in Starsem, and Daimler Aerospace (now Astrium GmbH), a 51% stockholder in Eurockot.¹⁹² The partnership was also related to a decision by Ariespace to support a combined Rockot, Soyuz, and Ariane 5 launch vehicle family that could cover almost any customer's needs in the light, medium, and heavy lift categories, respectively.

To date, Starsem has invested some \$100 million to upgrade launch and payload facilities at Baikonur in Kazakhstan to accommodate customers, and to aid development of the new Soyuz ST version. Starsem's CEO and chairman, Jean-Yves Le Gall, stated in a recent interview that the company hoped to be profitable

¹⁹¹ www.eurockot.com.

¹⁹² www.starsem.com/news/release.htm.

within four years.¹⁹³ The demonstrated reliability of the Soyuz rocket (last failure occurred in 1996), its high flight rate (more than one per month), and its relatively short preparation time (about two months) are all sources of competitive advantage for Starsem. Le Gall notes that the unmanned Soyuz rockets are manufactured with the same level of quality as that of the manned version, resulting in a marketing advantage.¹⁹⁴

Microcosm – Scorpius

Microcosm is a small business specializing in reducing space mission costs through several products ranging from control systems to space qualified torquers.¹⁹⁵ Established in 1984, Microcosm is currently developing the Scorpius family of very low cost, responsive ELVs with a wide range of payload / performance capability, from suborbital rockets with 200 lb payloads to heavy lift ELVs capable of placing 160,000 lb to LEO.¹⁹⁶ Program focus is on low-cost technology and simplified vehicle design with the goal to transform space launch from its current high-risk, high cost, and long lead time paradigm to a low cost, responsive, normal occurrence. Microcosm has conducted at least two successful suborbital flight tests to date, including the Scorpius SR-S in January 1999, and Scorpius SR-XM in March 2001. An earlier September 1998 test of the SR-S was seriously damaged in an aborted launch accident in which the rocket caught fire.¹⁹⁷

The Air Force Research Laboratory funded the early development of the Scorpius suborbital ELVs under Small Business Innovation Research contracts. NASA, the Ballistic Missile Defense Office, the Air Force, and Congressional plus-

¹⁹³ Pirard, Théo, "Conversations with Jean-Yves Le Gall," *Aerospace America*. April 2001.

¹⁹⁴ Ibid.

¹⁹⁵ www.smad.com/about/profile.html

¹⁹⁶ Berry, James V., Conger, Robert E., and Wertz, James R., "The Sprite Mini-Lift Vehicle: Performance, Cost, and Schedule Projections for the First of the Scorpius Low-Cost Launch Vehicles," SSC99-X-7, 13th Annual AIAA/USU Conference on Small Satellites, www.smad.com

¹⁹⁷ Berry, James V., Conger, Robert E., and Wertz, James R., "The Sprite Mini-Lift Vehicle: Performance, Cost, and Schedule Projections for the First of the Scorpius Low-Cost Launch Vehicles," SSC99-X-7, 13th Annual AIAA/USU Conference on Small Satellites, www.smad.com

ups have provided additional funding. The effort has included development of low cost, pressure-fed liquid oxygen / kerosene rocket engines.

International Launch Services (ILS) – Atlas & Proton

International Launch Services, established in 1995, is a joint venture between Lockheed Martin and Lockheed Khrunichev Energia International to provide launch services with Lockheed Martin's Atlas and Russian Proton ELVs. Business appears to be brisk; in 2000 alone ILS executed six successful Proton launches and eight successful Atlas launches.¹⁹⁸

First launch of the new Atlas III took place in May 2000, a notable launch for another reason too: it was the first U.S. built rocket to be powered by the RD-180, originally a Russian-built engine, and produced for ILS by a joint venture of Pratt & Whitney and Russia's NPO Energomash.¹⁹⁹ Priced at only about \$10 million, the RD-180 delivers about three times the thrust of a Space Shuttle Main Engine for less than a third of the cost. The Atlas 3 was the culmination of a five-year, \$400 million development effort. The Atlas began commercial payload launch operations in June 1987.²⁰⁰

The Proton, which has been the primary heavy lift workhorse for Russian unmanned space missions since the early 1960s, conducted its first Western commercial launch in April 1996.

Failed Entrepreneurial Expendable Space Launch Vehicle Efforts

The past is littered with expendable space launch vehicle entrepreneurial companies that failed due to either technical difficulties or insufficient raised capital, or both. To date, every single entrepreneurial orbital venture without government

¹⁹⁸ "ILS Awarded Two Launches of Astra Satellites in 2001," *Spaceflight Now*, www.spaceflightnow.com.

¹⁹⁹ Williams, Craig H., "The Year in Review: Space Transportation," *Aerospace America*, December 2000, p. 93.

²⁰⁰ World Technology Division, *Global Satellite Communications Technology and Systems*, International Technology Research Institute, December 1998

involvement has failed. Among them were Beal Aerospace, American Rocket Company, Starstruck, Inc., Transpace Carriers Inc., E'Prime Aerospace Corporation, Space Services, Inc., Conatec, Inc., OTRAG, and Space Services, Inc. The first three are notable in that they all ambitiously tried to develop new technologies rather than simply adopting or modifying off-the-shelf technologies. The efforts of these companies are briefly described below.

Beal Aerospace – BA-2, 1997 - 2000

Beal Aerospace was established in 1997 by banker Andrew Beal as a response to the booming satellite launch market. Instead of seeking angel and venture capital as the RLV entrepreneurial firms did around that time, Beal funded the company himself, using the profits from his 99% ownership of Beal Bank.²⁰¹

The BA-2 concept was a heavy lift, expendable launch vehicle design capable of placing 13,200 pounds into geosynchronous orbit. If it had been successful, the BA-2 would have competed with Arianespace's Ariane 5 and heavy lift EELV variants. Beal Aerospace made significant progress in its development of the BA-2, especially the huge BA-810 rocket engine which would have been the largest hydrogen peroxide / kerosene engine ever built.

In September 2000, Beal Aerospace laid off 80 employees, over half of its work force. About a month later the company closed down, blaming "intolerable' competition from government supported initiatives," namely NASA's Space Launch initiative program and the Air Force's Evolved Expendable Launch Vehicle program.²⁰²

²⁰¹ Foust, Jeff, "Beal Aerospace Shuts Down; Cites 'Intolerable' Gov't Interference As Factor," 23 October 2000, www.space.com.

²⁰² Ibid. Both the EELV and SLI (under a different name) programs were underway in 1997, the same year Beal Aerospace was established. It is curious that Andrew Beal was not deterred from starting Beal Aerospace at that time, even though the launch vehicle market was a bull. It may be a coincidence that Beal Aerospace closed its doors around the time the projected launch vehicle market became a bear.

Starstruck, Inc. – Dolphin, 1981 - 1984

In August 1984 Starstruck, Inc. conducted one partially successful test launch of its prototype Dolphin liquid ELV, from a submerged platform in the ocean. This was only the second privately funded rocket launch by a U.S. company. The Dolphin was meant to be a predecessor to Starstruck's four-stage commercial launch vehicle, the Constellation. Discouraged by higher than expected development costs, the Redwood City, California company ceased operations not long after the launch.²⁰³

American Rocket Company (AMROC) – Aquila, SMLV, 1985 - 1994

Born from the ashes of Starstruck in 1985, AMROC successfully designed, built, and extensively tested hybrid liquid-solid rocket engines. Eventually, the company incorporated these engines into their SMLV expendable launch vehicle. Their only test launch took place in October 1989 and suffered an in-flight failure.

SpaceDev, a commercial space exploration company, acquired exclusive worldwide license rights to Amroc intellectual property in August 1998 for a minimum of five years.²⁰⁴ If successful in commercializing this technology, SpaceDev will have the rights to purchase the technology with discounted stock. The intellectual property included three patents on hybrid rocket engine technology. Recently SpaceDev test fired a small hybrid rocket engine to be incorporated into a prototype orbital transfer vehicle.²⁰⁵

Space Services, Inc. – Conestoga, 1980 - 1990

One of the earliest private ELV ventures, Space Services Inc. (SSI) carried out the first successful privately funded rocket launch by a U.S. company in September 1982.²⁰⁶ However, SSI's original launch vehicle, the Percheron, was not so

²⁰³ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989, p 137

²⁰⁴ "SpaceDev Acquires Hybrid Rocket Technology," *SPACEDAILY*, August 14, 1998, www.spacedaily.com/news

²⁰⁵ "SpaceDev Successfully Fires First Rocket Motor," *Business Wire*, November 16, 2000.

²⁰⁶ *Ibid*

successful. The Percheron was a liquid propellant rocket designed by SSI that violently exploded during its first engine static test in August 1981.²⁰⁷ In response, SSI adapted quickly, switching to an ELV design using existing, operational solid propellant rocket motors. Established in September 1980, Space Services Inc.'s goal became to develop the Conestoga family of low-cost, reliable ELVs using off-the-shelf technology. The Conestoga was a modular, multiple-stage ELV built with a core rocket motor and with additional motors strapped around it. The rocket motors were Morton Thiokol Castor-4 solid rocket boosters, which had a well-demonstrated high reliability as a strap-on for the Delta expendable launch vehicle. SSI contracted the experienced Space Data Corporation to build the Conestoga for them. SSI planned for the Conestoga launch vehicle family to be comprised of four rockets ranging in performance from 300 lb to 3000 lb payload to LEO, utilizing various Thiokol boosters including the Castor-4, Star-37, and Star-48 motors.²⁰⁸

After SSI's successful 1982 launch of a sub-scale rocket, the company began looking for customers for its Conestoga family of launch vehicles. Although numerous organizations from around the world showed some interest, potential customers elected not to sign on, in many cases citing the company's lack of experience and existing launch vehicle inventory.²⁰⁹ After several years passed without a booking, Space Services Inc. attempted to market their launch services for a particularly unique application – launching human cremated ashes into space.²¹⁰ After receiving thousands of orders over multiple years, SSI still did not have enough to make a dedicated launch economically viable and the space “burial” project was abandoned.²¹¹

²⁰⁷ Serra, Jean-Jacques, “Conestoga,” *The Satellite Encyclopedia*, www.tbs-satellite.com/tse/online/lanc_conestoga.html.

²⁰⁸ From: Ibid and Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989.

²⁰⁹ Apparently “Just In Time” supply-chain techniques weren't appreciated as much as today.

²¹⁰ Brooks, Timothy A, “Regulating International Trade in Launch Services,” *Berkley Technology Law Journal*, Volume 6:1, Spring 1991, www.law.berkeley.edu/journals/btlj/articles/vol6.html

²¹¹ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989.

EER Systems - Conestoga

In December 1990, EER Systems Corporation acquired the Conestoga design with their purchase of Space Services Inc., which became EER's Space Services Division.²¹² Like SSI, EER spent significant effort trying to find customers to service. EER succeeded in obtaining a five-launch contract with the Strategic Defense Initiative Office (later, the Ballistic Missile Defense Organization) for launch of Star Wars program elements. However, the contract was cancelled when the Star Wars program was cancelled.²¹³ EER eventually finally obtained NASA as a customer by their involvement with NASA's COMET (Commercial Experiment Transporter) program that began in 1990. EER's only launch of the Conestoga took place in October 1995. The rocket broke into pieces less than a minute after launch, putting EER out of the launch services business.²¹⁴

OTRAG (Orbital Transport and Rocket Corporation²¹⁵) – OTRAG-1, 1974 - 1987

OTRAG was a very controversial German company founded around 1974 to create a very low cost, modular ELV. According to sources, Dr. Lutz Kayser, a student of the famous German rocket pioneer Eugene Sänger, received West German government funding from 1971 to 1974 to study a very low cost ELV.²¹⁶ After the government halted funding, Kayser started OTRAG, with a registered home office in Stuttgart, Germany, and acquired the aid of Kurt Debus, former director of the German Peenemünde Center during World War II, and later former director of the Kennedy Space Center.²¹⁷

Kayser planned to create a family of rockets capable of placing payloads ranging from 200 to 10,000 kg (440 to 22,000 lb) to low Earth orbit. Each rocket employed a

²¹² Serra, Jean-Jacques, "Conestoga," *The Satellite Encyclopedia*, www.tbs-satellite.com/tse/online/lanc_conestoga.html

²¹³ Butrica, Andrew J, "The Commercial Launch Industry, Technological Change, and Government-Industry Relations," www.hq.nasa.gov/office/pao/History/X-33/butr02.htm

²¹⁴ *Ibid.*

²¹⁵ More accurately, Orbital Transport und Raketen Aktiengesellschaft.

²¹⁶ www.jcsw.com/john/Rocketry/otrag.htm (attributed to Always, Peter, *Rockets of the World*, 3rd Ed)

²¹⁷ www.univ-perp.fr/fuseurop/otrag_e.htm.

number of simple, pressure-fed rocket engines using nitric acid and kerosene propellants, selected for their low cost and ease of handling. Each engine had its own separate propellant tanks, and numerous modules were clustered together to provide varying levels of performance. The vehicles were controlled via independently throttling the clustered engine modules.

Besides being highly modularized, OTRAG rockets made use of as many commercial off-the-shelf components as possible. The very low technology, high weights of such rockets plays havoc with the exponential nature of rocket launch, where the necessary change in speed required to reach orbital velocity is (to the first order) an exponential function of the rocket's initial to final weight ratio. Coupled with such low specific impulse (efficiency) propellants, systems like OTRAG²¹⁸ suffer an unusually high performance penalty and thus require many more modules to be used than necessary, increasing the overall system cost and complexity, and reducing reliability.

In May 1977 and May 1978 OTRAG successfully flight-tested two small 6-meter suborbital rockets in Zaire (now the Democratic Republic of Congo), reaching altitudes of 20 and 30 km, respectfully.²¹⁹ A larger, four-module, 12-meter high suborbital test rocket failed in its launch in June 1978. Bizarre stories circulate today about OTRAG and their relationship with the Zaire government, and a possible secret German weapons program. OTRAG's difficult political relationship with the Zaire government allegedly eventually forced the company to relocate in Libya in 1979 where suborbital flight-tests were conducted in 1980. Some reports indicate OTRAG had two unsuccessful flight tests there in 1981, and were actually working with Libya to develop missiles.²²⁰ Once again forced to relocate, this time due to political pressure from the German government and/or the United States, OTRAG moved to Sweden. In September 1983 OTRAG conducted its last flight test in Sweden's Kiruna facility in 1983. The launch was a failure. Due to both technical

²¹⁸ The American Scorpion rocket concept, for example.

²¹⁹ www.univ-perp.fr/fuseurop/otrag_e.htm.

and political problems OTRAG closed down in 1984 or 1987 (depending on the source).

In a strange twist, Kayser surfaced again in May of 2000, claiming to have finished the development and testing of his modular low-cost ELV and seeking business partners to begin production.²²¹

²²⁰ Federation of American Scientists, www.fas.org/irp/threat/missile/libya.htm.

²²¹ Orbital Report News Agency, Space-Launcher.com, www.orbireport.com/News2000-05.html.

5. Space Transportation Supply: Reusable Launch Vehicle Programs & Concepts

This chapter contains an overview of RLV programs and concepts currently under development, concentrating on small, private, entrepreneurial development of reusable launch vehicles. Large corporate commercial RLV programs are examined first, followed by the entrepreneurial RLV ventures, including a brief look at the X PRIZE contestants. This is followed by an overview of United States government RLV programs and international efforts.

As noted in Chapter 1, the scale and scope of this research effort did not allow me to examine all of the RLV development efforts available in the literature. I thus was forced to down-select from a larger population the programs and concepts I found most interesting or relevant to this work as a whole. In the case of entrepreneurial RLV ventures, I attempted to select the most mature concepts from the literature.

Large Corporate Commercial RLV Programs

Not all of the commercial RLV developers are small entrepreneurial companies. Lockheed Martin has been working over the past few years on its VentureStar RLV design. The Boeing Company, Northrop Grumman, and Orbital Sciences have also recently studied or are currently studying reusable launch vehicle system designs and architectures under Air Force Military Spaceplane and NASA Space Launch Initiative contracts, but at significantly lower levels of effort.

Lockheed Martin – VentureStar

Lockheed Martin has been (until very recently) developing the X-33 RLV technology demonstrator with NASA in parallel with its planned follow-on single-stage-to-orbit commercial RLV, the VentureStar. The purpose of the X-33 program was to flight-test and demonstrate numerous advanced technologies required to

develop a full-scale, orbit capable, RLV.²²² At a cost of a little more than \$1 billion, the X-33 was supposed to be approximately a one-half linear scale of VentureStar. Multi-year schedule slips and extensive cost overruns, partly due to significant technical difficulties, recently caused NASA to cancel the X-33 program. The technical difficulties included design and fabrication of the advanced technology composite propellant tanks and the linear aerospike rocket engine, both critical to the success of the VentureStar.

Lockheed Martin had estimated the cost to develop their VentureStar single-stage-to-orbit commercial RLV in mid-1998 to be about \$5 billion.²²³ This number had already increased from a 1996 estimate of between \$4.5 and \$5 billion for a fleet of two or three VentureStar RLVs.²²⁴ Over the following two years this number climbed to at least \$6 billion; some industry experts estimate the cost would be even higher. Interestingly, as in the case of many of the entrepreneurs, the showstopper for VentureStar (at least claimed by Lockheed Martin at one time) is financial rather than technical. Lockheed Martin stated last year that their private VentureStar RLV program could not obtain adequate financing from Wall Street without government loan guarantees.²²⁵ Many believe VentureStar died with the death of the X-33 program.

Entrepreneurial Commercial RLV Ventures

Except for the partially reusable Space Shuttle system, every orbit capable rocket today is an expendable launch vehicle. Yet many studies promise RLVs will someday provide an order of magnitude decrease in cost and several orders of magnitude increase in reliability and safety, in essence the "Holy Grail" of space

²²² The X-33 program is discussed in more detail in Chapter 6.

²²³ "Lockheed Martin Sees Commercial Space Market Doubling by '05," *Aerospace Daily*, Vol. 187, No. 21, July 31, 1998, p. 174.

²²⁴ Gonzales, Daniel, et al., *Proceedings of the RAND Project AIR FORCE Workshop on Transatmospheric Vehicles*, RAND Corporation, Santa Monica, California, 1997.

²²⁵ "Loan Guarantees Required to Obtain VentureStar Financing, Lockheed Says," *Aerospace Daily*, Vol. 190, No. 39, May 25, 1999, p. 1.

transportation. It is no wonder that RLVs have been earnestly pursued in research and development programs for approximately 40 years.

Unfortunately, successful development of reusable launch vehicles has proven to be extremely difficult. Even with R&D investments collectively exceeding tens of billions of dollars, no developmental RLV program has succeeded.²²⁶ Yet in the last decade more than 15 small entrepreneurial RLV companies have formed, all vying to do what governments and the aerospace giants such as Lockheed Martin and Boeing have failed to do - develop a commercially viable RLV. This, in the face of a Space Shuttle development bill of about \$40 billion, the failure of the National Aero Space Plane program to the tune of \$3 billion, the recent failures of the X-33 and X-34 programs at over \$1.5 billion, as well as a host of other formidable deterrents. And this, despite the fact that the past is littered with failed ELV entrepreneurial efforts, a much less challenging development effort than that posed by an RLV.

The enthusiasm, creativity, courage, and commitment of these RLV entrepreneurs are obvious, even if technical design viability remains elusive to some. The odds are that most, if not all, of the current entrepreneurial RLV development efforts will fail.²²⁷ Regardless, there is always a chance one of the leading candidates will succeed. Certainly, the potential payoff is huge; a successful RLV (in terms of cost effectiveness, safety, and reliability) would be a disruptive product, revolutionizing the space launch and earning fame and wealth for the winners, as well as a well-deserved place in history books alongside the likes of the Wright brothers.

The entrepreneurial firms examined below are Kistler Aerospace Corporation, Pioneer Rocketplane, Kelly Space and Technology, Rotary Rocket Company, and Space Access, LLC. Kistler, Andrews Space & Technology, and Universal Space Lines were all recently chosen for funding by an initial round of NASA's Space

²²⁶ Recall that the Space Shuttle is a partially reusable system.

Launch Initiative (SLI) program.²²⁸ Kelly, Pioneer, and Space Access were reportedly passed over on this initial SLI phase.²²⁹

Of the following entrepreneurial companies, Kistler Aerospace Corporation appears to be head and shoulders in front of the rest with respect to design maturity, management team, capitalization, and fabrication. In addition, Kistler has been generous in publishing conference papers, providing a large amount of information about the company and its technical approach. For these reasons, my coverage of Kistler in this thesis is appropriately deeper than my examination of other entrepreneurial efforts.

Kistler Aerospace Corporation – K-1

For several years, Kistler Aerospace Corporation has been considered by many industry experts to be the undisputed front-runner of the entrepreneurial reusable launch vehicle development ventures. This is due to Kistler's leadership in several facets including system design viability, business plan, management team ability and experience, percentage completion of prototype, and amount of capital obtained to date. Due to their leadership position, Kistler is worth a closer look than the other entrepreneurial RLV developers.

The K-1 RLV Concept

Kistler Aerospace Corporation is developing the K-1 reusable launch vehicle, a two-stage-to-orbit, rocket that will be able to launch 4,500 kg (8,800 lb) into LEO. The K-1 is designed to use as much off-the-shelf technology and components as possible, for example using Aerojet AJ26 liquid oxygen / kerosene rocket engines based on the venerable, reliable Russian NK-33 and -43 engines.²³⁰ The K-1 will

²²⁷ Note that in addition to the hurdles mentioned here, statistically very few new business starts succeed.

²²⁸ Berger, Brian, "Rocket Entrepreneurs Take Share of Early SLI Funding," *Space News*, SpaceNews.com, March 6, 2001.

²²⁹ Ibid.

²³⁰ Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

launch vertically, and the first stage, the Launch Assist Platform, is recovered using an innovative approach: after stage separation one of the Launch Assist Platform's three AJ26 rocket engines is re-ignited and the stage flies a return trajectory to a designated landing site not far from the launch site. Parachutes are deployed after engine shut-off to slow the descent, and air bags are used to soften the landing. Upon reaching orbit, the second stage, or Orbital Vehicle, releases the payload and remains in LEO for approximately a day, waiting for the Earth's rotation to provide the correct ground trace before reentering the Earth's atmosphere. Like the first stage, the Orbital Vehicle utilizes parachutes and airbags during recovery.

When fully developed, Kistler Aerospace Corporation expects to be able to offer a price of \$17 million per launch, more than 50% less than current Western launcher prices, allowing the company to meet government-supported competition from Russia, Ukraine, and China.²³¹ Kistler also plans for a remarkable nine-day turn-around time. With a fleet of five vehicles, Kistler anticipates being able to launch with as short notice as three days, an unprecedented responsiveness for a space launch vehicle. Kistler plans to launch from the Woomera, South Australia spaceport, but has also worked towards establishing a second spaceport in Nevada to support additional capacity if needed.

While primarily focused on LEO missions, Kistler has also completed a conceptual design for an additional upper stage or "Active Dispenser." The Active Dispenser would propel payloads to medium Earth orbit, geosynchronous transfer orbit (GTO), or an interplanetary orbit, allowing the K-1 to deliver 1,570 kg (3,450 lb) to GTO for approximately \$25 million.²³² Kistler is also working with Astrium Ltd. to examine development of a reusable payload dispenser for launching multiple small

²³¹ Mueller, George, Written Statement of Kistler Aerospace Corporation, Presented at the "Commercial Spaceplanes" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 13 October 1999, www.house.gov/science/.

²³² Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

payloads, based on a similar expendable dispenser Astrium created for the Ariane 4 and Ariane 5 ELVs.²³³

In his October 1999 conference paper, Kistler Aerospace Corporation's CEO Dr. George Mueller reported that the first K-1 vehicle is in final assembly with 75% of the vehicle manufactured.²³⁴ Mueller also noted that at that point Kistler had secured over \$500 million of private financing, and planned to conduct their first launch flight test in 2000. However, financing problems have stalled completion of the prototype K-1 to this day.

The Business

Walter Kistler and Bob Citron founded Kistler Aerospace Corporation in 1993.²³⁵ Unlike many, perhaps even most, current RLV entrepreneurial efforts, the founders both had successful prior experiences of establishing and managing high technology, entrepreneurial ventures. Kistler Aerospace built an impressive, highly experienced management and technical team,²³⁶ maintaining a small, flexible staff of less than 50 employees, and incorporating a horizontal management structure.²³⁷ The company's undeviating focus from the start was on commercial launch, and developing the world's first true RLV.

Kistler has made extensive use of expert contractors to design and manufacture K-1 components, including Lockheed Martin, Northrop Grumman, GenCorp Aerojet, Draper Laboratory, AlliedSignal Aerospace, Irvin Aerospace, and Oceaneering Space Systems.²³⁸ Kistler has also employed an integrated product team system

²³³ Ibid.

²³⁴ Mueller, G.E, et al., "Building The K-1 Reusable Aerospace Vehicle As A Commercial Venture," 50th International Astronautical Congress, Amsterdam, The Netherlands, October 4 - 8, 1999.

²³⁵ Ibid.

²³⁶ CEO George Mueller, for example, was former head of NASA's Manned Space Flight Program throughout much of the 1960's Apollo era.

²³⁷ Mueller, G.E, et al., "Building The K-1 Reusable Aerospace Vehicle As A Commercial Venture," 50th International Astronautical Congress, Amsterdam, The Netherlands, October 4 - 8, 1999.

²³⁸ Mueller, George, Written Statement of Kistler Aerospace Corporation, Presented at the "Commercial Spaceplanes" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 13 October 1999, www.house.gov/science/

development approach where contractor representatives actively participate and work closely with Kistler employees. Kistler's contractors were involved in writing realistic requirements and specifications, and were brought in early into the development process. Kistler's development philosophy as given by Mueller is:²³⁹

- Use of proven technologies to reduce research, development, test, and evaluation time, cost, and risk as well as increase reliability. This includes use of the best available systems, such as the Russian engine technology.
- Full reusability to reduce costs (amortization of the K-1 costs over many flights), increase reliability (reuse of flight-proven systems and subsystems), and increase launch schedule flexibility and response time (by deleting long lead-time manufacturing from the operations timetable).
- Modular construction with liberal use of line replaceable units to reduce manufacturing and operation costs and time, and increase reliability.
- Use of commercial practices (to reduce development cost and time), enabled by all private financing.

Mueller states that totally private financing permitted Kistler to employ a number of advantageous commercial business practices in their system development.²⁴⁰ Analogous government programs require compliance with Federal Acquisition Regulations, which, for example, dictate use of time-consuming competitive procurement processes for contracting. In contrast, Kistler Aerospace Corporation freely selected businesses that are leaders in their respective technologies, and directly negotiated contracts. This and other like practices, contends Mueller, resulted in an accelerated development program schedule and significant cost savings for both Kistler and its contractors.

Kistler Finances

Apparently, Kistler has been in financial limbo since 1998, attempting unsuccessfully to find additional private financing to complete the first K-1. A

²³⁹ Mueller, G.E, et al., "Building The K-1 Reusable Aerospace Vehicle As A Commercial Venture," 50th International Astronautical Congress, Amsterdam, The Netherlands, October 4 - 8, 1999.

²⁴⁰ Ibid.

September 2000 article in *The Seattle Times* by Chuck Taylor reported that Kistler Aerospace had raised and spent \$600 million and needed another \$500 million to finish development and flight test of the prototype K-1.²⁴¹ In 1999 Kistler contractor Northrop Grumman reportedly forgave a \$30 million bill in exchange for equity in the company. Kistler has apparently been stymied by three financial roadblocks: a vanished high-yield debt market, much lower than expected demand for LEO commercial launches, and the dot-com investment craze.²⁴²

Taylor also reports that Kistler was recently awarded a \$264,000 contract with NASA to study use of the K-1 for the International Space Station supply missions.²⁴³ NASA is examining launcher options in addition to the Space Shuttle as insurance to congressional concern that Russian may not be able to afford their launch commitments to re-supply ISS. As noted in Section 3, however, impositions on an RLV system requirements by the ISS supply mission might require significant design modifications, potentially a very expensive proposition in terms of both cost and schedule. Kistler Aerospace Corporation's CEO, Dr. George Mueller, thinks that even a NASA endorsement of the K-1's utility - even if not a service contract - could spark additional private investment in the company.²⁴⁴

Current Situation

More recent developments, however, indicate an even grimmer financial picture. In February 2001, at the time this was written, Kistler Aerospace Corporation is in the midst of restructuring in an attempt to raise \$700 million to meet its financing needs through its projected point of positive cash flow.²⁴⁵ Bay Harbour Management L.C. is apparently considering providing Kistler \$385 million in exchange for 72% equity in the company. Under the terms of the deal, some existing shareholders

²⁴¹ Taylor, Chuck, "Half a Billion Shy of Building a Better Rocket," *The Seattle Times*, September 5, 2000.

²⁴² Ibid. At least the latter roadblock has disappeared.

²⁴³ Taylor, Chuck, "Half a Billion Shy of Building a Better Rocket," *The Seattle Times*, September 5, 2000.

²⁴⁴ Ibid.

²⁴⁵ "Reusable Launch Vehicle Developers Face Major Financial Barriers, Wary Investors," *Satellite News*, Vol. 24, No. 7, February 12, 2001.

who agreed to extend and increase Kistler's \$180.5 million line of credit will be offered 10% of the restructured company, while the remaining 18% of equity will go to existing shareholders, investment bankers, and Bay Harbour. This appears to be a major dilution of current shareholders equity. Kistler contractors will also be offered restructured debt or equity in exchange for its approximately \$85 million in outstanding accounts payable.²⁴⁶

Pioneer Rocketplane - Pathfinder

Pioneer Rocketplane's Pathfinder concept is a winged, piloted, reusable first stage of a two-stage-to-orbit system. The Pathfinder takes off horizontally from a conventional runway with a full complement of kerosene but with only a partial load of liquid oxygen aboard. The Pathfinder climbs using its two General Electric F404 turbofan engines and meets up with a modified KC-135 tanker aircraft. Analogous to standard aerial refueling, aerial propellant transfer occurs between the two aircraft, transferring about 130,000 lb of liquid oxygen from the KC-135 tanker to the Pathfinder's tanks. After disconnecting from the tanker, the Pathfinder's RD-120 kerosene / liquid oxygen rocket engine propels it into space on a suborbital trajectory. At an altitude of about 75 miles, the Pathfinder releases a liquid expendable upper stage that propels the payload into orbit. After reentry deceleration to subsonic speeds, the Pathfinder restarts its turbofans and makes a powered landing. Payload capability is from 5,000 - 7,000 lb to LEO.

The Pathfinder concept traces its roots back to the Air Force Research Laboratory's "Black Horse" military spaceplane concept from the mid-1990s, developed by Pioneer Rocketplane CEO, Mitchell Clapp, while in the USAF. (Other references indicate the Black Horse concept may have had its origins from an older aerial propellant transfer conceptual design study from Aerospace Corporation,²⁴⁷ or perhaps from former Pioneer Rocketplane partner, Bob Zubrin, who developed his

²⁴⁶ Ibid.

²⁴⁷ Personal discussions with Aerospace Corporation's Jay Penn, circa 1997.

“Black Colt” concept while an employee of Martin Marietta in 1993 and 1994.²⁴⁸) The company bid unsuccessfully for NASA’s X-34 project, but subsequent concept development was funded under the NASA Low Cost Boost Technology Program, as well as multiple grants from the state of California where the company is headquartered.²⁴⁹

Pioneer attributes aerial propellant transfer to giving their RLV vast improvements in safety, operational flexibility, and cost, enabling new market opportunities including passenger service from point-to-point on Earth, suborbital space tourism, and fast package delivery.²⁵⁰ The Pathfinder concept extensively leverages existing technologies, and employs commercial-off-the-shelf components wherever possible. Pioneer Rocketplane anticipates pricing satellite launches in the range from \$7 to 10 million per flight, a fraction of the price charged by today’s ELVs. Development of the Pathfinder RLV was estimated in 1998 to cost about \$275 million.²⁵¹

In September 2000, Pioneer signed a memorandum of understanding with the Oklahoma Space Industry Development Authority. With this agreement, Pioneer will conduct operations from the proposed Oklahoma Spaceport in Washita County, Oklahoma, in exchange for up to \$300 million in revenue bond financing to help develop the Pathfinder concept.²⁵²

²⁴⁸ Iannotta, Ben, “Small Start-ups Vie for Big Business,” *Aerospace America*, August 1998, p. 34.

²⁴⁹ Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

²⁵⁰ Clapp, Mitchell Burnside, Testimony at the “Commercial Spaceplanes” hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 13 October 1999, www.house.gov/science/

²⁵¹ Iannotta, Ben, “Small Start-ups Vie for Big Business,” *Aerospace America*, August 1998, p. 34.

²⁵² Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

Space Access, LLC - SA-1

Founded in 1994, Space Access, LLC has been among the more stealthy entrepreneurial RLV development ventures, rarely presenting business or system design information in a public forum. Space Access's SA-1 concept is an unmanned, multi-stage reusable launch vehicle that will be able to deliver a wide range of payloads into low, medium, and geosynchronous Earth orbits. The RLV takes off horizontally from a conventional runway, powered by a hybrid propulsion system utilizing liquid hydrogen and atmospheric oxygen in the first stage. This propulsion system includes a proprietary modification to an ejector ramjet design that was developed and first demonstrated in ground tests more than 30 years ago. A single rocket powered upper stage is used to deliver up to 15,000 kg (33,000 lb) to LEO; a second rocket powered upper stage delivers about 5,200 kg (11,400 lb) to GTO.²⁵³ All three stages are completely reusable and are recovered via horizontal landings at the original launch site. Space Access has reportedly studied developing a crewed version of its second stage under contract with NASA.²⁵⁴

In contrast to most of its RLV brethren, the SA-1 is significantly larger and does not adhere to the philosophy of strict use of commercial off-the-shelf components or even current technology, as evidenced by their development of new propulsion and thermal protection system technologies. Although originally designed for LEO missions, Space Access has reacted to the soft LEO market and now lists GTO missions as the system's market focus, and is considering ISS re-supply missions as well. As late as 1998, Space Access stated that flight tests of the SA-1 would begin in 2001, and the system would be operational by 2002.²⁵⁵ The author does not know Space Access's current status.

Kelly Space and Technology – 2nd Generation RLV System / Astroliner

Kelly Space and Technology was founded in San Bernardino, California in 1993 by Mike Kelly and Mike Gallo. Their goal was to “develop significantly less

²⁵³ Ibid.

²⁵⁴ Ibid.

expensive, safer, more reliably performing and frequently operated Space Launch Vehicles.”²⁵⁶ Privately financed, Kelly has been working on their piloted horizontal takeoff, horizontal landing RLV concept capable of inserting 10,500 lb into LEO.

Kelly plans to develop a two-stage-to-orbit system, with a reusable first stage called the Astroliner and an expendable upper stage. Kelly uses a “Tow to Launch Site” approach, where the Astroliner would be towed into the air from a conventional runway by a modified Boeing 747 aircraft.²⁵⁷ The Astroliner incorporates rockets as well as F100 jet engines, with the latter used to supplement the 747’s thrust early in the trajectory. At about 20,000 feet altitude, the Astroliner is released from the tow tether, and it ascends under rocket power to the stage separation point, at an altitude of about 400,000 feet.²⁵⁸ After stage separation, the Astroliner reenters the atmosphere and performs a powered horizontal landing on a conventional runway.

Kelly Space and Technology has been awarded a U.S. patent for their tow technique, which they claim will eliminate substantial ground facility infrastructure, saving costs as well as increasing reliability and safety. Kelly successfully tested their RLV tow techniques in 1997 and 1998 with scale flight tests at Edwards Air Force Base in California using a modified QF-106 aircraft towed into the air by a C-141A airplane.

Like Kistler, Kelly Space and Technology has reacted to the softening LEO market over the past few years by refocusing the development effort from primarily a LEO launch service (the Astroliner concept) to a much broader market. Reportedly, Kelly is now aiming to provide launch of cargo to suborbital, low, medium, and geosynchronous orbits, and cargo and personnel to the International Space Station

²⁵⁵ Iannotta, Ben, “Small Start-ups Vie for Big Business,” *Aerospace America*, August 1998, p. 34.

²⁵⁶ Davis, Robert, Testimony on Commercial Spaceplanes, Presented at the “Commercial Spaceplanes” hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 13 October 1999, www.house.gov/science/

²⁵⁷ Ibid.

²⁵⁸ Iannotta, Ben, “Small Start-ups Vie for Big Business,” *Aerospace America*, August 1998, p. 34.

with their "Second Generation Launch System."²⁵⁹ To do so Kelly plans to develop several different upper stage concepts. Among these are an unmanned, cargo delivery, reusable upper stage, and a seven person Crew Transfer Vehicle.

NASA has sponsored Kelly for several studies over the past few years on NASA's Second Generation RLV program. Kelly recently announced it would team with Vought Aircraft Industries to work on their second generation RLV concept.²⁶⁰

In the past, Kelly Space and Technology has reported to need a mere \$450 million to develop their Astroliner RLV.²⁶¹ Sources report that Kelly had spent only about \$10 million as of May 1999, indicating the concept's immaturity. As late as last year, Kelly planned to first launch the Astroliner in 2002, but more recently pushed the first launch of their Second Generation Launch System to sometime after 2006.²⁶²

Failed Entrepreneurial RLV Efforts

With the zeal and optimism for the current ELV and RLV entrepreneurial ventures so prevalent in the literature today one might think their ilk has never been before seen in the aerospace industry. But then one would be ignoring the periodicity that at times seems to tirelessly affect every facet of the aerospace industry. The fact is that developing an orbital ELV system is extremely difficult and risky. It has been attempted numerous times before by ELV entrepreneurs, every one a failure. Beal Aerospace, American Rocket Company, Starstruck, Transpace Carriers, E'Prime Aerospace Corporation, Space Services, Conatec, OTRAG, and others all wanted to change the world. A very sobering consideration is that developing a reusable

²⁵⁹ Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

²⁶⁰ "Kelly and Vought Team Up For New Spaceplane," *SPACEDAILY*, January 23, 2001.

²⁶¹ Iannotta, Ben, "Small Start-ups Vie for Big Business," *Aerospace America*, August 1998, p. 34.

²⁶² Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

launch vehicle is so much more difficult than on ELV, in terms of technical risk, funding magnitude, and development time.

The current wave of entrepreneurial RLV ventures were almost all started in the mid-1990s, originally bolstered by a bullish, even exuberant, LEO communications satellite market that appeared to underestimate the threat of fiber optics. With the bankruptcies or deep financial straits experienced by Iridium, ICO, Orbcomm, Globalstar and others, the LEO market has since declined. Rotary Rocket is the first of this wave to fall,²⁶³ additional RLV entrepreneurial ventures will likely soon follow its lead.

Rotary Rocket Company – Roton, 1996 - 2000

Rotary Rocket Company began development of their Roton RLV concept in 1996, but experienced great difficulty in raising capital throughout its existence. In June 1999, for example, Rotary announced layoffs and restructuring, dropping about 60% of its workforce.²⁶⁴ Rotary ceased engineering and development work on their RLV last summer, and CEO Gary Hudson resigned. At the end of 2000 Rotary Rocket Company mothballed the organization indefinitely.²⁶⁵ The company had raised about \$30 million²⁶⁶ (of which \$1 million is said to have been invested by famous author Tom Clancy) but supposedly needed an additional \$150 million to complete the project.²⁶⁷ Rotary barely managed to avoid auction of its property at Mojave Airport in Kern County, California early this year by paying delinquent 2000 taxes at the last moment.²⁶⁸

²⁶³ The status of Rotary is actually somewhat ambiguous. Although the literature implies the company has dissolved, it may actually be only currently "mothballed."

²⁶⁴ Lindsay, Clark S, Editor, Reusable Launch Vehicle Information Web Site, www.hobbyspace.com/Links/RLVCountdown.html.

²⁶⁵ Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

²⁶⁶ Lindsay, Clark S, Editor, Reusable Launch Vehicle Information Web Site, www.hobbyspace.com/Links/RLVCountdown.html.

²⁶⁷ Bedell, Christine, "Delinquent Rocket Firm Sends Cash, Insults to Kern," *The Bakersfield Californian*, December 28, 2000.

The Roton is a single-stage-to-orbit RLV concept designed for launching LEO satellites as well as transferring crew to and from the International Space Station. The vertical takeoff Roton concept ascended to orbit using conventional liquid oxygen / kerosene rocket engines, and landed vertically like a helicopter but using an innovative powered rotor system. Folded during ascent for low drag, the rotor blades deployed after reentry into the atmosphere, and were powered by small hydrogen peroxide / methanol rocket engines built into the blade tips. Rotary Rocket Company originally planned to design, develop and use their proprietary RocketJet rocket engines, but later abandoned this avenue in favor of a derivative of the liquid oxygen / kerosene Fastrac rocket engine developed in-house at NASA Marshall Space Flight Center. Ironically, Rotary attributed this decision to an attempt to reduce development time and technical risk. With the problems NASA has experienced with their Fastrac engines, however, this may have been an unfortunate strategy had Rotary been able to acquire the capital to continue operations.

Rotary Rocket Company completed construction of a manufacturing and flight operations facility at the Mojave Airport in California in January 1999. There they built and flight-tested a low speed, full-scale, 64 foot tall vehicle prototype, the Roton Atmospheric Test Vehicle (ATV). In three flight tests, the ATV successfully demonstrating approach and landing flight characteristics.²⁶⁹

The X PRIZE Competitors

As discussed in Chapter 3, space tourism has the potential to be a large emerging market, an industry with economic value that could someday dwarf all of our present commercial space endeavors. A common premise in the literature is that space tourism will drive entrepreneurial development of successive generations of lower and lower cost RLVs, breaking the current paradigm that space travel is only the venue of governments and their large aerospace contractors. All that is

²⁶⁸ Ibid.

²⁶⁹ Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

needed, the argument goes, is a privately developed, passenger carrying, suborbital reusable launch vehicle to start the ball rolling. It is no surprise then that space tourism is the primary market focus for many current RLV entrepreneurial ventures.

The X PRIZE Foundation, a nonprofit organization, was established in 1994 to inspire such development through creating a \$10 million international prize to be awarded to the first privately funded person or team who safely travels to and from space. Rules dictate the vehicle must demonstrate the ability to fly three persons on a *suborbital* flight to an altitude of 100 km, as well as fly twice within a two-week span. Some 20 international teams have registered to compete since the X PRIZE was publicly announced in 1996.²⁷⁰ Modeled after the hundreds of early aviation prizes offered between 1905 and 1935 which successfully stimulated a plethora of new aircraft designs, the X PRIZE aims to prompt development of space tourism primarily through entrepreneurial development of relatively low technology, suborbital²⁷¹ RLVs that would enable space tourism affordable to the general public.²⁷²

The X PRIZE foundation lists the following categories of public benefits to be gained from the technologies and other outcomes resulting from the X PRIZE:²⁷³

- Rapid transportation point-to-point on Earth - for both cargo and passengers.
- Access to space – advancing telecommunications and enabling access to space resources.
- Philosophical and motivational benefits – changing personal worldviews, generating heroes, and promoting education.

²⁷⁰ X Prize Foundation Web Site, www.xprize.org, January 2001.

²⁷¹ I use the phrase "low technology, suborbital" rather loosely. The prize can be won by a suborbital RLV rather than a higher performance, orbit capable RLV. The former would require significantly less technological sophistication than its orbit-capable counterpart.

²⁷² X Prize Foundation Web Site, www.xprize.org, January 2001.

²⁷³ Diamandis, P, and Maryniak, G, "The X Prize Competition: Creating a New Generation of Reusable, Passenger-Carrying Spaceships," IAF Paper 98-1501, 49th International Astronautical Congress, Melbourne, Australia, September 28 - October 2, 1998.

The following is a list of current registered entrants, followed by the name of their RLV concept:²⁷⁴

- Advent Launch Services - Advent
- AeroAstro, LLC - PA-X2
- Mr. Mickey L. Badgero - Lucky Seven
- Bristol Spaceplanes, Ltd. (England) - Ascender
- Canadian Arrow (Canada) - Canadian Arrow
- Cerulean Freight Forwarding Company - Kitten
- CosmopolisXXI (Russia) - CosmopolisXXI
- The daVinci Project (Canada) - daVinci
- Discraft Corporation - The Space Tourist
- Graham Dorrington (England) - Green Arrow
- Earth Space Transport System Corporation
- Kelly Space and Technology - Eclipse Astroliner
- Lone Star Space Access Corporation - Cosmos Mariner
- Pablo De Leon & Associates (Argentina) - Gauchito
- Pan Aero, Inc. - XVan2001
- Pioneer Rocketplane, Inc. - Pathfinder
- Scaled Composites, Inc. - Proteus
- Starchaser Foundation (England) - Thunderbird
- TGV Rockets - Michelle-B

The sophistication of these concepts appears to vary widely, ranging from some that can only be politely described as “interesting” to others that seem technically viable and very innovative.

The Starchaser Foundation team and the Pablo de Leon and Associates were reportedly actively involved last year in testing system components, Starchaser testing a launch escape system and avionics for their Thunderbird concept with a

²⁷⁴ Ibid.

two-stage rocket test launch and Pablo de Leon and Associates testing subscale hybrid rocket motors for their Gauchito concept.²⁷⁵

It will be very interesting to witness the eventual affect the X PRIZE has on RLV development. Will the X PRIZE act as a critical catalyst or will it have no lasting or appreciable effect? Supporters are quick to argue that the great success of analogous prizes in the aircraft industry in prompting innovative airplane development in the first few decades of the twentieth century will translate easily into RLV development. Yet skeptics contend that the levels of technological sophistication and capital required to successfully develop an aircraft 90 years ago is far, far less than that required today, and even further removed from that required to develop a viable manned RLV. In truth, while the image of creative inventors who produced wildly successful, disruptive products working out of a bicycle shop in Dayton, Ohio or out of a one-car garage in Palo Alto, California²⁷⁶ is romantic and compelling, today it is very rare indeed, especially in the technologically complex and high cost aerospace industry. The Boeing 777 aircraft, for example, has over 85,000 components and over four million parts, requiring the expertise of thousands of specialized engineers. It was not designed and developed out of a garage, smali shop, or basement. The capital required to undertake major aerospace development efforts has risen dramatically too; ESA's cost to develop the Ariane 5 ELV, a derivative of their Ariane 4 launcher, has been estimated at \$9 billion, including required spaceport infrastructure. It seems doubtful that a small entrepreneurial private firm could succeed in developing a successful RLV where industry giants such as Boeing and Lockheed have failed. Yet it would not be prudent to rule them out either; improbable is not impossible.

Another skepticism against the X PRIZE's effectiveness is the magnitude of the prize amount. With the cost of developing unmanned ELVs typically in the billions of

²⁷⁵ Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

²⁷⁶ Orville and Wilbur Wright, and Bill Hewlett and Dave Packard, respectively.

dollars, far exceeding what a small group of entrepreneurs can usually generate, is there an adequate economic incentive behind a mere ten million dollar prize? One might argue that the prize would have to be increased to at least an order of magnitude to have a significant effect on encouraging a large number of high quality entrants, entrants with the appropriate level of funding to contract out for the technologies they need help developing.

Perhaps one of the most important outcomes of the X PRIZE will be the focus they are providing on incremental development of reusable launch vehicles. Rather than requiring orbital RLV flight to win the prize, it can be won by the relatively modest accomplishment of a suborbital flight. By this approach, the X PRIZE Foundation is wisely encouraging a stepping-stone, evolutionary development for full-scale, orbit-capable RLVs, and thus increasing the likelihood of success. This circumvention of the time-honored but almost always failing technology “leap-frog” or revolutionary approach is both pragmatic and admirable.

U.S. Government Reusable Launch Vehicle Programs

NASA’s “1st Generation” RLV: The Space Shuttle

The Space Shuttle, or Space Transportation System (STS), is composed of a reusable delta-wing spacecraft called the orbiter, two solid propellant rocket boosters, and a large expendable tank carried externally. Often called a first generation reusable launch vehicle, the Space Shuttle²⁷⁷ is actually only partially reusable – the large external tank is emptied and discarded during launch just shy of orbit. After separation, the external tank reenters the atmosphere and either burns up or crashes into the sea. The two solid rocket boosters are thrown away early in the launch, parachuting into the ocean where they are recovered, refurbished and rebuilt, and eventually reused up to 25 times each. After dropping the solid rocket boosters and the large external tank, the Space Shuttle orbiter travels on to orbit. The Space Shuttle (Figure 4) can remain in orbit for extended periods of time,

allowing its astronauts to complete a wide variety of missions including payload deployment and recovery, satellite repair, scientific experimentation, and lately, ISS construction. Upon mission completion the orbiter reenters the atmosphere and lands. An enormously expensive repair and refurbishment program is then undertaken to prepare the orbiter for its next launch.²⁷⁸ Future missions include additional International Space Station construction and re-supply, which should preoccupy the system through the next five to ten years.

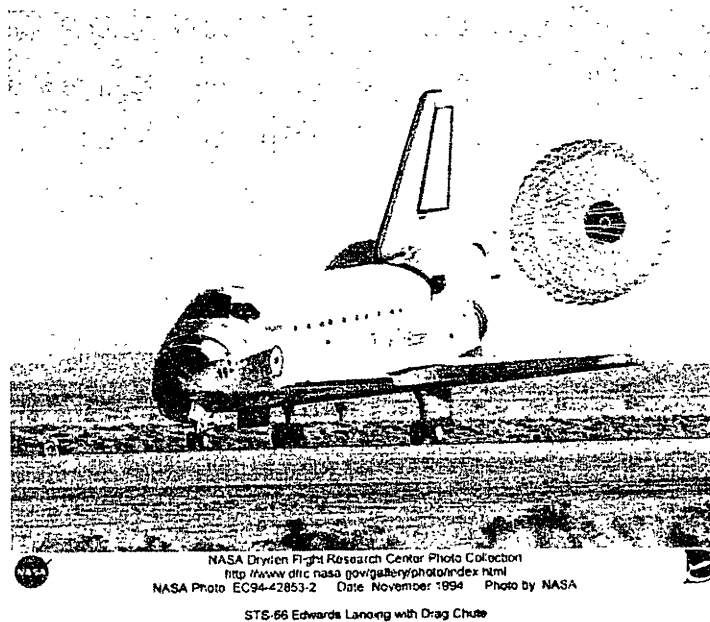


Figure 4 Space Shuttle Landing
(Photograph compliments NASA)

The first of its kind, the partially reusable Space Shuttle system is the nearest forerunner to the revolutionary RLVs of tomorrow. The Shuttle provides an impressive capability and versatility for placing humans and satellites in orbit, and it frequently acts as a temporary space station, hosting numerous experiments and tests. Currently, the Shuttle is the only man-rated launch system in the West, and it has been the sole mode of human transport to space for the United States since

²⁷⁷ Here and elsewhere in this thesis I use "Space Shuttle" to indicate the United State's version. Note that the Soviet Union also developed a space shuttle system, the Energia-Buran Reusable Space System, which was nearly a U.S. Space Shuttle clone and is not operational.

²⁷⁸ A few flights required more than a staggering 30,000 man-hours merely to refurbish the thermal protection system between flights.

1981. However, the Space Shuttle system is by far the most expensive launch system in the world, with a publicized cost per pound of payload delivered to low Earth orbit of approximately \$10,000 per pound. In contrast, modern unmanned expendable launch vehicles currently cost from about \$3,000 to \$8,000 per pound to low Earth orbit. In addition, the Shuttle fleet is capable of only infrequent launch operations, approximately half a dozen to a dozen launches per year. The very high costs and low launch frequency of the Shuttle system hence make it a very ineffective for the "space truck" mission for which it was originally intended. Interestingly, the original estimated cost for shuttle launch was about \$100 per pound to LEO per flight,²⁷⁹ and the initial launch was planned for 1978, with a flight rate of about 50 launches per year.²⁸⁰ First flight occurred in April 1981 after a four-year delay due to funding shortfalls and technical problems with the engine and thermal protection system development.²⁸¹ A couple of years ago, before ISS spending ballooned, space launch (primarily the Space Shuttle) ate roughly 25% of NASA's budget.²⁸²

The additional system complexity and weight required to carry astronauts, as well as it being the first of its kind, translate into very high fixed and recurring costs for the Shuttle system. NASA published total average costs per flight for the Space Shuttle for fiscal years 1996, 1997, and 1998, were \$590 million, \$380 million, and \$409 million, respectively. In fiscal year 1999, however, due to required repairs on the Shuttle fleet there were only three flights to amortize that year's approximately \$3.1 billion Shuttle operations budget, giving an average cost per flight of about \$1000 million, or roughly \$20,000 per pound to low Earth orbit.²⁸³ Development costs for the Shuttle are as impressive as its launch costs. Total cost in fiscal year

²⁷⁹ Cole, Bob, *The Prospects for U.S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989.

²⁸⁰ Teal Group Corporation, *World Space Systems Briefing: Space Shuttle*, June 2000, www.tealgroup.com.

²⁸¹ *Ibid.*

²⁸² McWilliams, James, "Bold Steps for Space Travel Are On Horizon," *The Huntsville Times*, October 28, 1999.

²⁸³ There are 7 to 8 Shuttle flights in a typical fiscal year.

2000 dollars for the design and development of the first four Space Shuttles was about \$40 billion.²⁸⁴

"Thirty years ago, President Richard Nixon initiated the Space Shuttle program as the 'next big project' for NASA after Apollo. But instead on delivering the promised 'space truck' that would fly 50 times per year for perhaps \$10 million a flight, NASA built a complicated vehicle that still requires 20,000 people to fly at 1/10 as much per year for fifty times as much cost."

- Space Frontier Foundation²⁸⁵

Some lay the blame for Space Shuttle deficiencies on its design that was allegedly compromised in attempt to acquire the political support of key users - in particular extended growth of the system's payload capability in order to handle heavy lift Department of Defense surveillance satellites. Others lay the guilt on a shortage of development funds that forced the program office to select only a partially reusable design, essentially trading significant up-front development costs required to make the system completely reusable for higher recurring costs.

The 100th STS flight took place in October 2000. With a fleet of four vehicles, each with a 100 flight lifetime, the Space Shuttle system could possibly keep flying for another 20 to 30 years, especially if NASA continues to upgrade the vehicles on a regular basis.²⁸⁶ However, its great expense may drive NASA to pursue a replacement long before then.

In 1996, United Space Alliance (USA) took over the everyday operations and management of the Space Shuttle fleet under a six-year contract with NASA. USA,

²⁸⁴ Mulville, Daniel, Statement of Daniel Mulville, Chief Engineer, Office of the Administrator, NASA, at the "Space Transportation Architecture Studies: The Future of Earth-to-Orbit Spaceflight" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 27 October 1999, www.house.gov/science/.

²⁸⁵ Space Frontier Foundation Press Release, "Space Frontier Foundation Ridicules NASA for Praising and Perpetuating Expensive Socialist Spaceflight Monopoly," October 5, 2000, 140

a joint venture between Lockheed Martin Corporation and Rockwell International (now, The Boeing Company), also acquired USBI Company in October 1999, obtaining accountability for the assembly, test, and refurbishment of the Solid Rocket Boosters.²⁸⁷ USA claims they have successfully reduced the overall cost of the Space Shuttle program nearly \$300 million in the first two years of their contract, from fiscal years 1996 to 1998 while meeting all mission objectives and maintaining safety and reliability as top priorities.²⁸⁸

A solid examination of issues in privatizing the Space Shuttle is presented in a 2000 article by Hertzfeld.²⁸⁹ In this work he concludes that although privatization of the Space Shuttle is possible, government safety rules (primarily due to the system being manned) make the system too expensive to form a viable business without government subsidies. He also observes that the Shuttle was not designed for commercial operations, and that its primary utility over the next few years is International Space Station completion and maintenance.

NASA's SLI Program: 2nd Generation RLV Program

"At this juncture, there is no market driven business case for a human-rated launch system."

- U.S. Congressmen Dana Rohrabacher²⁹⁰

NASA's lists its goal for the Space Launch Initiative (SLI) as substantially reducing the technical, programmatic and business risks associated with developing a safe, reliable, and affordable 2nd Generation RLV. The intent of the SLI program

²⁸⁶ At the current scheduled rate of 8 to 10 flights per year, and barring any major accidents, the STS could conceivably keep flying until beyond 2030. Note that the B-52 has set this precedent. It first flew in March of 1961, and will likely fly for another decade or more for the USAF.

²⁸⁷ Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

²⁸⁸ www.unitedspacealliance.com/about/.

²⁸⁹ Hertzfeld, Henry R, "Issues in Privatizing the Space Shuttle," AIAA Paper 2000-5123, AIAA Space 2000 Conference and Exposition, Long Beach, CA, September 19 - 21, 2000.

²⁹⁰ Rohrabacher, Dana, "NASA's Space Launch Initiative Is Off Course," *Aviation Week & Space Technology*, February 19, 2001, www.aviationnow.com.

is to develop 2nd generation RLV architecture options to enable a launch services competition in 2005 that would meet NASA's human space flight operational needs by 2010.²⁹¹

NASA currently plans to replace the Space Shuttle system with either a new, Shuttle-derived launch vehicle or a "clean sheet designed" RLV, developed and operated by industry.²⁹² NASA has targeted either 2010 or 2012 (depending on the source) for initial operations of this system and has already invested heavily in RLV technologies and experimental flight demonstrators, including the X-33, X-34, and X-37 programs. NASA has spent more than a billion dollars in this area over the last few years and intends to spend more than \$4.5 billion over the next five years under the Space Launch Initiative program to continue this work. As noted above, as of the end of 2000 NASA's plan was to make a decision in 2005 whether or not to initiate the Space Shuttle replacement program.

SLI has provoked intense controversy. A great debate rages on whether to upgrade the Shuttle, an outrageously expensive yet working system with a unique capability to carry astronauts, or to risk many billions of dollars on yet another development program – in the wake of a number of false starts and cancelled programs for lack of schedule, cost, and or technical progress such as the reported \$3 billion shelled out on NASP, more than \$1.5 billion spent on X-33 and X-34, and nearly \$1 billion spent on the Space Transportation Main Engine²⁹³ over the last decade in a half with little produced.²⁹⁴

U.S. Congressmen Dana Rohrabacher (R-Calif.), Chairman of the House Science Space and Aeronautics Subcommittee, said recently that he will hold hearings to ensure NASA properly spends SLI funding, to develop the next generation of reusable launch vehicles, rather than to pay for space shuttle

²⁹¹ std.msfc.nasa.gov/2ndgen/about2ndgen.html.

²⁹² I believe the latter is more likely... assuming the inevitable political backlash to current NASA's X-33 and International Space Station program development woes is not insurmountable.

²⁹³ Grey, Jerry, "The Rocky Road to Space-Launch Heaven," *Aerospace America*, November 1996.

upgrades.²⁹⁵ In a February 2001 letter to *Aviation Week & Space Technology*, Rohrabacher notes that SLI's goals of "commercially competitive, privately owned, low-cost, safe Earth-to-orbit launch for human spaceflight," are over-specified, and that the SLI program's requirements are "...too narrowly focused on meeting NASA's post-shuttle spaceflight needs. Yet the country's greatest need is to reduce the cost of launching unmanned spacecraft."²⁹⁶ Rohrabacher further observes that NASA's human spaceflight requirements will likely defeat any potential cost savings derived from the program. Such an astute assessment is encouraging, especially by such an influential congressman.

The Space Frontier Foundation has often condemned NASA for not privatizing the Space Shuttle years ago, for not supporting commercial space transportation, and for maintaining a monopoly in the Western world in human spaceflight. The Foundation has also heavily criticized NASA's X-33 program and the Space Launch Initiative, the latter viewed as "a veiled attempt to create Shuttle II."²⁹⁷ Like numerous other industry watch groups, the Space Frontier Foundation believes that SLI will provide a near-impregnable barrier for entry for new private companies that are trying to develop new, lower cost RLVs. In essence, they believe SLI will threaten the existence of innovative launch vehicle entrepreneurs since few firms could compete with a government sponsored (directly or indirectly subsidized) program like Shuttle II. This may indeed be true in light of the current financial markets.

²⁹⁴ These numbers include industry investment as well as NASA's.

²⁹⁵ Magnuson, Stew, "House to Hold Hearings on Space Launch Initiative Funding," *Space News*, February 14, 2001, www.spacenews.com.

²⁹⁶ Rohrabacher, Dana, "NASA's Space Launch Initiative Is Off Course," *Aviation Week & Space Technology*, February 19, 2001, www.aviationnow.com.

²⁹⁷ Space Frontier Foundation Press Release, "Space Frontier Foundation Says: 'Space Launch Initiative Program (SLIP): Fix it or Kill it'," February 8, 2001, www.space-frontier.org

The independent Aerospace Safety Advisory Panel (ASAP) assessed the Shuttle's current situation in its recent 2001 annual report and made the very somber conclusion that ²⁹⁸

"...shuttle flight safety could be compromised over the long term because NASA has been focusing too heavily on commercial or other optimistic shuttle replacement options, as opposed to longer term shuttle upgrades."

The panel reported to NASA that the space agency needs to face reality as well as the far-reaching implications of its space transportation planning. ASAP's report further noted that the current Space Shuttle will likely be the ²⁹⁹

"...primary U.S. manned launch vehicle for another 20 years, to 2020 or so, through the minimal projected life of the International Space Station. The debates and tradeoffs involved in these issues involve tens of billions of dollars and will ultimately affect U.S. manned space operations into the middle of this century."

Currently, NASA plans to perform about \$1.5 billion in shuttle upgrades through 2005, but they are focused on relatively low cost subsystem upgrades rather than major system design changes such as a new crew escape module or liquid flyback boosters to replace the solid rocket boosters, for example. ASAP stated their belief that the 2012 Shuttle phase-out date is restricting consideration of important safety upgrades that if not implemented may be critical to the long-term safety of both the space shuttle and the ISS.

At least some ASAP members feel NASA has been too focused on unrealistic commercial RLV concepts, due largely to overly enthusiastic support for commercial solutions within Congress, the previous administration and aerospace industry

²⁹⁸ Covault, Craig, "Safety Panel to Goldin: Gear Shuttle Toward 2020," Aviation Week & Space Technology, Vol.154, No. 8, p. 25, February 19, 2001.

²⁹⁹ Ibid.

special interest groups. In fact, a recent *Aviation Week & Space Technology* article³⁰⁰ quoted an unnamed senior space manager as saying, "Unfortunately the Clinton Administration and the current NASA administrator put more faith in (RLV) commercial marketing and viewgraphs than they should have." Some would argue the proof for this lies in NASA's investment in X-33, X-34, NASP, and several controversial entrepreneurial efforts. My own experiences in leading a number of independent design and technology maturation assessments of entrepreneurial RLV concepts since the mid-1990s support the notion that some RLV ventures take "viewgraph engineering"³⁰¹ to a new acme.

ASAP's conclusions are weighty considering the importance NASA and the United States government give to the safety of the Space Shuttle system. Interestingly, these inputs may have been important enough to alter the SLI schedule; recent interaction with contacts at NASA Marshall Space Flight Center indicates NASA may be currently examining the option of moving the 2nd generation RLV initial operational capability date from 2010 to 2020.³⁰² If this were done, it would require yet another delay in the decision to commit to developing either a new RLV or a Space Shuttle upgrade. The 1994 National Space Transportation Policy (NSTC-4) called for "government and private sector decisions by the end of this decade on development of an operational, next-generation reusable launch system."³⁰³ Yet NASA's Chief Engineer Dan Mulville stated in testimony to the House Subcommittee on Space and Aeronautics, U.S. Congress, in October 1999 that after five years of already studying space transportation architectures NASA was putting off this decision until 2005.³⁰⁴ An additional five or ten year delay might not be politically tenable.

³⁰⁰ Ibid.

³⁰¹ A common engineering management term to say "great form but no content," or "nice pictures but no substantiating technical analysis," or even "where's the beef?" as in the popular Wendy's restaurant commercial of old.

³⁰² Personal correspondence, April 2001.

³⁰³ Mulville, Daniel, Statement of Daniel Mulville, Chief Engineer, Office of the Administrator, NASA, at the "Space Transportation Architecture Studies: The Future of Earth-to-Orbit Spaceflight" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 27 October 1999, www.house.gov/science/

³⁰⁴ Ibid.

With Donald Rumsfeld, the new Bush Administration's Secretary of Defense, strongly supporting military space research that includes development of an Air Force spaceplane, industry experts speculate that NASA's exclusive control of RLV development will not last.³⁰⁵ Likewise, it appears the Space Launch Initiative will likely be overhauled after NASA administrator, Daniel Goldin, departs, probably later this year.³⁰⁶

United States Air Force – Military Spaceplane System

Due to a number of key deficiencies in its current space operational capabilities, the Air Force Space Command component of the United States Air Force has documented draft needs for the capability for a militarized RLV system. In response, the Air Force Research Laboratory in concert with NASA is currently developing critical technologies for its Military Spaceplane System, a reusable space system architecture to perform a wide range of missions including launch-on-demand, reconnaissance, surveillance, satellite orbit transfer, and space defense.

As currently conceived, the Military Spaceplane System includes the Space Operations Vehicle, a militarized reusable launch vehicle, the Space Maneuver Vehicle, a reusable upper stage / reusable satellite bus, the Orbital Transfer Vehicle for on-orbit asset relocation, and the Modular Insertion Stage, a low cost expendable upper stage. From a user perspective, the Space Operations Vehicle would be ideally as different from a civil or commercial RLV as an F-111 is from a Boeing 737, with emphasis on operational characteristics such as mission flexibility, rapid launch, rapid turn around, and all weather operations, rather than minimum cost launch. Like its commercial counterpart, however, a critical enabler for the Military Spaceplane System is affordability. With a target date for initial operations around 2018 – 2020, there is some likelihood that the Space Operations Vehicle will be

³⁰⁵ Sietzen, Frank, Jr, "Spacelift Washington: Commission to Recommend Military Space Boost, New Programs," January 10, 2001, www.spaceref.com.

³⁰⁶ Sietzen, Frank, Jr, "Spacelift Washington: U.S. Space Launch Policy Facing Uncertain Overhaul," March 25, 2001, www.spaceref.com.

derived from a commercial or civil predecessor. Space Operations Vehicle concepts studied in the past include extensively modified, scaled derivatives of Lockheed Martin's X-33 and Boeing's DC-XA RLV designs.

Space Maneuver Vehicle concepts have also been studied over the past few years. Under USAF contracts, Boeing designed, fabricated, and tested the X-40A, a scale model of their Space Maneuver Vehicle concept in 1997 and 1998.³⁰⁷ The program culminated in a successful autonomous approach and landing flight test by Boeing and the Air Force in August 1998 at Holloman Air Force Base in New Mexico.³⁰⁸ The X-40A flight test vehicle is on loan to NASA and is currently being flight-tested at Dryden Flight Research Center at Edwards, California as part of the X-37 program.³⁰⁹

While a number of "transatmospheric vehicles", "aerospaceplanes", and military spaceplane concepts have been studied over the years,³¹⁰ the Air Force has not yet committed to any one solution, strategically leaving the door open for other system options, such as a militarized derivative of a commercially developed RLV such as Lockheed Martin's VentureStar or interim, partially reusable solutions such as Boeing's AirLaunch concept.³¹¹

International Reusable Launch Vehicle Concepts

India - AVATAR

India's Defense Research Development Organization (DRDO) announced in May 1998 that it was working on the design of a small RLV, the AVATAR (Aerobic

³⁰⁷ Karasopoulos, H., et al., "Space Maneuver Vehicle Development by the Mini-Spaceplane Technology Program," AIAA 98-4149, AIAA Atmospheric Flight Mechanics Conference, Boston, Massachusetts, Aug 98.

³⁰⁸ Baker, Sue, "First Flight: Space Maneuver Vehicle Tries Its Wings," *Leading Edge Magazine*, October 1998, p. 17.

³⁰⁹ NASA News Release, "Second Successful Free Flight of X-40A Conducted as Part of NASA's X-37 Program," April 17, 2001.

³¹⁰ See for example: Gonzales, Daniel, et al., Proceedings of the RAND Project AIR FORCE Workshop on Transatmospheric Vehicles, RAND Corporation, Santa Monica, California, 1997; and Hart, Don, "A Military Spaceplane – Its Time Has Come," *Aerospace America*, May 1997.

³¹¹ Wilson, J. R., "AirLaunch on Demand," *Aerospace America*, January 2001, p. 43.

Vehicle for Advanced Trans-Atmospheric Research).³¹² The AVATAR is supposed to be the size of a fighter or bomber aircraft, and employ supersonic combustion ramjets in conjunction with an air liquefaction / oxygen extraction system to carry payloads from 500 – 1,000 kg (1,100 – 2,200 lb) into LEO. The advanced cycle engine and the oxygen collection system have reportedly been successfully ground tested at DDRO and at the Indian Institute of Science.³¹³

Japan – Hope-X, SSTO Spaceplane

In 1987 the National Space Development Agency of Japan (NASDA) began examining development of a small, reusable upper stage to be lifted with their H-2 ELV.³¹⁴ The unmanned RLV is called the “H2 Orbiting Plane Experimental” or Hope-X. Since 1987, NASDA and the National Aerospace Laboratory (NAL) have accomplished much in their pragmatic, stepping-stone approach towards developing the Hope-X, executing a series of successful flight test programs over the last decade. The Orbital Reentry Experiment (OREX) was completed in 1994, and the Hypersonic Flight Experiment (HYFLEX) and the Automatic Landing Experiment (ALFLEX) were both completed in 1996. The extensive and successful autonomous approach and landing flight tests completed under ALFLEX were conducted at Australia’s Woomera spaceport, a possible site for the eventual operational RLV system. The flight test series continues with the High Speed Flight Demonstration (HSFD) planned for 2002, and will culminate in flight tests of the Hope-X using the H2A ELV beginning in 2004 or later.³¹⁵

How the program is impacted by the cancellation of the H-2 (Chapter 4) and development delays on H-2A is unknown. According to a report by The Orbital Report News Agency, Japan's Science & Technology Agency has decided to put the

³¹² Associate Administrator for Commercial Space Transportation (AST), *2000 Reusable Launch Vehicle Programs & Concepts – With a Special Section on Spaceports*, Federal Aviation Administration, January 2000, www.ast.faa.gov.

³¹³ Ibid.

³¹⁴ Ibid.

³¹⁵ Ibid.

Hope-X program on hold, while considering other launch options.³¹⁶ I was unable to confirm this, even with a review of NASDA's and NAL's Hope-X program web sites.

According to the Federal Aviation Administration's report by the Associate Administrator for Commercial Space Transportation, *2000 Reusable Launch Vehicle Programs & Concepts – With a Special Section on Spaceports*,³¹⁷ Japan's long-term objective is to develop a single-stage-to-orbit (SSTO) RLV. Reminiscent of the U.S.'s National Aero Space Plane (NASP) program of the late 1980s and early 1990s, NAL is looking at designs for a horizontal takeoff, horizontal landing spaceplane that would incorporate advanced airbreathing engines, such as scramjets and liquid air cycle engines, in addition to rockets – either integrated separately into the airframe or as a combined cycle engine. NAL plans to develop their SSTO RLV prototype by 2010 and a follow-on, fully operational version by 2020. The Japanese government has modified the HOPE program in order to streamline the development of the SSTO spaceplane, and a number of Japanese aerospace companies (Mitsubishi, Ishikawa-Jima-Harima, Kawasaki, Fuji, and Sumitomo) have been studying advanced propulsion systems.³¹⁸

Reportedly, Japan and France have discussed collaborative RLV development, and the possibility exists France's space agency, CNES, might join in the program.³¹⁹

Europe

The Europeans have examined a number of RLV concepts over the past few decades, such as Sänger and HOTOL, but are not currently engaged in a major RLV

³¹⁶ Space-Launcher.com, The Orbital Report News Agency, August 2, 2000, www.orbireport.com/News2000-08.html.

³¹⁷ Associate Administrator for Commercial Space Transportation (AST), *2000 Reusable Launch Vehicle Programs & Concepts – With a Special Section on Spaceports*, Federal Aviation Administration, January 2000, www.ast.faa.gov.

³¹⁸ Ibid.

³¹⁹ Cáceres, Marco, A, "Many RLVs Still a Distant Dream," *Aviation Week & Space Technology*, Vol. 154, No. 3, January 15, 2001, p.148.

development program. However, recent studies are of interest to the context of this thesis and are hence discussed briefly.

In the late 1990s, ESA conducted the Future European Space Transportation Investigation Programme (FESTIP) and initiated the Future Launcher Technology Programme (FLTP).³²⁰ Both programs were devised to determine what the most promising launch system would be for Europe after the Ariane 5. The primary interest of these efforts was in reducing launch costs in order to be competitive in future commercial markets. An impressive array of unmanned reusable launch vehicle concepts was comprehensively examined under the FESTIP study. Included in the concepts examined were single- and multi-stage-to-orbit RLV designs, some powered by rockets, some by advanced airbreathing engines, and some by combined cycle engines. Also included were ESA-scaled variants of Lockheed Martin's X-33 / VentureStar and Boeing's DC-XA RLV designs, neither of which made the down-selection for further study.

Among the three preferred designs down-selected for further study was a two-stage-to-orbit semi-reusable launch vehicle concept formed from the core of the Ariane 5 booster mated to a liquid fly-back booster.³²¹ Stage separation would occur at Mach 4.6 after which the liquid fly-back booster component would cruise back to the launch site under the power of two turbofan engines. This concept would require little technological push and result in launch cost savings of about 15% less than that of the current Ariane 5.³²² The future? According to industry analyst, Marco

³²⁰ Staniszewski, Edgar A, "Semi-Reusable Launch Vehicle - A Next Step For Europe?" AIAA Paper 99-4826, AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 9th, Norfolk, VA, November 1 - 5, 1999.

³²¹ Kuczera, H, and Johnson, C, "The Major Results of the FESTIP System Study," 9th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Norfolk, VA, November 1 - 5, 1999.

³²² Staniszewski, Edgar A, "Semi-Reusable Launch Vehicle - A Next Step For Europe?" AIAA Paper 99-4826, AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 9th, Norfolk, VA, November 1 - 5, 1999.

Cáceres, there currently appears not to be a strong European commitment to spend significant funds on FLTP.³²³

China

Although information is very sketchy, *SpaceDaily* reported that China announced in September 2000 that it intends to begin research and development of a reusable launch vehicle.³²⁴ Initial research "will be in reducing a two-stage launcher to a single-stage reusable launcher and developing technologies and techniques in retrieval of portions of the RLV," according to the article.³²⁵

³²³ Cáceres, Marco, A, "Many RLVs Still a Distant Dream," *Aviation Week & Space Technology*, Vol. 154, No. 3, January 15, 2001, p.148.

³²⁴ Long, Wei, "China To Develop New Generation of Rockets With View To Moon Landing," *SPACEDAILY*, September 19, 2000, www.spacedaily.com/news/china-00zzd.html.

³²⁵ *Ibid.*

6. Reusable Launch Vehicle Development

This chapter presents an overview of some selected reusable launch vehicle development issues, focusing on technology development programs and their strategies. The chapter also examines a few of the other development challenges or barriers to entry for small, private, entrepreneurial RLV ventures attempting to enter the space transportation industry marketplace.

Technical Challenges

The technical challenges in developing an affordable and reliable reusable launch vehicle are enormous, and the effective integration of all of these technologies into an operationally effective system is at least as challenging. The technological difficulties stem from a plethora of sources, including the space environment, launch and reentry environments, and the extreme sensitivity of the design's performance to weight growth.

The on-orbit, ascent, and reentry environments are very harsh. The vacuum, radiation, micrometeorite, and temperature extremes in orbit pose difficult materials and design challenges. The difference in temperature on the external surfaces of the Space Shuttle can vary from -250 degrees F. on the shaded side to several hundred degrees above zero on the side facing the sun. Solar flares and storms can erupt with little or no warning, and micrometeorites can impact a spacecraft with relative closing speeds of more than 30,000 feet per second (over 20,000 miles per hour). Accelerations during launch are very high, as are the acoustical loads imparted from the rocket engines. Reentry temperatures on an RLV can exceed over 3,000 degrees F., and even higher temperatures are possible during ascent for certain airbreathing concepts. At the same time, cryogenic propellants such as liquid hydrogen and liquid oxygen require tanks, propellant lines, valves, seals, and other hardware that can handle temperatures as low as -420 and -285 degrees F, respectively.

RLVs have a natural hurdle to overcome in order to attain orbit – reach a minimum final speed of more than 25,500 feet per second.³²⁶ Unlike the case of their aircraft cousins, the performance of a reusable launch vehicle is a highly nonlinear function of its design. A few percent of growth in dry weight of a typical aircraft, for example, may translate to roughly a linear decrease in range of a few percent. In contrast, dry weight³²⁷ growth of a typical RLV design of a mere few percent may translate to a failed design that cannot achieve orbit. Thus, the weight growth of the RLV during development, an inevitable occurrence, must be very carefully managed. One pound of additional weight added to an RLV's structure due to an unforeseen technical problem or integration requirement can translate to 20 to 40 pounds of required additional weight for the overall RLV. Part of this additional weight is the increased propellant required to achieve the minimum orbital velocity due to the extra structural weight. Another part is due to the additional tankage required to hold that propellant, the additional thermal protection system and structure required to contain the tankage, and additional iterations of this reinforcing loop (e.g. the additional weight added to the RLV in order to hold the extra propellant must itself be propelled to orbital speeds, thus requiring additional propellant and propellant related weight). Thus, small increases in dry weight have a large, ripple-down affect on the overall design of the RLV, making the integration process very important and the overall development very difficult, especially with the general very high level of risk of the employed technologies.

RLV Dominant Design

The difficulty in RLV design has spawned a general lack of consensus among industry experts and design engineers on not only what the optimal design of an RLV should be, but also its overriding system architecture. The dominant RLV design has yet to be established, and rocket engineers and program managers fiercely dispute which technologies should be the focus of their limited resources, in essence, arguing over which technologies (some disruptive, some not) will win the

³²⁶ This value varies somewhat with the type of orbit.

day. This situation is analogous to early twentieth century competition to establish the dominant design of the automobile from a spectrum of candidates powered by various means including electric motors, steam engines, and internal combustion engines. For the RLV case, some technologists believe that only advanced airbreathing engines such as supersonic combustion ramjets, combined cycles, or liquid air cycle engines potentially offer a disruptive enough increase in propulsion system performance to be worth the investment. Others point to the billions of dollars invested in this area with little to show as well as the intensive additional design complexity it requires and thus instead favor a more incremental, evolutionary technology approach to developing RLVs. The latter viewpoint notes that the overall objective is not to pour billions of dollars into maturing the latest set of trendy, flashy, disruptive technologies to somehow integrate into a new RLV design but rather to provide a disruptive increase in the performance of the entire RLV system.³²⁸

Teece³²⁹ notes the importance of selecting the right design in the “preparadigmatic stages,” and gives the early history of the automobile industry and De Havilland’s Comet I as exemplifications. Although significant innovation exists in many architectural features of current RLV entrepreneurial designs (staging Mach number and altitude, number of stages, engine selection, etc.) it is yet unclear which of these designs are viable enough to take to a preparadigmatic stage, where products are actually built and compete with one another over market share of lead users. Kistler appears to be close but many of the others are far from this point. Teece theorizes that the best strategy is to let the basic design “float” until sufficient evidence accrues supporting that design will become the industry standard. This may be an unaffordable luxury in an industry like space transportation where the investment is measured in billions of dollars and product development times can

³²⁷ Dry weight is essentially the weight of the vehicle in orbit, after the vast bulk of its propellant it has been consumed during ascent.

³²⁸ More on this debate in a later section.

³²⁹ Teece, David J., “Profiting from technological innovation: Implications for integration, collaboration, licensing, and public policy,” *Research Policy*, No. 15, 1986, pp. 285-305.

take 5 to 10 years. Indeed, with only a single 1st generation RLV in existence the current stage is probably more accurately deemed a “pre-paradigmatic” stage.

Since the total number of RLVs produced is likely to be small, the space transportation market is effectively a niche market with perhaps less than a dozen RLVs sufficient to meet worldwide low Earth orbit launch demand for some time. With this in mind, the first successful RLV stands a good chance of being the de facto dominant design (here, a “successful” RLV is one which meets NASA’s Space Launch Initiative 2nd Generation RLV program cost goal of \$1,000 per lb to LEO and reliability goal of 0.9999, respectively). With such lengthy development times, large required investment, and other barriers to entry, the first successful RLV fleet may tip the commercial market toward a “winner take all” situation. Although many commercial launch systems would be driven out of business, some of those subsidized by their governments would likely survive due to nationalistic and strategic considerations, including the reluctance of customers to rely on a sole source launch provider. An accident or design flaw, for example, could ground the entire RLV fleet as occurred with the Space Shuttle in the mid-1980s.

RLV Technology Development Programs

The development of critical technologies for reusable launch vehicles has been carried out for over 40 years at various levels of intensity. One could fill hundreds of pages describing the many current and past projects and programs in this area. For brevity, I consider only some of the most important and more recent RLV technology development and demonstration programs below.

NASP, X-30

The full story of the controversial, highly classified National Aero-Space Plane (NASP) program would certainly be fascinating, and might possibly be told with a contrasting mix of engineering excellence and incompetence, political influence and bureaucratic posturing, wasted funding and splendid technical achievement. When

the dust settled after the program was cancelled in 1994, NASA and the Air Force had spent somewhere around \$3.0 billion.³³⁰

The NASP program had its roots in the highly classified Copper Canyon project of 1982 to 1985 by the Defense Advanced Research Projects Agency (DARPA).³³¹ This study examined the feasibility of horizontal takeoff and landing single-stage-to-orbit reusable launch vehicles, and prompted the NASP program which was intended to develop the technologies for an RLV and a sustained hypersonic cruise vehicle, both powered by an advanced airbreathing propulsion system.

In his February 1986 State of the Union Address, President Ronald Reagan introduced the NASP program as enabling an exciting new hypersonic aircraft,

“...a new Orient Express that could, by the end of the next decade, take off from Dulles Airport and accelerate up to twenty-five times the speed of sound, attaining low Earth orbit or flying to Tokyo within two hours...”

Jointly run by NASA and the Air Force, the NASP program began in 1986 to mature the technologies leading to a manned experimental aircraft designated the X-30. The concept exploration phase pointed to vast military, civil, and commercial utility of the hypersonic cruiser and RLV concepts, for example, claiming a large reduction in space launch costs as well as a dramatic reduction in transit time for long-range (atmospheric) flights. Proponents argued that NASP would replace the Space Shuttle, with 24 hour turn-around times and billions of dollars of costs saving to the U.S. due to launch costs of about two orders of magnitude lower than the Shuttle's. The program was co-managed and funded by NASA and USAF. The

³³⁰ Although the estimates in the literature vary considerably, estimates from two program insiders I spoke with were around \$2.5 to \$3 billion including both contractor and government investments. One literature reference indicating more than \$3 billion is: Sponable, Jess M, "It's The Operations, Stupid! Not More Technology," editorial letter in *Aviation Week & Space Technology*, originally published May 24, 1999, www.aviationnow.com.

³³¹ Pike, John, "X-30 National Aerospace Plane (NASP)," FAS Intelligence Resource Program, Mystery Aircraft, www.fas.org/irp/mystery/naps.htm.

development price for the National Aero-Space Plane was originally estimated to be a mere \$3.1 billion over 8 years.³³²

NASP program technology focus was on the rocket-based combined cycle ramjet/scramjet propulsion system required by the various NASP concepts, as well as the extensive materials and structures advancements required to withstand the enormous heat loads associated with sustained, high hypersonic atmospheric flight. While significant technological progress was made, the technical difficulty of the project was vastly underestimated and consequently later estimates of program cost and schedule dramatically increased - some reports estimated the program was 11 years behind schedule and 500% over-budget.³³³ Congress cancelled the National Aero-Space Plane program in 1994 due to cost increases and technology problems.³³⁴

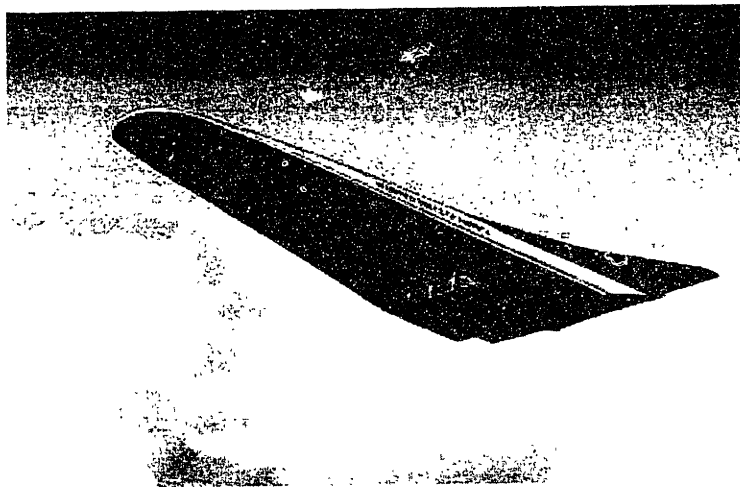


Figure 5 NASP X-30 Concept
(Sketch compliments of NASA)

Many of the exaggerations by NASP proponents of the ease and costs to mature critical NASP technologies, and of the performance and operability advantages of the advanced airbreathing propulsion systems were not difficult to discern by experienced RLV designers in the early days of the program. Eventually, designers were forced to incorporate conventional rockets into some of the X-30 designs in

³³² Ibid.

³³³ Ibid

³³⁴ www.dfrc.nasa.gov/History/x-planes.html.

order to augment the extremely complex airbreathing engines and provide the needed thrust to boost the vehicle outside the sensible atmosphere. Yet even with this coupled with a number of other integration-related design modifications that severely reduced NASP launch flight performance, proponents still claimed the design to be a success.³³⁵ It is astonishing that the NASP program continued for as long as it did in the face of the criticisms it received from sources both internal and external to the Air Force and NASA.

In 1987 the Air Force tasked RAND³³⁶ to evaluate the status of the program and the results were not encouraging. Despite several years of intensive research (by the time the review was conducted) RAND found that many critical technology development issues were unresolved, particularly in the realms of computational fluid dynamics and the airbreathing combined cycle propulsion system.³³⁷ The Defense Science Board (DSB) Task Force also reviewed the NASP program in 1988. The DSB found that the program had unrealistic development schedules for every one of the concept's six critical technology areas: aerodynamics, supersonic mixing and fuel-air combustion, high-temperature materials, actively cooled structures, control systems, and computational fluid dynamics.³³⁸ Interestingly, both RAND and DSB concluded that the latter technology was inadequate as the primary NASP design tool and would be for a decade or more. These and other program assessments also pointed to the very high levels of uncertainty associated with the flows through engine inlets and combustion chambers including turbulent flow transitions and engine mode transitions, and materials problems associated with cryogenic hydrogen used in active cooling of various vehicle components and structures heated to very high temperatures. The program ground on, however, with

³³⁵ Curiously, many airbreathing advocates implicitly assume that merely incorporating an airbreathing engine, no matter how complex, into an RLV will automatically give the launch vehicle aircraft-like operations, so highly desired. Evidence for this has been sorely lacking.

³³⁶ RAND is a non-profit organization located in Santa Monica, California that conducts research and analysis for public policy issues.

³³⁷ Gonzales, Daniel, et al., Proceedings of the RAND Project AIR FORCE Workshop on Transatmospheric Vehicles, RAND Corporation, Santa Monica, California, 1997.

³³⁸ Ibid.

most of these problems unsolved, even after burning through several billions of dollars.

Regardless of this, the NASP program succeeded in some important technology efforts. According to a NASA historical note on the program,³³⁹

“The program developed significant advances in high-temperature, carbon-carbon materials, lightweight titanium and beryllium alloys, and high strength, corrosion-resistant titanium-alloy composites. These technologies and the program’s work with supersonic-combustion ramjet propulsion will all be useful to subsequent U.S. aerospace efforts in the hypersonic area.”

NASP-derivative technology programs still exist today, and can be seen in the NASA Hyper-X X-43A program (below), AFRL’s HyTech hydrocarbon scramjet engine program, and numerous other projects.

DC-X, DC-XA

The Ballistic Missile Defense Organization’s Single Stage Rocket Technology (SSRT) program was chartered to demonstrate aircraft-like operations for a reusable single stage rocket. As part of the SSRT program, BMDO built an experimental suborbital launch vehicle, officially designated the SX-1 (Spaceplane Experimental), and later known as the DC-X (Delta Clipper-Experimental). The vehicle was flight-tested at White Sands Missile Range in New Mexico in the mid-1990s.³⁴⁰

The DC-X was designed to take off vertically, fly a pre-programmed maneuver, and return and land vertically. Its purpose was to test simplified, low cost ground and flight operations, vehicle maintainability, operability, reliability, supportability, and rapid turnaround, all characteristics relevant to future RLVs. Rather than a standing army of operations personnel, for example, the DC-X’s highly automated

³³⁹ www.dfrc.nasa.gov/History/x-planes.html.

³⁴⁰ www.hq.nasa.gov/office/pao/history/x-33/dc-xa.htm.

control center system was manned by only three people: two for flight operations and one for ground operations and servicing. The Delta Clipper Experimental was also intended to be a one-third-scale model of McDonnell Douglas's proposed single-stage-to-orbit RLV.

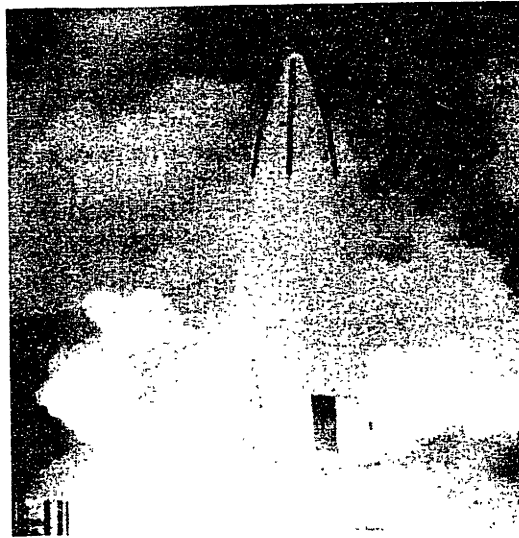


Figure 6 BMDO - McDonnell Douglas DC-X Launch
(Sketch compliments of NASA)

The Delta Clipper Experimental was constructed in 1991 - 1993 by McDonnell Douglas (now Boeing) at their Huntington Beach facility. The DC-X had a conical shape measuring 40 feet high and 13 1/3 feet at base. It was powered by four liquid oxygen / liquid hydrogen RL-10A5 rocket engines, each throttleable from 30% to 100%. The vehicle weighed 20,000 lb dry, and 41,600 lb with a full propellant load.³⁴¹ The DC-X first flew in August 1993 (Figure 6) and successfully completed eight flights before being returned to Huntington Beach for conversion into the DC-XA. Lt Col Jess Sponable of the Air Force's Phillips Laboratory served as the program manager.

The Delta Clipper Graham Experimental Advanced, or DC-XA (later renamed the Clipper Graham) was a modified version of the DC-X, incorporating a number of advanced technologies required for later orbit capable derivatives. Modifications

³⁴¹ Ibid.

included a lightweight graphite-epoxy liquid hydrogen tank and an advanced graphite / aluminum honeycomb intertank built by McDonnell Douglas, an aluminum-lithium liquid oxygen tank built by Energia, and an improved reaction control system from Aerojet.³⁴² The DC-XA was operated by NASA and the Air Force, and was tested at White Sands during the summer of 1996. The DC-XA demonstrated a 26-hour turnaround between its second and third flights, a first for any rocket, but was destroyed by fire due to a collapsed landing gear at the end of its fourth flight, ending the program. An investigation board later determined the cause of the accident was an unconnected helium pressurant line that supplied hydraulic pressure to extend the landing strut.³⁴³

X-33

The purpose of NASA's X-33 program was to prove the technological feasibility of a single-stage-to-orbit reusable launch vehicle. When first begun, the X-33 program was according to NASA the "centerpiece of a NASA 5-year plan aimed at generating the data needed to support a national policy decision on RLV development by the year 2000." This decision was dictated to NASA by law under the 1994 National Space Transportation Policy (NSTC-4),³⁴⁴ under the Space Launch initiative Program (Chapter 5). NASA planned to build and test a series of "Trailblazer" and "Pathfinder" flying technology testbeds to serve as proofs of concept for follow-on medium or heavy-lift RLVs. The Trailblazer RLV technology programs, of which the X-33 was the first, would be focused on large, integrating RLV concepts costing on the order of a billion dollars. The Pathfinders (e.g. X-34) would be flight test programs based on smaller, more limited concepts. NASA planned to initiate new Pathfinder and Trailblazer programs every few years, leading eventually to the development of operational first and second generation RLVs.

³⁴² www.hq.nasa.gov/office/pao/history/x-33/dc-xa.htm.

³⁴³ *Ibid.*

³⁴⁴ Mulville, Daniel, Statement of Daniel Mulville, Chief Engineer, Office of the Administrator, NASA, at the "Space Transportation Architecture Studies: The Future of Earth-to-Orbit Spaceflight" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 27 October 1999, www.house.gov/science/.

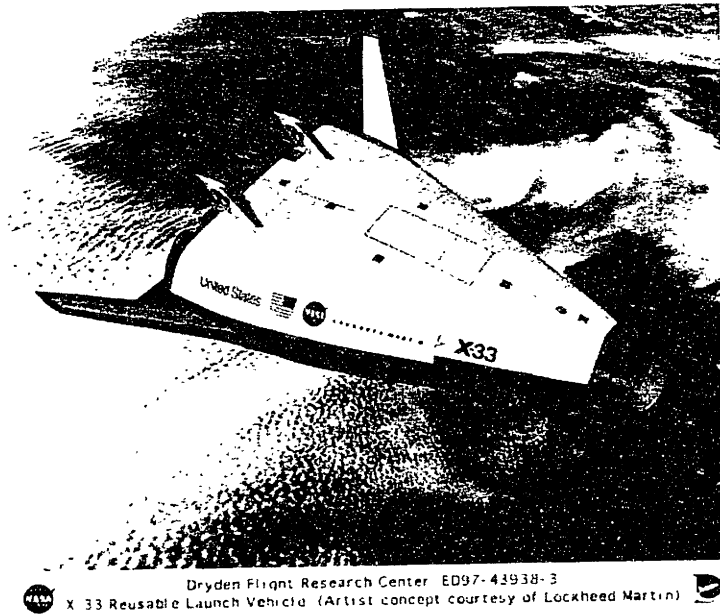


Figure 7 NASA - Lockheed Martin X-33 Concept
(Sketch compliments of NASA)

After a controversial selection of the winning contractor from a bidder pool that also included Rockwell International and McDonnell Douglas, NASA awarded the X-33 contract to Lockheed Martin on July 1996. Under the terms of the cooperative agreement and cost-sharing arrangement, Lockheed planned to invest \$212 million of its own funds in the X-33 program, while NASA budgeted \$837 million for Lockheed and \$104 in internal funds for NASA's own program work.³⁴⁵ The overall program cost was thus originally estimated to be \$1.14 billion. The first flight of the X-33 was scheduled for March 1999 to allow NASA and the U.S. government time to abide to NSTC-4.

Lockheed Martin's interest in the X-33 (Figure 7) was fundamentally to reduce development risk for a commercially developed and operated single-stage-to-orbit RLV, called VentureStar (Chapter 5), by proving critical technologies and design principles. The X-33 was intended to be an approximate half-scale, suborbital prototype of the orbital VentureStar. Like the X-33, the VentureStar was to be

³⁴⁵ Gonzales, Daniel, et al., Proceedings of the RAND Project AIR FORCE Workshop on Transatmospheric Vehicles, RAND Corporation, Santa Monica, California, 1997

uninhabited, take-off vertically, and land horizontally. Among the technologies NASA and Lockheed had intended to demonstrate with the X-33 program are:

- Linear aerospike liquid oxygen / liquid hydrogen engine
- Composite liquid hydrogen propellant tanks
- Thermal protection system concepts including advanced flexible reusable blankets, durable metallic systems, integrated standoff systems, and carbon / carbon leading edges
- Lifting body aerodynamics and performance
- Hot control surface structure
- Composite thrust structure
- Integrated vehicle health management systems
- Autonomous vehicle operations

In addition to these and other technologies, the X-33 program aimed to demonstrate a number of ground operational processes of significant improvement over current Shuttle operations. Included in these demonstrations were plans to attempt a two-day turnaround of the X-33.^{346, 347}

The X-33 program had a number of technical difficulties that ate up funds and schedule. Development of the linear aerospike rocket engine took longer than expected, pushing the first flight test back by about six months. In parallel work on a derivative of this engine for the VentureStar, difficulties also surfaced in the design of the engine expansion ramps, which would be subjected to intense thermal and acoustic loads. Although a number of smaller problems contributed to cost and schedule overruns, the biggest technical problem for the X-33 program was the failure (catastrophic de-lamination) of one of the graphite composite liquid hydrogen tanks during ground testing. Originally blamed on a manufacturing error, a review found the tank's design to be faulty. Program managers estimated an additional \$55 million would have been required by the program in order to design and fabricate

³⁴⁶ Wilson, J. R, "X-33 and RLV Take Parallel Paths," *Aerospace America*, February 1999, p. 38.

two aluminum replacement tanks. Accompanying the increased costs, the vehicle's weight would have risen, significantly degrading the X-33's flight performance.³⁴⁸

The X-33 program was dumped by NASA in March 2001 due to extensive cost overruns after an expenditure of \$912 million by NASA and \$356 million by Lockheed Martin, the latter about \$145 million more than planned.³⁴⁹ The X-33 was to have flown 15 high-Mach suborbital flights by 2000. Instead, when the program was cancelled the flight test vehicle was only about 90% complete and the earliest advertised flight test date was 2003.³⁵⁰ Even more telling, however, was the dramatic drop in the flight test vehicle's estimated performance, rumored to have dropped from a maximum flight speed goal earlier in the program of about Mach 15 to Mach 10 or 11 or even lower, raising concerns that the vehicle could even meet its minimum ranges imposed by the launch facility at Edwards Air Force Base in California and the landing facilities at Michael Army Air Field at Dugway Proving Ground, Utah and Malstrom Air Force Base, Montana.

Lockheed's X-33 concept was generally thought to be far more risky and much more complicated than Rockwell's or McDonnell Douglas's concepts. Many RLV designers were surprised at NASA's selection of this concept over the others. Some attributed it to NASA's apparent tendency to select revolutionary rather than evolutionary concepts to develop. Others attribute NASA's decision to two determinants based on political and psychological reasoning: first, that a Rockwell design could not be selected since Rockwell built the expensive Space Shuttle system and the focus of X-33 was on order of magnitude launch cost reduction; and second that the McDonnell Douglas DC-X design was too risky as demonstrated by the landing gear failure of the DC-XA. If true, the latter argument is especially ironic

³⁴⁷ Although they received relatively little notice, some of the planned ground operations demonstrations could have been invaluable for future RLV development.

³⁴⁸ From: Cabbage, Michael, "Liftoff In Doubt for Heir to Shuttle," *The Orlando Sentinel*, August 20, 2000; and Cabbage, Michael, "NASA Shells Out \$68 Million to Bail Out X-33 Space Plane," *The Orlando Sentinel*, September 30, 2000.

³⁴⁹ Hoversten, Paul, "Citing Costs, NASA Kills Futuristic X-33, X-34," *Aviation Week and Space Technology*, www.AviationNow.com, 1 March 2001.

³⁵⁰ *Ibid.*

since the Europeans found from their Future European Space Transportation Investigation Programme (FESTIP) that the probability of catastrophic loss of their FSSC-3 concept (a vertical-vertical, single-stage-to-orbit RLV concept derived from the DC-XA), was approximately only one third that of their FSSC-5 RLV concept (a derivative of the X-33).³⁵¹ An alternative hypothesis is that NASA's down-selection decision depended on which company most effectively convinced NASA it would pursue financing and developing a follow-on, operational reusable launch vehicle.³⁵² Regardless of the real reason, NASA gambled on the riskiest approach and lost.

X-34

NASA's X-34 program has the unsavory distinction of being one of the few programs ever cancelled twice.³⁵³ The original X-34 program was awarded in the mid-1990s to the industry team of Rockwell International and Orbital Sciences Corporation. The original program goals were to develop a suborbital, air-launched RLV testbed capable of reaching a speed between Mach 12 to 14 at about 100 miles altitude. NASA's hope was for the technology demonstration program to enable a follow-on commercial system that would deploy an upper stage at apogee to orbit payloads. However, the original, \$60 million, ill-fated X-34 program was abandoned due to program cost growth and disagreements between Rockwell and Orbital over which rocket engine to use, the Russian RD-120 or Rocketdyne's RS-27.³⁵⁴

After the cancellation of the first X-34 program, NASA competitively awarded the new and improved X-34 program to Orbital Sciences in 1996. This \$85.7 million contract was for X-34 design, development, and flight tests. Three test vehicles were to be built, one for ground tests and un-powered flight tests and two for powered flight tests. The new X-34 program's goal was to provide a much more

³⁵¹ González, P., "Influence of the Abort Capability in Reusable Systems Reliability – FESTIP Results Overview," AIAA Paper 1999-4928, 9th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Norfolk, VA, November 1 - 5, 1999.

³⁵² Grey, Jerry, "The Rocky Road to Space-Launch Heaven," *Aerospace America*, November 1996.

³⁵³ By some accounts the X-34 program was instead abandoned once by the contractors and cancelled once by NASA.

³⁵⁴ Gonzales, Daniel, et al., Proceedings of the RAND Project AIR FORCE Workshop on Transatmospheric Vehicles, RAND Corporation, Santa Monica, California, 1997.

modest suborbital, air-launched RLV testbed, with a maximum speed of only Mach 8. The X-34 (Figure 8) was to demonstrate new, efficient vehicle processing and launch operations, evaluate performance of advanced RLV technologies, and host alternative RLV technology experiments in “realistic”³⁵⁵ RLV environments. The technologies that were intended to be demonstrated include:

- Reusable Liquid Oxygen / Kerosene Rocket Engine
- Thermal Protection System Concepts
- Advanced Carbon Silicon Carbide Hot Structures
- Titanium Aluminide Structure
- Encapsulated Carbon Matrix Composite Materials
- Mechanically Attached Composite Structure and Skin
- Electric Actuation
- Rapid Turn-Around Capability (24 Hour Goal)
- Autonomous Flight Operations Through Adverse Weather (Rain and Fog)
- Integrated Structural Health Monitoring System for Kerosene Tank.

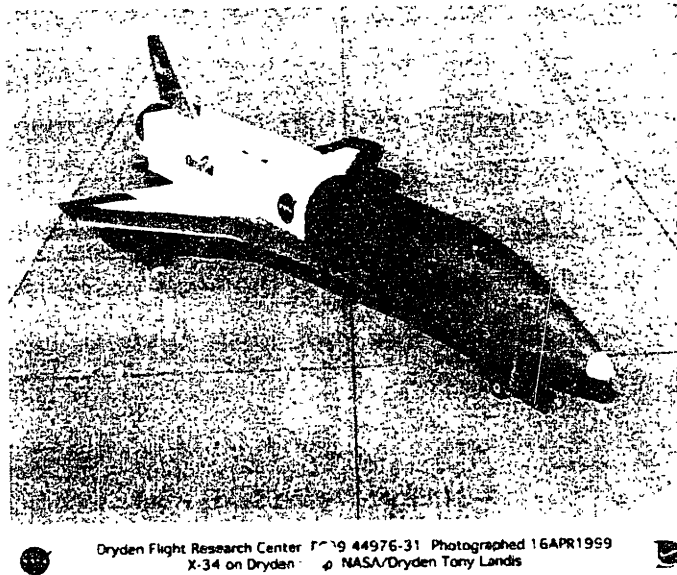


Figure 8 NASA - Orbital Science X-34
(Photograph compliments of NASA)

³⁵⁵ “Realistic” is debatable here since the flight environment at Mach 8 is far, far less demanding than reentry flight at triple these speeds.

An August 2000 *SpaceRef.com* article reported delays up to two years and extensive cost overruns.³⁵⁶ At this point powered flight tests, originally scheduled for 1999, were being slipped until at least 2002 assuming costs could be contained. The article also mentioned that NASA was considering dropping the number of flight tests from 27 to half a dozen or so, as well as reducing the X-34's maximum flight test speed from Mach 8 to 2.5.³⁵⁷

The X-34 program was cancelled in March 2001 due to extensive cost overruns after an expenditure of \$205 million by NASA.³⁵⁸ NASA and Orbital Sciences Corporation laid much of the blame for the failure of the program on each other. Orbital claimed that NASA made unnecessary design changes and intruded and interfered with Orbital's work, particularly after two 1999 well-publicized Mars probe failures when the agency began revamping their "better-faster-cheaper" philosophy.³⁵⁹ Another major problem cited by the contractor was the liquid oxygen / kerosene Fastrac rocket engine, under development by NASA in-house at NASA Marshall Space Flight Center. Like the Rotary Rocket Company, Orbital Sciences' X-34 program also ironically depended on NASA to develop this critical system in order to reduce development time and technical risk. However, NASA's Fastrac engine program ran into difficulties and had not yet produced an engine for the waiting X-34 flight test vehicles as of contract cancellation.³⁶⁰ NASA, on the other hand, claimed that the program was cancelled due to spiraling costs, not their Fastrac engine, and that the investigations of the Mars probe failures had impacted the X-34 program by pointing out that redundant systems were needed in even unmanned vehicles.³⁶¹

³⁵⁶ Cowing, Keith, "Two Year Delay in X-34 Flight Testing Being Considered by NASA," August 24, 2000, www.spaceref.com.

³⁵⁷ *Ibid.* The value of a Mach 8 demonstrator for proving out technologies designed to withstand much higher speed flight was already suspect. A maximum speed of Mach 2.5 was ludicrous.

³⁵⁸ Hoversten, Paul, "Citing Costs, NASA Kills Futuristic X-33, X-34," *Aviation Week and Space Technology*, www.AviationNow.com, 1 March 2001.

³⁵⁹ Spires, Shelby G., "Builder of X-34 Faults NASA," *The Huntsville Times*, March 8, 2001.

³⁶⁰ After completing development of the engine in 1999, NASA contracted Summa Technology to manufacture three Fastrac engines for the X-34 program according to: Associate Administrator for Commercial Space Transportation (AST), *Reusable Launch Vehicles & Spaceports: Programs & Concepts for 2001*, Federal Aviation Administration, January 2001, www.ast.faa.gov.

³⁶¹ Spires, Shelby G., "Builder of X-34 Faults NASA," *The Huntsville Times*, March 8, 2001.

X-37

NASA's X-37 program is another reusable launch vehicle technology testbed, but it differs significantly from the X-33 and X-34 concepts in a very important facet – the X-37 will be designed and demonstrated in both the atmosphere and in space, thus testing RLV components throughout their entire flight envelope. The X-37 is hence designed for flight ranging from low speed autonomous approach and landing on a conventional airport runway to Earth atmospheric reentry at speeds exceeding Mach 25. In contrast, the X-33 and X-34 were designed for maximum flight speeds of Mach 15 and Mach 8, respectively.



Figure 9 USAF - Boeing X-40A Space Maneuver Vehicle
(Photograph compliments of NASA)

In July 1999, NASA awarded The Boeing Company of Seal Beach, California a four-year cooperative agreement to develop the X-37. The total value of the cooperative agreement is about \$173 million, and the agreement calls for an approximately equal sharing of development costs between Boeing and the U.S. government.³⁶² The main contributor for the latter is NASA; the Air Force, however, is contributing about \$16 million as well as the use of the X-40A flight test vehicle

(from the Military Spaceplane Program discussed earlier) to the program in order for the X-37 to demonstrate certain technologies of interest to the military.

The X-37 is about 27.5 feet long, has a wingspan of about 15 feet, and weighs in the neighborhood of 12,000 pounds.³⁶³ The X-37 is a reusable upper stage / reusable satellite bus concept that was originally designed to be part of an overall reusable launch vehicle system. The X-37 is a 120 percent scale derivative of the Air Force's X-40A, which itself was derived from Boeing's Space Maneuver Vehicle concept (part of the Air Force's Military Spaceplane System). The unpowered X-40A was designed and built by Boeing under Air Force Research Laboratory contracts in 1996 - 1997, and extensively ground-tested at Holloman Air Force Base, New Mexico. The initial phase of the USAF X-40A program culminated in a successful autonomous approach and landing flight in August 1998.³⁶⁴ The Air Force's follow-on X-40A flight test phase was overtaken by NASA's X-37 program, in which many additional approach and landing flight tests of the X-40A are currently being conducted by NASA at Edwards Air Force Base, California to reduce X-37 risk (Figure 9).³⁶⁵

The X-37 is powered by the venerable AR-2/3 hydrogen peroxide / kerosene rocket engine, and it is designed to be able to maneuver and remain in orbit for up to three weeks. Initial program plans were for the Space Shuttle to carry the X-37 into orbit where the flight test vehicle would be released, conduct an orbital maneuvering flight test, reenter the Earth's atmosphere, and land autonomously. Two orbital flight tests were scheduled in Shuttle launches in 2002 and 2003 at no cost to the program.

³⁶² David, Leonard, "X-37: An Orbital Test Bed," *Aerospace America*, June 2000, p. 39.

³⁶³ NASA Marshall Space Flight Center X-37 Fact Sheet, www.msfc.nasa.gov/news/background/facts/x37.htm.

³⁶⁴ Karasopoulos, H., et al., "Space Maneuver Vehicle Development by the Mini-Spaceplane Technology Program," AIAA 98-4149, AIAA Atmospheric Flight Mechanics Conference, Boston, Massachusetts, August 1998.

³⁶⁵ Davis, Brett, "X-40A Components Tested in Gliding Flight," *Aerospace Daily*, March 14, 2001.



**Figure 10 1998 X-40A Space Maneuver Vehicle Flight
Test at White Sands Missile Range, NM**
(Photograph compliments of AFRL)

A multitude of RLV flight experiments and advanced technology demonstrations will be carried by the X-37 including the following:

- Sub-Surface/Flush High Data Rate Antenna
- Fiber Optic Data Bus System
- Fault Tolerant, Autonomous Operations
- Small Crew Flight Operations Control Center
- All Weather, Windward Adaptive Guidance
- Rapid Mission Data Loading
- Auto Rendezvous - Close Approach
- High Temperature Electronics
- High Energy Density Batteries
- Integrated Vehicle Health Monitoring
- Rapid-Global Thermal Protection System Damage Detection
- Calculated Air Data System
- High Temperature Graphite Beryllium Matrix Sandwich Structure
- Standard Payload Interfaces
- Non-Toxic, Storable Propellant Reaction Control System
- Composite Propellant Feed Lines & Values
- Conformal Reusable Insulation (Windward)
- Durable, Unitized Ceramic Leading Edge Tiles

- High Temp, Low Cost Joints & Seals
- Loop Heat Pipe Thermal Control System
- Durable Advanced Flexible Reusable Surface Insulation
- Highly Operable Metallic Thermal Protection System

The future of the promising X-37 program appears to be currently uncertain. Sources inside the program point to internal NASA squabbling on which NASA center will have to fund the promised Shuttle rides as a major factor in a schedule delay... and a potential showstopper for the overall program. Reportedly, ELV launch options are being examined in case the promised Shuttle launches are withdrawn. Other sources mention potential Shuttle safety concerns with carrying the X-37 in the payload bay. Still other reports note that the X-37 and NASA's use of the Air Force / Boeing X-40A could be dropped as soon as April 2001 if the program doesn't succeed in competition for NASA's own Space Launch Initiative funding.³⁶⁶ It is reported that the program has spent \$132 million as of March 2001.³⁶⁷

Hyper-X, X-43A

The Hyper-X X-43A is a hypersonic flight test vehicle program with the goal of validating designs of an airframe-integrated, airbreathing hypersonic propulsion system. The propulsion system to be tested on the X-43A is a hydrogen-fueled supersonic combustion ramjet, or scramjet, which is a possible future engine for 3rd generation RLV concepts.³⁶⁸ The Hyper-X program appears to be wisely testing a number of hypersonic propulsion related technologies that were developed under the NASP program at significant expense but were never tested.

Each of the three un-piloted Hyper-X research vehicles is 12 feet long and is manufactured by Micro Craft Inc. of Tullahoma, Tennessee. Micro Craft is also providing overall program management for the industry team that includes Boeing North American of Seal Beach, California, GASL Inc. of Ronkonkoma, New York,

³⁶⁶ Hoversten, Paul, "Budget Concerns Could Shrink X-Fleet Further," *Aviation Week and Space Technology*, www.AviationNow.com, 2 March 2001.

³⁶⁷ *Ibid.*

³⁶⁸ NASA currently estimates the development of a 3rd generation RLV around the year 2025.

and Accurate Automation of Chattanooga, Tennessee. Boeing is conducting vehicle aerodynamic, thermal, and structural design analysis, GASL is designing and fabricating the scramjet engine and fuel system, and Accurate Automation is handling the instrumentation.³⁶⁹

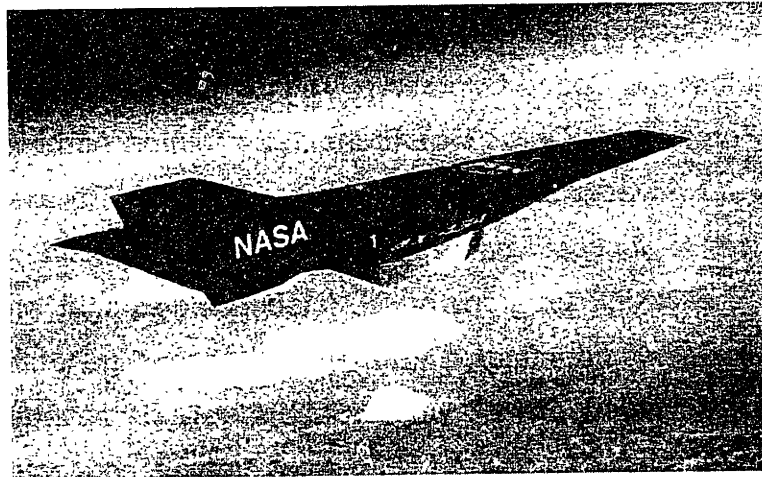


Figure 11 NASA – Micro Craft X-43A
(Artist sketch compliments of NASA)

The X-43A vehicles (Figure 11) will be mated to Orbital Science Pegasus rocket boosters that will accelerate the flight test vehicles up to Mach 7 and Mach 10 test conditions after air-launch from Dryden's B-52 research airplane. The program plans to conduct three flight tests within the Western Test Range off the coast of southern California, two at Mach 7, and one at Mach 10. The flight test vehicles are unrecoverable and will conduct aerodynamic and propulsion experiments before crashing into the Pacific Ocean. The first flight test is scheduled for this year.

Initiated in March 1997, the Hyper-X program had originally scheduled its first flight test for early fiscal year 1999. The X-43A program had spent \$183 million as of March 2001 without a test flight to date.³⁷⁰ Curiously, the original contract funding could not be located even with an intensive search on NASA's official X-43 web

³⁶⁹ Freeman, Delma C, et al., "The NASA Hyper-X Program," 48th International Astronautical Congress, Turin, Italy, October 6-10, 1997.

³⁷⁰ Hoversten, Paul, "Budget Concerns Could Shrink X-Fleet Further," *Aviation Week and Space Technology*, www.AviationNow.com, 2 March 2001

pages, numerous other Internet sites, the media, and even a number of program overview papers.^{371, 372}

Space Operations Vehicle Technology Program

While currently at much lower funding levels than NASA, the Air Force Research Laboratory is conducting significant research in reusable launch vehicle technology development under the Space Operations Vehicle Technology Program, at Wright-Patterson Air Force Base, Ohio. Due to the 1994 Clinton Administration order that NASA would lead government RLV development, the Air Force's RLV technology maturation effort is focused primarily on either critical technologies not being addressed by the NASA program or RLV technologies that are military-unique. AFRL's effort is closely coordinated with NASA's second generation RLV program and the two organizations are working collaboratively on several RLV technology programs, such as the X-37. Space Operations Vehicle concepts appear in Figure 12 and Figure 13.



Figure 12 Lockheed Martin – USAF Space Operations Vehicle & Modular Insertion Stage Concepts
(Artist sketch compliments of AFRL)

³⁷¹ Freeman, Delma C, et al., "The NASA Hyper-X Program," 48th International Astronautical Congress, Turin, Italy, October 6-10, 1997

³⁷² Micro Craft's website (http://www.microcraft.com/IO_hyperX.htm) indicates their contract was worth \$33.4 million over 55 months to build 4 vehicles, with the first flight scheduled for early fiscal year 1999.

In the area of reusable propulsion, AFRL has research programs on advanced liquid hydrogen / liquid oxygen rocket engine components such as turbopumps, pre-burners, hydrostatic bearings, light weight thrust chambers, and light weight cryogenic lines and ducts.³⁷³ AFRL is also conducting research in military RLV designs, hot primary and control surfaces, out-of-autoclave composite processing, advanced thermal protection systems and non-destructive inspection of them, photonic vehicle management systems, electric actuation, and advanced energy storage techniques.³⁷⁴

In addition to these programs, AFRL is conducting research related to other reusable elements of the Military Spaceplane System, including the Space Maneuver Vehicle and the Orbital Transfer Vehicle.

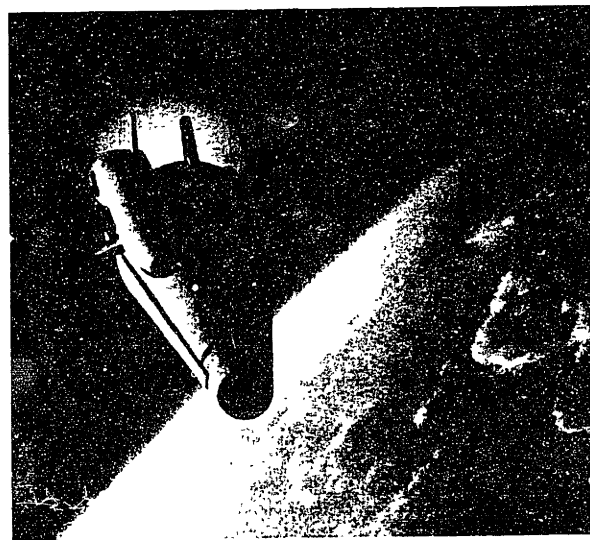


Figure 13 Boeing – USAF Space Operations Vehicle & Space Maneuver Vehicle Concepts
(Artist sketch compliments of AFRL)

³⁷³ Karasopoulos, Harry. and Gillard, William, "Space Operations Vehicle (SOV) Technology Program," Military Spaceplane ITTP Review, Kirtland Air Force Base, New Mexico, 21 March 2000.

³⁷⁴ Ibid.

Technology Development Observations

This section presents some observations of technology strategies, issues, and trends garnered from the ELV and RLV development programs discussed in Chapters 4 and 5 as well as the RLV technology demonstration programs presented in this chapter. The observations are unapologetically colored somewhat by my own prior engineering and management experiences in RLV technology development and assessments of entrepreneurial RLV designs and technology maturity.

Entrepreneurial Launch Vehicle Development is Very Challenging

Entrepreneurial reusable launch vehicle development poses an extremely risky and difficult challenge. There have been a number of failed entrepreneurial launch vehicle development ventures in the past (Figure 14), and to date no entrepreneurial ELV or RLV venture has succeeded. Government and corporate programs have fared no better. NASA cancelled their X-33 and X-34 programs just a few weeks ago at a cost of \$1.5 billion due to technological problems and excessive cost and schedule growth. Further, the entire current crop of entrepreneurial RLV developers appears to be foundering, at least with respect to acquiring sufficient capital to complete development.

That this is the case should not be surprising. Almost every existing ELV today was an evolutionary derivative of a successful, prior existing, and operational system. This is as easy as development can get, yet such projects still require staggering amounts of capital and many years to complete. And even with the expertise of the aerospace industry giants and large consortiums, a very high percentage of these new ELVs fail on their first launch. On top of all of this, ELVs are far less complex and far easier to develop than RLVs since all the components need only work once and many additional ones are required for reentry, landing, health monitoring, etc.

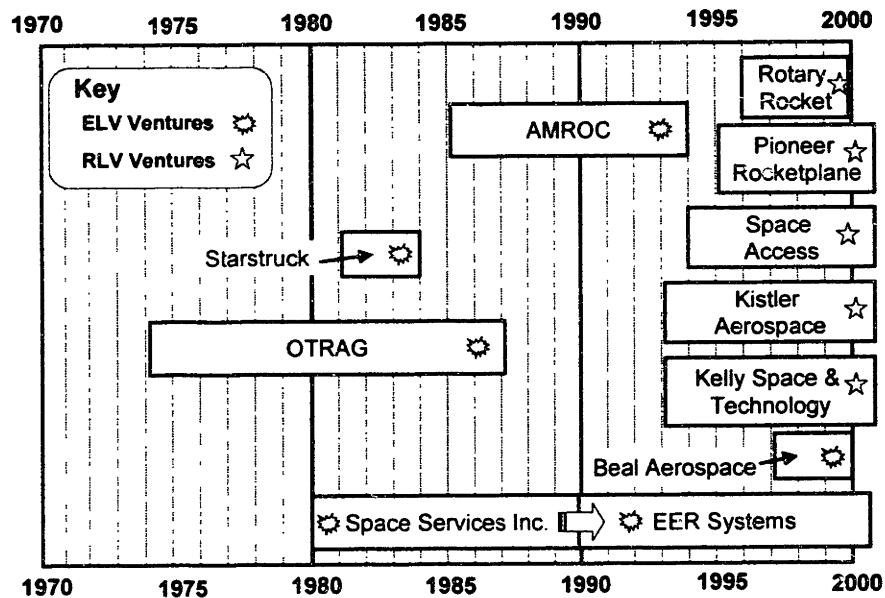


Figure 14 Some of the Entrepreneurial RLV and ELV Ventures since the 1970s

Entrepreneurial Developers Almost Exclusively Use Current Technology

"It's The Operations, Stupid! Not More Technology"

- Lt. Col. Jess M. Sponable (USAF, Ret.)³⁷⁵

With recognition of the daunting challenges and risks facing an entrepreneurial RLV developer, and an industry consensus that current technology is probably sufficient for constructing an RLV,³⁷⁶ it is no wonder that almost all of the entrepreneurial designs employ current technology almost exclusively. Additionally, most ventures also emphasize their use of commercial off-the-shelf components wherever possible, notably Russian liquid oxygen / kerosene rocket engines. These companies generally hold little intellectual property protection other than on an architectural level or for special discriminating innovative designs, such as Kelly's patented tow-launch assist, Kistler's landing recovery system, or Pioneer's aerial

³⁷⁵ "It's The Operations, Stupid! Not More Technology," title of an editorial letter in *Aviation Week & Space Technology*, originally published May 24, 1999, www.aviationnow.com. Lt. Col. Sponable also served as Program Manager for the DC-X and Military Spaceplane Programs, Kirtland Air Force Base, NM.

propellant transfer. Most of the few entrepreneurial launch vehicle developers that did more extensive technology development perished (e.g. Beal, Rotary Rocket, Starstruck, American Rocket Company).

The risk of success in developing complex new RLV technologies is very high. Even with some \$3 billion invested, NASP was still stymied by the complexity, cost, and integration of a myriad of advanced technologies required to develop or integrate its high technology airbreathing engines. X-33 was similarly stalled with its high technology rocket engine and advanced composite propellant tanks. The list of RLV and ELV vehicle development programs that failed due to failed critical technology development is long.

With the limited human resources and complementary assets held by the entrepreneurial firms, and the great challenges posed by integration, the low technology approach appears to be the most sensible. The furthest along of any of the entrepreneurs, Kistler, has followed this tactic more strictly than the other leading RLV developers, diverging from a classic ELV design the least.³⁷⁷ Kistler reportedly originally developed their K-0 design in 1993 – 1994 but scrapped it in 1995 due to the management decision that the design relied too much on immature technology.³⁷⁸

Trend in Design Simplicity

Related to the call for no new technology is a philosophical design approach for RLVs or their critical systems and subsystems that seems to be becoming more predominant with RLV technology developers. This approach is the purposeful eschewing of design complexity for simplicity, epitomized by the expression, “Keep it simple, stupid” or KISS. Generally, the more complex the system, the higher the parts count, cost, and risk of failure, and the more difficult and expensive it is to

³⁷⁶ Although there is some debate whether a full order of magnitude cost reduction could be realized.

³⁷⁷ Kistler is the only leading entrepreneurial RLV concept not to employ wings. At least one, less mature suborbital RLV developer, TGV Rockets, plans to follow suit.

operate. A KISS design approach can produce very powerful results. Under AFRL's Integrated Powerhead Demonstration program, for example, careful design and investment in particular technologies allowed part counts in a rocket engine's oxygen and hydrogen turbopumps to be reduced by factors of 9 and 3, respectively. This greatly increased estimated reliability and decreased manufacturing costs.³⁷⁹ Ariane's design simplicity and modularity helped Arianespace wrest considerable market share from U.S. competitors and was obtained by ESA's use of "...a high degree of commonality in the design of different vehicle stages, and evolutionary design from one vehicle to the next."³⁸⁰ Likewise, Airbus's dominance over Boeing through much of the 1990s is also partially attributed to the former's fundamental design philosophy of simplicity and modularity.

Kistler CEO, Dr. George Mueller, discussed simplicity in his testimony to the House Subcommittee on Space and Aeronautics in October 1999:³⁸¹

"Our most important design criterion is simplicity. Kistler is NOT a development program for new technologies. Rather we are using only proven technologies adapted for our purposes. We are building a truck for delivering payloads to orbit."

Stepping Stone, "Build a Little, Fly a Little" Approach

Simplicity is not only important for launch vehicle design but in the design of the overall development program as well. One of the reasons why NASA's experimental RLV demonstrators are failing at an alarming rate is their very high level of complexity, induced by their attempt to leapfrog evolutionary technologies. Rather

³⁷⁸ Mueller, G.E., et al., "Building The K-1 Reusable Aerospace Vehicle As A Commercial Venture," 50th International Astronautical Congress, Amsterdam, The Netherlands, October 4 - 8, 1999.

³⁷⁹ From Karasopoulos, Harry, Space Operations Vehicle Technology Program status briefing, Air Force Research Laboratory, AFRL/VA, Wright Patterson Air Force Base, OH, December 1999. Original information provided by Integrated Powerhead Demonstration program manager, Matt Jones, AFRL/PRRE, Edwards Air Force Base, CA.

³⁸⁰ United States Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28, Washington, DC, September 1988.

³⁸¹ Mueller, George, Written Statement of Kistler Aerospace Corporation, Presented at the "Commercial Spaceplanes" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 13 October 1999, www.house.gov/science/.

than a pragmatic, stepping stone solution to system development as epitomized by the classic, iterative “build a little, fly a little” approach NASA employed so effectively in the 1950s, 1960s, and 1970s with experimental aircraft,³⁸² NASA has consistently attempted to skip intermediate steps in a rush to a final 2nd generation RLV solution. The failures of the very costly and very complex X-30, X-33, and X-34 programs to achieve their ambitious goals are examples of the outcome of abandoning the more evolutionary stepping-stone approach. In contrast, DoD’s modestly funded DC-X and X-40A programs set challenging but practical goals which they very successfully achieved.

As noted in Chapter 5, perhaps one of the most important outcomes of the X PRIZE will be the focus the contest is providing on incremental development of reusable launch vehicles. Rather than requiring orbital RLV flight to win the prize, it can be won by the relatively modest accomplishment of a suborbital flight. By this approach, the X PRIZE Foundation is wisely encouraging a stepping-stone, evolutionary development for full-scale, orbit-capable RLVs, and thus increasing the likelihood of success. This circumvention of the time-honored, but almost always failing, technology “leap-frog” or revolutionary approach is both pragmatic and admirable.

Disruptive RLV Technologies versus Disruptive RLV Systems

A successful Reusable Launch Vehicle (one that could meet NASA’s 2nd generation RLV goals of a reduction of launch costs and an increase in safety from current Shuttle values of about \$10,000 per lb to LEO and 0.993, to \$1,000 per lb to LEO and 0.9999, respectively) would indisputably be a disruptive product, and would revolutionize the space industry. Interestingly, it appears that the RLV research community has nearly always implicitly assumed that revolutionary technology

³⁸² A succession of aircraft X vehicles was produced over these years with incrementally increasing performance. Some of these represented an evolutionary exploration of aircraft handling characteristics at speeds near and greater than the speed of sound, Mach 1. Unfortunately, the prevailing opinion of RLV development is that the intermediate steps can be skipped to save development costs. In following this revolutionary product development approach, however, we fail

advances are required in order to create a revolutionary product. This is not the case with some very complex, highly nonlinear systems such as RLVs where integration of a myriad of evolutionary technology advances can sum to a revolutionary product, that is, a reusable launch vehicle having a revolutionary performance capability.

This is an important hypothesis worth restating somewhat differently for clarity: with the highly nonlinear relationship between RLV integration and performance, it stands to reason that the proper integration of a number of sustaining technological advances into a suitable reusable launch vehicle design can produce a final RLV system having a disruptive performance capability. The suitable RLV design is one that is produced by a system engineering analysis of the entire RLV system, including ground and flight operations. Rather than the traditional approach of trying to integrate a collection of RLV systems, subsystems, or even components, each individually developed by specialists via optimization with component-specific payoff functions, system engineering optimizes the design of the entire system for the overall performance parameters of interest – in this case system cost and reliability.³⁸³

The more traditional approach, unfortunately, is thus that of isolated component specialization and optimization. This approach is strengthened by the high level of technological complexity of even the minutest components, resulting in laboratories where technology specialists are now the norm and generalists very rare. The professional interests of the researchers usually serves to strengthen their enthrallment with disruptive technologies; the lure of high technology is often

far more often with the consequence that accumulated RLV development costs far exceed those that a more evolutionary series of experimental developments would have entailed.

³⁸³ The definition of system versus subsystem versus component can be a bit blurry in the literature. Here I assume the term “system” refers to the overall reusable launch vehicle and all of its complementary assets required for operations such as launch facilities and infrastructure, the operators themselves, maintenance and refurbishment staff and equipment, etc. The term “subsystems” thus refers to major RLV systems such as propulsion, thermal protection, controls, etc. Lastly, the term “component” or “sub-subsystem” would be the next breakout below, such as a hydrogen turbopump (itself an intricate system) or an actively cooled wing leading edge heat pipe.

dizzying for RLV development managers and engineers who succumb to the mirage of exciting, potentially disruptive, subsystem technologies – technologies that might prove to provide a disruptive performance capability for the subsystem in isolation - and lose sight of overall system objectives. In the case of RLVs, upon attempting to integrate the disruptive subsystem into a complex system, a plethora of integration problems inevitably erupts, converting the once seemingly revolutionary gain into a hopeless loss of overall system performance. RLV designers found this to be the case with the NASP program with the revolutionary, advanced airbreathing propulsion system, spending billions of dollars to discover their error.

Unfortunately, evolutionary technology advances are not very interesting to many RLV scientists, engineers, and managers. They are often motivated and rewarded more for flailing away at a flashy, revolutionary, technology project for years on end before admitting defeat than for succeeding at a sensible, evolutionary technology project that by itself provides only a modest advancement but, as a critical part of an integrated whole, can enable a revolutionary RLV. Conventional technology management teachings point out the competitive advantages of innovation, of disruptive technologies, and of risk taking. Unfortunately, revolutionary technology development efforts are often misdirected, focusing on subsystem optimization parameters that do not optimize the overall RLV system. Such programs can drain valuable limited resources away from evolutionary technology projects that are critical to the RLV system. This is not to recommend abandoning innovative, high-risk RLV subsystem technology development projects, but rather ensuring: (1) overall system optimization is carried out to discern what the proper subsystem optimization parameters should be, and (2) a proper balance of the technology portfolio is maintained, by tuning it specifically for the nonlinear integration problem of RLVs.

Knowledge Capture & Lessons Learned

Lessons and mistakes learned from past efforts are crucial to future RLV development, and especially so while RLVs are in their infancy stage. The tens of

billions of dollars spent on operations inefficiency with the Shuttle, for example, will be wasted if the associated, invaluable design and operations knowledge is not applied to future RLV generations. The same holds true for the many more billions of dollars spent on failed technology development programs such as NASP, X-33, X-34 and others.

As the world's only operational first generation RLV, the engineers, technicians, and managers that work on the Space Shuttle program at Kennedy Space Center in Florida and elsewhere should be the focus of a massive knowledge capture effort. The countless years of experience and expertise of those who have worked or are currently working the program should be mined with vigor. Likewise, a massive learning effort by 2nd generation RLV designers and program managers should be undertaken in order to take advantage of this knowledge. Curiously, two interviews I conducted last year with mid-level NASA Kennedy space shuttle managers indicated that little was being accomplished in this area. One interviewee even expressed his disappointment that the separate NASA RLV development program offices located at NASA Marshall Space Flight Center in Huntsville, Alabama very rarely interacted with Space Shuttle operations personnel and didn't seem interested in their working knowledge. Hopefully, industry is doing more in this area although I could find no evidence of it in the open literature. On a more positive note, NASA is now beginning to apply a knowledge capturing process although it seems likely it will take considerable time to ramp up and become effective.³⁸⁴

It seems blatantly obvious that explicit knowledge capturing and sharing techniques should be applied to acquire and utilize as many of these lessons-learned as possible from past RLV programs. Mining the Space Shuttle program should be the highest priority since the rate of knowledge dissipation is likely high: the Shuttle was developed in the 1970s, some 30 years ago, and retirements must be seriously eroding the knowledge base. Fortunately, some past work has been done in capturing Shuttle operations experiences. One excellent classic that should

³⁸⁴ Matthews, William, "NASA plans knowledge database," Federal Computer Week, April 17, 2000.

be studied carefully by all current RLV developers is the report, *Reducing Launch Operations Costs: New Technologies and Practices*, by the Office of Technology Assessment of the United States Congress.³⁸⁵

U.S. Government Investment

The primary motive for government investment in space transportation was initially national security and national prestige. As time passed, however, other considerations, such as keeping a skilled labor force employed and maintaining an advanced scientific and engineering research and development capability, also weighed-in and become a part of national strategy. Further, over the years the value of the space industry to our nation's economic and strategic well-being has risen dramatically, and the future potential is even more compelling. Large macroeconomic benefits can likely be realized by proper government investment in reusable launch vehicles. Successful RLV development will greatly increase space launch affordability, flexibility, and responsiveness, and decrease launch price. If prices fall sufficiently, market elasticity will likely drive a large, nonlinear increase in space business activity in many areas including some of the emerging markets discussed in Chapter 3. This should provide large increases in tax revenues, exports, and employment. Lower launch costs would also lower costs for government space projects, allowing additional missions for a fixed investment.

Typically, the United States government has relied on industry to bear much of the costs and risks for major new systems and their infrastructures. Where deemed too critical for national interests to wait for a market-driven development effort, however, governments have often stepped into the fray, providing assistance in funding, incentives, and other instruments to catalyze or directly support technology and infrastructure development. Historical examples include railroads, aviation, and electrical power; many feel the government should do the same for reusable launch vehicles.

³⁸⁵ United States Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28. Washington, DC, September 1988.

Investment decisions by government and industry often are made using a cost-benefit analysis, usually via discounted cash flow or return on investment. However, their analyses of the same project will produce very different results. Large-scale technology development projects such as RLV development are often long-term, high-cost investments that are acceptable to government but not industry. Industry has equity investors to placate and profit margins to maintain. Industry's interest rate for financing such high risk programs is generally very high – for an RLV program possibly 25% or more - and thus industry's time horizons for return-on-investment are generally short. The government, on the other hand, can afford to wait 30 or more years to realize a payback, and the payback can be much lower as the government pays only a small risk premium above the inflation rate. But even if the government can afford to invest vastly differently than industry, it often doesn't.

Hertzfeld argues that the United States government often makes investment decisions very much like that of corporations, focusing primarily on the short-term, bottom-line profit position.³⁸⁶ The U.S. government's short-term focus contrasts sharply from that of many other governments, and in some cases prove to be detrimental to the U.S.'s global competitive position. A good aerospace example posed by Hertzfeld is the case of the Concorde commercial supersonic transport (SST).³⁸⁷

Although the United States had the technical capability to develop a commercial SST (as evidenced by the XB-70 and XR-71 aircraft), the U.S. opted not to develop the aircraft due to the poor business case for the venture, which was predicted to be unprofitable. The British and French were not thwarted by such economic pessimism and charged ahead. With significant effort they succeeded in developing a successful, delightful commercial aircraft that was the envy of the world. However,

³⁸⁶ Hertzfeld, Henry R, "Economic, Market, and Policy Issues of International Launch Vehicle Competition," in *International Space Policy*, Papp, Daniel S, and John, McIntyre, R., Editors, Greenwood Press, Inc., Westport, Connecticut, 1987.

³⁸⁷ Ibid.

the U.S. analysts were correct - the British and French joint SST program was by itself a financial failure. It was, however, a technical triumph. More importantly, Hertzfeld compellingly makes a case that in the long-term the British and French probably made a very shrewd and profitable investment due to SST program's intangible benefits of (1) thrusting the United Kingdom and France to the forefront of aerospace technology³⁸⁸ by training and creating a highly skilled engineering labor force, and (2) providing a nationalistic technological confidence in aerospace excellence that was successfully leveraged in subsequent aerospace endeavors such as the development of the Airbus aircraft family, the Ariane ELV, and other highly globally competitive programs. Hertzfeld asks,³⁸⁹

"If not for the Concorde, would French industry have been able to design, build, and successfully market the Airbus? Would the Ariane launcher as a commercial vehicle have been undertaken and been successful?"

While we will never know the factual answer, intuitively there was an obvious vast return on investment, one far greater than a Net Present Value calculation could disclose. The straightforward analogy is that the country that invests the considerable capital needed to successfully develop a 2nd generation reusable launch vehicle may also reap many rewards beyond the already impressive economic ones.

RLV Barriers to Entry

The space launch industry is characterized by very large barriers-to-entry, so large in fact that nearly every successful ELV entrant was originally sponsored by its respective government. Among these barriers are very high technical and developmental costs and risk, significant market risk, large financial investments, legitimacy, lengthy research & development cycles, heavily subsidized competition,

³⁸⁸ Prior to the program they were technologically behind the U.S.

insurance risk,³⁹⁰ long production cycles, long test and evaluation cycles, regulatory risk,³⁹¹ and large economic rents for infrastructure, knowledgeable human resources,³⁹² and demonstrated past performance to obtain new contracts. Many of these barriers to entry have already been addressed or at least alluded to in prior sections. Unfortunately, the scope of this thesis did not allow me to address the remainder except for an overview of financing and legitimacy issues, which are critically important to entrepreneurial reusable launch vehicle development. This section thus presents a brief introduction to financial and legitimacy barriers to entry, recognizing that both issues deserve a more detailed examination. The legitimacy of government agency RLV technology development is also discussed.

Financing Issues

The multi-billion dollar government investments in reusable launch vehicle technology over the past decade have both helped and hurt entrepreneurial RLV developers. While potential beneficiaries of any government-developed technology that are not subject to contractor proprietary limitations, most entrepreneurial RLV developers are relying instead on current technology, and in most cases, commercial off-the-shelf solutions. Thus most of these ventures view NASA investment in RLV technology and especially in RLV flight demonstrators as direct

³⁸⁹ Hertzfeld, Henry R, "Economic, Market, and Policy Issues of International Launch Vehicle Competition," in *International Space Policy*, Papp, Daniel S, and John, McIntyre, R., Editors, Greenwood Press, Inc., Westport, Connecticut, 1987.

³⁹⁰ See for example the excellent assessment by Moore in: Moore, Roscoe M, III, "Risk Analysis And The Regulation Of Reusable Launch Vehicles," *Journal of Air Law and Commerce*, Vol. 64, No. 1, Winter 1998, p. 245. Moore notes that the safety risk of an RLV could be particularly high for reentry due to a number of factors including RLV's extensive use of thermal protection materials, and higher coefficients of lift for debris.

³⁹¹ See for example the following: "RLV Startups Have Enough Capital, But Worry About Regulation," *Aerospace America*, Vol. 185, No. 29, February 13, 1998, p. 232; and "Industry Praises RLV Regulatory Effort but Questions Cost and Risk," *Aerospace Daily*, Vol. 191, No. 13, July 20, 1999.

³⁹² Recruiting and retaining talented and highly educated staff can be challenging today in the space launch technology arena. This is due to a number of factors including: (1) relatively easy migration to higher paying high technology jobs in more trendy industries such as Internet, biotechnology, communications, etc.; (2) repeated national program failures and cancellations provide a poor sense of accomplishment and generates little excitement – my generation has yet to succeed on a large RLV development program - whereas other industries actually offer opportunities to complete projects; (3) erosion of the experienced launch vehicle designer and operator experience base due to retirement. The latter is especially disheartening, especially the loss of extensive invaluable Space Shuttle operations and design knowledge.

subsidization of their competitors. And not just any competitors: the vast majority of this government funding has been given to established launch industry incumbents Boeing Aerospace Company and Lockheed Martin Corporation who, in the eyes of the entrepreneurs, are the least needy and perhaps least deserving of taxpayer money. Indeed, the \$912 million spent by NASA on the failed Lockheed Martin X-33 program was especially irksome to other RLV developers not only because they felt they should have been recipients of a piece of it, but also because of the competition for financial investors from Lockheed's planned follow-on VentureStar commercial RLV program.

"One of the worst consequences of the X-33 and X-34 fiascos was that they effectively prevented private RLV companies from being able to raise commercial investment for the last six years, since investors cannot afford to compete with government projects – which suited NASA fine."

*- Space Future Journal*³⁹³

It is interesting to see the change in the perceived financial climate for the RLV developers as portrayed in the literature over the past five years. "RLV Startups Have Enough Capital, But Worry About Regulation," was the headline of an Aerospace Daily article as recent as February 1998, in which top officials of Pioneer Rocketplane Corporation, Rotary Rocket Company, Kelly Space & Technology, and Kistler Aerospace Corporation all indicated they anticipated no trouble raising the capital they needed to develop their RLVs.³⁹⁴ The very strong U.S. economy and bull market apparently appeared at that time to be an ideal setting for acquiring financing. But something went wrong and sufficient capital never materialized. Most of these entrepreneurial ventures succeeded in raising only a small fraction of the total development funds required. Kistler was an exception, raising over half a billion

³⁹³ "X-34 Joins X-33 as Fiasco," *Space Future Journal*, September 19, 2000.

³⁹⁴ "RLV Startups Have Enough Capital, But Worry About Regulation," *Aerospace America*, Vol. 185, No. 29, February 13, 1998, p. 232.

dollars, but still only roughly half of that needed to bring their K-1 RLV to an operational status.³⁹⁵

What went wrong is undoubtedly a combined effect from many factors but which single factor dominated is anyone's guess. Although investment money reached record highs over the past few years, with angel investors and investment capitalists seemingly rolling wheelbarrows of money to anyone with a business plan, their focus was on other high technology arenas such as the Internet, communications, and biotechnology. The opportunity costs were and apparently are still too high. I think Jess Sponable said it best near the peak of the dot.com frenzy with:

"In an era where billions of dollars are routinely invested in Internet vaporware, it is ironic that the current business environment won't support investments in next generation transportation."

- Jess Sponable, Universal Space Lines, July 1999³⁹⁶

Another factor creating difficulty for RLV developers to find financing was the large drop in the expected demand for LEO commercial launches in the late 1990s. As noted in Chapter 3, FAA's ten year LEO launches forecast dropped by approximately 50% from its boom prediction in 1997 to 2000 and recent articles with titles like, "Launch Supply Could Exceed Demand for Next Decade," are now the norm.³⁹⁷ Such demand volatility would be unsettling in almost any market.

The financial failure of the Iridium system in August 1999 had a profound effect on the ability of both new and established space enterprises to generate investment capital. Called the "Iridium Effect" by some in the space and financial community,³⁹⁸ it shook investor confidence to the core. ICO, Orbcomm, and Globalstar quickly

³⁹⁵ Kistler's financial challenges were discussed in more detail in Chapter 5

³⁹⁶ Sponable, Jess, "Opening the Spaceways," Conference on Next Generation Launch Systems, Space Technology and Applications International Forum, STAIF-00, Albuquerque, NM, 2000 (Also in *Space Policy Digest*, July 1999, www.spacepolicy.org/page_js0799.html).

³⁹⁷ Ferster, Warren, "Launch Supply Could Exceed Demand for Next Decade," *Space News*, January 22, 2001, p. 8.

³⁹⁸ "The Year in Review: Space Systems," *Aerospace America*, December 2000.

followed into financial distress, further eroding investor interest in space related ventures as well as decimating LEO demand.

Other factors are likely culprits. The high barriers to entry mentioned above are not secret and would be obvious with an even meager effort of due diligence. And some investors must have reasoned, "why invest in very high risk space launch ventures when every past entrepreneurial ELV and RLV commercial development ventures has failed?" or "How can a small entrepreneurial RLV company accomplish what the industry giants with their vast resources could not, even with NASA's technical help and billions of dollars?"

It appears that financing launch vehicle system development is very difficult and will require large amounts of risk capital that far exceed venture capital markets. Thus, large corporate joint ventures, syndicates, United States government, or other large funding sources will be necessary. U.S. government involvement in the financing equation could take many forms, both direct and indirect. In 1999 congressional testimony, for example, Kelly Space and Technology Inc. strongly supported reductions in or the elimination of capital gains taxes on returns made from space business development investments. Kelly also called for NASA, "prudently guided by Congress," to invest in small companies that offer entrepreneurial space launch concepts, funding design, development, and flight test of demonstrators.³⁹⁹

Recognizing the difficulties RLV developers were having acquiring funding, in 1999 Sen. John Breaux (D. Louisiana) sponsored the Commercial Space Transportation Cost Reduction Act, Senate bill S. 469. This remake of S. 2121, introduced the prior year, called for the establishment of Federal government loan guarantees for RLV companies.⁴⁰⁰ Discussions on this bill of what government

³⁹⁹ Davis, Robert, Testimony on Commercial Spaceplanes, Presented at the "Commercial Spaceplanes" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 13 October 1999, www.house.gov/science/.

⁴⁰⁰ Ibid.

could do to improve RLV development revolved around the following: investments in research and development to reduce technical risk; incentives via loan guarantees; incentives from advance purchase agreements; incentives via tax credits, and improvement in “the investment climate through policy stability, regulatory streamlining, predictable certification, and appropriate indemnification.”⁴⁰¹

Support for Senate bill S. 469 from industry was lopsided. Although championed by Lockheed, S. 469 generated little enthusiasm among many of the RLV entrepreneurial firms with perhaps the exception of Space Access. Boeing stated their preference instead for government-funded research and development of high-risk technologies. Other entities stated their concern that the bill might be too focused on Lockheed Martin, and furthermore expressed their concern on how to determine what companies would be selected to receive these loans. Some argued politics, ignorance, or perhaps a bias towards certain companies, past technologies, and launch system architectures by the evaluators (likely to be NASA or the Department of Transportation) may preclude the best option from being selected.⁴⁰²

Some financial experts pointed towards the effectiveness of government loan guarantees. According to Hoyt Davidson of Donaldson, Luftkin, and Jenrette of New York, government loan guarantees would allow RLV financing for “not much more than the Treasury rate versus the 35 - 50% rates of return required by venture capitalists for projects in the early development stage.”⁴⁰³ However, Hawthorne, Krauss & Associates, a NASA consultant hired to analyze these issues, urged caution on implementation of loan guarantees for RLV development. The consultant noted that such guarantees could shift far too much risk onto the government, thus critically reducing the developer’s motivation to perform well – yet allowing the developer to reap the financial rewards. Hawthorne, Krauss & Associates instead

⁴⁰¹ Johnson, Kristine, “Hearing on the U.S. Commercial Space Launch Industry before Senate Subcommittee on Science, Technology and Space, September 23, 1998,” NASA Memorandum for Record, September 23, 1998

⁴⁰² Ibid.

⁴⁰³ “Loan Guarantees Required to Obtain VentureStar Financing, Lockheed Says,” *Aerospace Daily*, Vol. 190, No. 39, May 25, 1999, p. 1.

recommended "the government take the role of second guarantor, so that creditors must seek repayment from the borrower and any parent companies before turning to the government for repayment." ⁴⁰⁴

Although S. 469 fizzled, numerous other proposals for direct U.S. government involvement in supporting RLV development have been proposed and debated, including Rep. Dana Rohrabacher's "zero-gravity, zero-tax" bill.⁴⁰⁵ More information on such options and excellent discussions of the effectiveness of various government incentives for RLV development are given by Shaw et al.,⁴⁰⁶ Scottoline and Coleman,⁴⁰⁷ and Greenberg.⁴⁰⁸ Discussed in these articles are numerous options including advanced purchase agreements, tax credits, tax holidays, targeted tax rebates, loan incentives, loan guarantees, insurance & indemnities, and government capitalization.

Government help in acquiring critical financing to enable aerospace vehicle development is neither exclusive to entrepreneurial firms nor to the last decade. In 1971 Lockheed successfully sought government loans necessary to manufacture their L-1011 Tristar commercial aircraft. In testimony during Congressional hearings, Lockheed asserted that they could not develop this new aircraft without the requested quarter billion-dollar loan (1971 dollars). Lockheed was successful in this request although the company eventually lost significant funds on the L-1011

⁴⁰⁴ From: "NASA Consultant Urges Caution on Loan Guarantees for RLV," *Aerospace Daily*, Vol. 188, No. 29, 10 November 1998, p. 225; and Hawthorne, Kraus & Associates, LLC, Analysis of Potential Alternatives to Reduce NASA's Cost of Human Access to Space, 20 September 1998.

⁴⁰⁵ Sietzen, Frank, Jr, "Conversations with Dana Rohrabacher," *Aerospace America*, March 2001.

⁴⁰⁶ Shaw, Eric J, et al., "Benefits of Government Incentives for Reusable Launch Vehicle Development," IAF Paper 98-1201, 49th International Astronautical Congress, Melbourne, Australia, September 28 - October 2, 1998

⁴⁰⁷ Scottoline, S, and Coleman, R, "Effectiveness of Loan Guarantees versus Tax Incentives for Space Launch Ventures," AIAA Conference on Space Technology, Albuquerque, New Mexico, 28 - 30 September 1999.

⁴⁰⁸ Greenberg, Joel S, "RLV Government/Industry Economic/Financial Issues," AIAA Paper 2000-5097, AIAA Space 2000 Conference and Exposition, Long Beach, CA, Sept. 19-21, 2000. Also see: Greenberg, Joel S, "Considerations When Analyzing Investment In Space Transportation Business Ventures," 50th International Astronautical Congress, Amsterdam, The Netherlands, October 4 - 8, 1999.

business venture.⁴⁰⁹ In 1999, Lockheed Martin again testified in congressional hearings, once again arguing that loan guarantees are needed. This time, however, the target for the government loans was their VentureStar reusable launch vehicle concept.⁴¹⁰

Lockheed was poised in the early 1970s to begin manufacturing of their L-1011 after spending a billion dollars on concept development. At the time Lockheed was deemed more than technically capable of building and selling the aircraft. However, their financial house was a mess and as a consequence banks would not loan Lockheed money to build its manufacturing facility.⁴¹¹ This, for an aircraft that was evolutionary in nature and for a company with numerous commercial aircraft successes in their past. Today's Lockheed Martin, in contrast, is trying to do something that has never been before accomplished - build an RLV. The technical risks are huge as evidenced by the development pains experienced by their X-33 vehicle, the technology demonstrator for their VentureStar.

Interestingly, Hertzfeld asserts that failures in entrepreneurial ELV ventures of the early to mid 1980's (e.g. OTRAG, Starstruck, Transpace Carriers, etc.) were due to a "combination of market timing, financing, and the government's reluctance to let go of controls."⁴¹² It seems nothing has changed.

⁴⁰⁹ See: Reinhardt, U.E., "Break-Even Analysis for Lockheed's TriStar: An Application of Financial Theory," *Journal of Finance*, Vol. 28, No. 4, September 1973, p. 821; and Maital, Shlomo, *Executive Economics – Ten Essential Tools for Managers*, The Free Press, Simon & Schuster Inc., New York, New York, 1994.

⁴¹⁰ See: Cowing, Keith, Editor, "Space Transportation Architecture Studies: Future of Earth-to-Orbit Spaceflight," Hearings before the House Committee on Science's Subcommittee on Space and Aeronautics, *NASA Watch*, 27 October 1999; and "Loan Guarantees Required to Obtain VentureStar Financing, Lockheed Says," *Aerospace Daily*, Vol. 190, No. 39, May 25, 1999, p. 1.

⁴¹¹ Maital, Shlomo, *Executive Economics – Ten Essential Tools for Managers*, The Free Press, Simon & Schuster Inc., New York, New York, 1994.

⁴¹² Hertzfeld, Henry R., "Economic, Market, and Policy Issues of International Launch Vehicle Competition," in *International Space Policy*, Papp, Daniel S, and John, McIntyre, R., Editors, Greenwood Press, Inc., Westport, Connecticut, 1987.

Legitimacy Issues

Since reliability is such a primary concern to customers, legitimacy plays a major role in the sales of launch services, particularly for future market entry of a small entrepreneurial firm with no established brand image and little manufacturing or integration experience. Some legitimacy concerns could be mitigated if the small entrepreneurial firm contracts to established industry figureheads for at least all critical systems and subsystems, if not integration as well. Some in the current wave of RLV entrepreneurs are utilizing these resources as part of their strategy to use current technology and commercial off-the-shelf components wherever possible. RLV developer Kistler Aerospace, for example, has made extensive use of expert contractors to design and manufacture K-1 components, including Lockheed Martin, Northrop Grumman, GenCorp Aerojet, Draper Laboratory, AlliedSignal Aerospace, Irvin Aerospace, and Oceaneering Space Systems.⁴¹³

Historically, small new entrants have essentially “bet the company” with each launch. A failure means an extended period of further engineering and redesign, often a showstopper for companies already with many years without incoming cash flows. Larger firms such as the incumbent primes, Boeing Aerospace and Lockheed Martin, have sufficient capital to fund any required additional development and sufficient brand to instill confidence in declared corrections of launch vehicle flaws. To them, a failed launch is troublesome but not life threatening. A new entrepreneurial RLV market entrant, however, will likely have neither the capital nor the brand to overcome an early catastrophic launch failure. Only with customer-perceived legitimacy can the RLV venture wrest market share from well-established space launch incumbents in an economically viable period of time. An *Aerospace America* article from November 1996 nicely sums up the legitimacy challenge facing RLVs:⁴¹⁴

⁴¹³ Mueller, George, Written Statement of Kistler Aerospace Corporation, Presented at the “Commercial Spaceplanes” hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 13 October 1999, www.house.gov/science/

⁴¹⁴ Grey, Jerry, “The Rocky Road to Space-Launch Heaven,” *Aerospace America*, November 1996.

“The last seven ‘new’ vehicles all failed on their maiden flights: Orbital Science’s Pegasus XL, EER’s Conestoga, Lockheed Martin’s LMLV-1, China Great Wall’s Long March 2E and 3B, the first five-stage version of Russia’s Start-1, and – most recently and most noteworthy – Ariane 5. With a wholly new technology base, the RLV is not likely to enjoy great customer confidence until it has demonstrated its reliability conclusively, even if it is offered at a price significantly lower than that of current competitors. This was clearly demonstrated by the loss of confidence in China’s Long March rockets after their back-to-back failures, despite their relatively low launch prices.”

Legitimacy plays an even more critical role when the payload is human. Even with adequate reusable launch vehicle offerings, the space tourism market will never grow significantly until the customers’ perception of safety is satisfied.⁴¹⁵ Public acceptance of a new space tourism business based on a new RLV concept will be obviously heavily influenced by the perceived legitimacy of the company offering the service. The company’s legitimacy and its ability to obtain investment capital, however, are also influenced to some extent by the overall industry’s safety and reliability records.

Legitimacy of certain elements in the space launch industry is already questionable today, leading to the commonly heard quote by industry experts, “the flake factor is huge in the launch business.” This and similar expressions refer to a number of usually well meaning, enthusiastic, but often unknowledgeable persons who form a very vocal minority and at times have surprisingly strong political clout. Conspiracy theories such as how NASA and the U.S. government are purposely trying to suppress entrepreneurial RLV efforts can be found on the Internet, and even occasionally in other news media. It seems, sometimes, that almost anyone these days can establish a web site with their own back-of-the-envelope RLV design, often with performance claims exceeding reality by at least an order of magnitude, attempting to encourage rightfully cautious investors to provide them

⁴¹⁵ This is discussed in more detail in Chapter 3

funding to support their hobby. Blatantly technically unviable RLV concepts regularly periodically appear in national news stories and television programs.

The fringe can even be more interesting. Unsolicited RLV proposals for designs employing mysterious anti-gravity devices, others using their stereotypical UFO shapes to somehow achieve aerodynamic performance so incredible as to negate the need for engines to travel to and through space, and still others that use helicopter rotors to propel them through "the ether of space" have all graced my work desk within the last decade. It seems doubtful that any other industry receives so much attention by so many enthusiasts. The allure of space is heady.

There may also be spillover of negative impact to RLV legitimacy from high profile problems with other space projects. The enduring classic case is NASA's International Space Station, currently called (in its incomplete state) Space Station Alpha. The ISS program is very tenacious, surviving 22 termination attempts in NASA funding bills since 1991.⁴¹⁶ The original space station design, Space Station Freedom, had a total price tag of \$8 billion in 1984. After 9 more years of work and extensive cost growth, Freedom was redesigned into the International Space Station in 1993 with a cost estimate of \$17.4 billion for project completion.⁴¹⁷ In the intervening years the cost has further inflated to today's estimate of over \$28 billion for just the hardware alone. In over 16 years of work, with numerous redesigns and cost cutting measures and with 16 nations now on board, the International Space Station is now estimated by NASA to cost a total of \$60 billion by assembly complete in 2006.⁴¹⁸ This figure includes operations and Space Shuttle transportation costs. Furthermore, the General Accounting Office estimates the total cost for ISS over its ten-year lifetime, including operations and transportation, will come to a staggering

⁴¹⁶ Smith, Marcia, S., "U.S. Space Programs: Civilian, Military, and Commercial, Issue Brief for Congress, January 22, 2001.

⁴¹⁷ Wheeler, Larry, and Siceloff, Steven, "Space Station Could Cost Another \$4 Billion," *Florida Today*, February 17, 2001.

⁴¹⁸ Moring, Frank, Jr., "NASA Told To Cover \$4B Station Cost Overrun," *Aerospace Daily*, 15 February 2001.

\$95 billion.⁴¹⁹ While undeniably a fascinating program, it may be hard for the public to maintain optimism and confidence in its utility in face of such overwhelming schedule and cost overruns. And any negativity in the public's image of large space investments, whether public or private, are sure to have impact on entrepreneurial RLV firms in their attempts to raise capital.

The legitimacy of NASA, DoD, the incumbent aerospace industry, and new RLV entrepreneurial ventures to develop an RLV is also seriously threatened by the highly visible and extremely costly failures in developing RLVs and RLV technology demonstrators. The false hopes and broken promises of NASP, X33, X34, and other poorly designed and executed programs cost taxpayers many billions of dollars and likely delayed the replacement of the Space Shuttle system by a more cost effective, more reliable, and safer RLV system for a decade or longer. NASA's X-33 and X-34 programs may have had other negative effects as well, such as discouraging private sector investment in commercial RLV ventures.

Numerous industry experts and industry watch groups have for years questioned the legitimacy of NASA to develop a cost effective reusable launch vehicle system. Critics' fire has been fueled by the massive cost and schedule overruns of nearly the entire crop of current NASA X vehicle programs, by the recent cancellations of the X-33 and X-34 programs, the massive International Space Station cost and schedule overruns, the Space Transportation Main Engine program, and the NASP X-30 program.

NASA's problems in conducting successful RLV development programs have not gone unnoticed,⁴²⁰ and will likely be scrutinized by the incoming Bush administration.

⁴¹⁹ Wheeler, Larry, and Siceloff, Steven, "Space Station Could Cost Another \$4 Billion," *Florida Today*, February 17, 2001.

⁴²⁰ See for example: "Space Access Update #95, Space Access Society, August 27, 2000, www.space-access.org/updates/sau95.html; "Space Access Update #96, Space Access Society, September 26, 2000, www.space-access.org/updates/sau96.html; and Rohrabacher, Dana, "NASA's Space Launch Initiative Is Off Course," *Aviation Week & Space Technology*, February 19, 2001, www.aviationnow.com.

One of the issues reportedly on the table is the issue of which U.S. government organization will lead future RLV development.

NASA control of United States government RLV development was formalized in the mid-1990s. The Space Launch Modernization Plan was produced in March 1994 as a tasking to DoD from Congress to develop a strategic plan to modernize U.S. space launch. One of the major findings of the Space Launch Modernization Plan (also known as the Moorman Report after Lt. Gen Thomas S. Moorman, Jr who led the study team) was that coordination between DoD and NASA space launch programs needed improvement.⁴²¹ To this end, the Moorman Report recommended that DoD take the lead in developing ELVs and NASA take the lead in developing RLVs. This recommendation was accepted and made official with the 1994 National Space Transportation Policy, which also called for the development of a commercially viable reusable launch system. Shortly after this policy was released, the Air Force initiated the EELV program and NASA developed an RLV development plan, which included a series of flight demonstration programs: DC-XA (from DoD's successful DC-X), X-33, and X-34. The 1994 National Space Transportation Policy was reaffirmed in the September 1996 National Space Policy.

Some debate whether DoD and NASA were assigned the appropriate roles. Hays⁴²² notes that military RLVs (military spaceplanes) would be a great deal more useful than ELVs for many DoD space missions, whereas many civil satellite launches are best suited for ELVs. A further consideration is whether either organization is well suited to deal effectively with the increasing needs of the commercial sector.⁴²³

⁴²¹ Gonzales, Daniel, et al , Proceedings of the RAND Project AIR FORCE Workshop on Transatmospheric Vehicles, RAND Corporation, Santa Monica, California, 1997.

⁴²² Hays, Lt. Col. Peter L., "Spacepower for a New Millennium: Examining Current U.S Capabilities and Policies," AIAA Paper 2000-5261, AIAA Space 2000 Conference, Long Beach, CA, 19 - 21 September 2000.

⁴²³ Ibid.

While DoD's role in jointly managing the NASP program with NASA was disappointing, DoD's RLV development efforts since then have been successful even though executed with shoestring budgets. In fact, the last two successful reusable launch vehicle technology demonstrators, the DC-X Delta Clipper / DC-XA Clipper Graham and the X-40A Space Maneuver Vehicle, were both developed by the Department of Defense. Both efforts produced successful flight test vehicles that were transitioned to NASA for continued use after extensive Air Force testing. Furthermore, the Delta Clipper was developed under budget and schedule, a stark contrast to X33, X-34, and the rest. Likewise, the X-40A was developed and tested for a pittance, at a fraction of the cost of the similar Japanese ALFLEX program.^{424,425}

DoD's success, or NASA's lack of it, has apparently caught the attention of the new Bush administration. According to a recent *SpaceRef.com* article by Frank Sietzen, Jr. on future U.S. space policy, congressional sources indicate the Clinton Administration's space transportation policy was received by the Bush Administration as "dead on arrival."⁴²⁶ Sietzen further notes that:⁴²⁷

"...with DoD Secretary Donald Rumsfeld strongly supporting military space research that includes development of an Air Force spaceplane and piloted quick reaction strike capability, NASA control of the RLV development agenda is believed headed for the dustbin."

⁴²⁴ Original cost and schedule projections on the original X-40A development contracts with Boeing, which the author managed, were rendered meaningless by large contract modifications to both scope and scale. The original Mini-Spaceplane Technology (MiST) program specified only system analysis and flight test vehicle design. The contract was sequentially modified to also fabricate the flight test vehicle, and then to require contractor to conduct extensive ground testing and an autonomous approach and landing flight test collaboratively with Air Force and Army flight test personnel.

⁴²⁵ See, among others: Karasopoulos, H., et al., "Space Maneuver Vehicle Development by the Mini-Spaceplane Technology Program," AIAA 98-4149, AIAA Atmospheric Flight Mechanics Conference, Boston, Massachusetts, Aug 98; and Baker, Sue, "First Flight: Space Maneuver Vehicle Tries Its Wings," *Leading Edge Magazine*, October 1998, p. 17.

⁴²⁶ Sietzen, Frank, Jr., "Spacelift Washington: U.S. Space Launch Policy Facing Uncertain Overhaul," March 25, 2001, www.spaceref.com.

⁴²⁷ *Ibid.*

However this plays out, the Bush Administration will likely be disappointed in the results of future RLV development unless a pragmatic, evolutionary approach is utilized. Without a careful “test and learn as you go” stepping stone development strategy, future RLV technology demonstrator development will almost certainly fail as NASP, X-33, X-34 and the rest did, by trying to short-cut fundamental learning processes and by focusing too much on revolutionary technologies instead of the overall, revolutionary, RLV system.

Technology and Market Entry Competitive Strategy

Market Entry

Traditional Market Entry of New Expendable Launch Vehicles

The very high costs associated with launch failure prompts a very conservative approach by both launch vehicle manufacturers and their customers, the former in adopting new technologies into their launch vehicle designs and the latter in signing on with newly developed ELVs that haven't yet established a record of reliability. Even though the cost of a satellite is typically insured for launch, a company on a tight schedule to initiate on-orbit, revenue-generating operations of a commercial satellite can ill afford a launch failure; the opportunity costs of losing the asset's revenues while waiting for a replacement satellite to be fabricated and launched can be quite large.⁴²⁸ Hence, many ELV companies launch their first newly developed rocket with a dummy payload. In some cases this practice represents a lost launch fee of more than \$100M dollars.⁴²⁹ After one or two successful launches, the provider can generally begin launching payloads for fees. Prices, however, can sometimes be more easily negotiated downwards for some number of launches following a failure... if a customer can even be found. Thus, diffusion into the market for a new ELV requires embracing significant costs and high risk. A launch failure

⁴²⁸ It can take more than a year just to schedule a launch. Depending on the type of satellite to be fabricated and the manufacturer's lead times and current capacity, the total process can take two years

⁴²⁹ In at least one case, the customer is actually paying for this. The United States Air Force will pay Boeing \$141M to launch a dummy payload on Boeing's premiere launch of its first Evolved Expendable Launch Vehicle next year. This payment, however, results from development program cost sharing arrangement that is anticipated to save the Air Force more than 25% of launch costs over the next few decades.

early-on may require the developer to invest in additional launches of dummy payloads or even in significant cost and schedule killing system redesigns.⁴³⁰ The costs and risks associated with diffusion of a new ELV can represent a formidable barrier to entry.

Market Entry of New Entrepreneurial ELVs

Rather than trying to enter the market through an unobtrusive niche or grabbing a modest share of an emerging market, every new entrepreneurial ELV entrant to date has focused on attacking the very well established, low Earth orbit payload market. This has pitted them against the giants of the launch vehicle industry, a formidable challenge especially considering that the costs and reliability aspects of the new entrant were not significantly better than the incumbents. On the contrary, in some cases predicted system reliability for the new entrants was considered particularly weak, to the degree that they had great difficulty attracting customers. An example of this was Space Services, Inc. (SSI). One of the earliest private expendable launch vehicle ventures, SSI carried out the first successful privately funded rocket launch by a private U.S. company in September 1982, but was never able to successfully market their final launch vehicle product.⁴³¹ Some relatively new entrepreneurial launch vehicle developers (e.g. TGV Rocket, Vela Technology) apparently have learned this lesson and are focusing on space tourism applications, a potential future emerging market.

Market Entry of New Entrepreneurial RLVs

The diffusion of an entrepreneurial RLV into the market is likely to be initially similar to that of an ELV, but with an extended initial "prove out" phase due to the RLV's higher level of complexity. Legitimacy concerns will be an important factor, especially if a small entrepreneurial firm with no established brand image and little

⁴³⁰ When a failure occurs with a major launch system, the system is grounded while launch accident investigative teams spend weeks, sometimes months, in determining the cause. Correction of the cause might take a considerable period of time, even a year or more as was the case with the Space Shuttle after the Challenger accident where significant subsystem design changes were required to assure reliability and safety.

manufacturing or integration experience developed the RLV without a prime's help. Like an ELV, an RLV will have to prove itself on several launches in order to establish customer confidence in the system's reliability and performance. Many RLV concepts, however, have a distinct advantage over their ELV cousins in this area by offering the opportunity for incremental flight testing and prove-out of the system, increasing the chance of finding and solving critical problems before they occur.

Once a reliability trend has been established, however, product diffusion for an RLV should be significantly different from an ELV. This is due to the RLV's huge advantage in costs, turn around time, and reliability.⁴³² Even if the developer does not choose to pass along the bulk of the cost savings to the customer, customers would still quickly come onboard due to high value provided by all three advantages working in concert. The RLV firm might offer prospective customers, "we'll launch your payload the same week the manufacturer completes it, whenever that is, at only 80 percent of our competitor's price and with a 100 times less chance of your payload being destroyed in flight or placed in a useless orbit." Such a proposition would be hard to resist by even the most conservative customer.

The well-proven strategy of keeping a low profile while attacking the market share of strong incumbents is lost on most new space launch entrants and entrepreneurial RLV and ELV developers, who seem to thrive on publicity. This might be because the potential downside (an incumbent's reaction such as a price war) is less feared than not being able to acquire enough capital to stay solvent, a critical problem for new entrants.

⁴³¹ Cole, Bob, *The Prospects for U S. Ventures in Space Launch*, IC2 Institute, The University of Texas at Austin, 1989

⁴³² I'm assuming a successful RLV development effort in terms of meeting NASA's SLI 2nd Generation RLV Program cost goal of \$1,000 per pound to LEO and reliability goal of 9999

Intellectual Property & Appropriability

A review of the entrepreneurial launch vehicle developers in the space launch industry as well as the number and scope of the U.S. patents held by those ventures seems to point to a polarization in technology complexity and intellectual property. Firms tended to either use a low technology, low appropriability⁴³³ approach, almost completely employing commercial off-the-shelf-technologies in their vehicle designs, or the opposite – a new technology, high appropriability approach. Historically, firms employing the latter strategy (e.g. Beal Aerospace, Starstruck, American Rocket Company) generally failed to complete vehicle development, usually running out of funds before a full-scale prototype could be test flown. ELV entrepreneurial firms employing the low technology / low appropriability approach (e.g. Space Services, OTRAG) were more successful in developing their vehicles but still failed, generally due to a poor performing product. Nearly all of the RLV entrepreneurial firms I examined also fell into the low technology / low appropriability category. Most of the current entrepreneurial RLV development firms employ a low risk design and development philosophy, using only current technology and commercial off-the-shelf components where possible. Intellectual property protection tended to be weak or even non-existent, and where it was employed it was generally done so at the architectural level. Pioneer Rocketplane, for example, holds patents on its aerial propellant transfer launch assist for its Pathfinder RLV concept. Likewise, Kelly Space and Technology's Astroliner RLV concept uses a patented tow-launch assist. Kistler Aerospace Corporation's K-1 is designed to use as much off-the-shelf technology and components as possible, yet the company holds several patents on their airbag recovery system.

Design trade secrets will likely provide significant protection for a successful RLV entrant into the space launch market. An RLV's very high flight rate should create large launch operations learning curve effects that should prompt process and product innovation, leading to increases in the company's tacit knowledge, trade

⁴³³ Intellectual property rights, tacit knowledge, trade secrets, etc

secrets, and number of patents. This operations learning curve is especially important to an RLV since operations can account for up to 45% of the cost of each launch.⁴³⁴

Complementary Assets & Strategic Alliances

Small, entrepreneurial reusable launch vehicle developers are likely to have relatively weak competitive positions with respect to the following complementary assets: marketing and sales, brand, reputation and relationships with customers and suppliers, capacity, and manufacturing capability. Thus, acquiring the complementary assets of one or more of the aerospace primes (Boeing, Northrop Grumman, Lockheed Martin) through strategic alliances may be critical to the RLV entrepreneur's success. The primes also could offer other assets such as in-house research and development engineering talent, invaluable launch vehicle manufacturing and integration experience, and test facilities that are either unique or of limited availability. In 1999, for example, Pioneer Rocketplane complained in congressional testimony of having to go to South Africa to get access to scarce wind tunnel resources.⁴³⁵ A prime may be able to access exclusive supply channels for critical RLV commercial components that a smaller new venture cannot; the inability to acquire licensed Russian rocket engines has already stymied at least one entrepreneurial RLV developer. A prime may also be utilized to help develop and build certain specialized complementary assets such as launch and payload processing facilities.

In many industries, one way to partially mitigate the wrath of established incumbents is for a new market entrant to establish strategic alliances with some of them, trading a portion of potential future wealth to acquire a toehold in the marketplace as well as critical complementary assets. I could not find evidence of such alliances occurring between the dozen or so entrepreneurial RLV developers I

⁴³⁴ United States Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*. OTA-TM-ISC-28, Washington, DC, September 1988

examined and the domestic, incumbent, launch service providers, Lockheed Martin and Boeing. This might be attributed to the reluctance of the incumbents to provide a competitor with a toehold. It might also be attributed to the very low degree of development maturity of the RLV entrepreneurs, except perhaps for Kistler.

Supply-side Economies of Scale & Learning Curve Benefits

Space launch services annually consume a relatively small number of extremely complicated and expensive rockets. Last year, for example, sixteen different private companies or government organizations launched an average of only approximately four times each. Due to the small number of rockets manufactured and launched, economies of scale are slight and ELV manufacturing and launch operations learning curves produce little benefit. Subsequently, launch costs have not decreased very much over the past few decades, and where prices have decreased substantially it is likely due to higher government subsidies rather than cost reduction due to economies of scale.

One exception might be some of the former Soviet Union's ELVs (e.g. Proton, Soyuz, Zenit) that are currently offered at launch prices significantly lower than Western rockets by Russia, Ukraine, and some international partnerships such as International Launch Services and Sea Launch. Due to the instability of the orbits they were geographically constrained to launch into and their shorter average satellite lifespan, the Soviets were forced to historically launch much more frequently than the West to maintain roughly comparable assets in space. In 1985, for example, the Soviet Union had 98 launches compared to only 17 for the United States.⁴³⁶ With such higher flight rates, steeper Soviet manufacturing and operations learning curves might be the main reason for the lower launch prices currently offered by members of the former Soviet block. Alternatively, the price

⁴³⁵ Clapp, Mitchell Burnside, Testimony at the "Commercial Spaceplanes" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 13 October 1999, www.house.gov/science/

⁴³⁶ Kranzberg, Meivin, "The Top Line Space as Man's New Frontier," in *International Space Policy*, Papp, Daniel S, and John, McIntyre, R., Editors, Greenwood Press, Inc., Westport, Connecticut, 1987, p. 17

differences could instead be the result of far less costly manufacturing, engineering, and operations labor, excess capacity, or perhaps the treatment of certain costs as sunk costs and not trying to reclaim their amortized values in launch fees.

The cumulative manufacturing learning curve for a future successful RLV entry into the space transportation market is also likely to be very flat due to the small fleet sizes, usually planned for only 2 to 6 vehicles. In contrast, however, the cumulative flight operations learning curve for an RLV should be steep, providing it with an additional critical competitive advantage over ELV competitors. This is because each RLV will be flown at a relatively high flight rate – perhaps eventually 25 times or more per year – and allow the firm to translate learned efficiencies and innovations in launch operations into reduced costs. Cost reductions passed along to the customer could stimulate increased demand, leading to a greater share of the current market. This in turn would lead to a further increase in flight rate, cost reductions associated with increased accumulated learning and operations innovations, and further cost reductions in a virtuous cycle.

If the price elasticity of launch is high enough, reduced costs could also cause significant market expansion as emerging markets become economically viable. These new businesses, in turn, may drive the demand for additional RLVs to be built and flown, increasing manufacturing learning curve economies of scale as well.

Several other factors unique to a new RLV entrant will contribute to the steepness of its learning curves and hence increase its cost advantage. In contrast to ELVs, an RLV will likely incorporate a standardized payload bay and payload-vehicle interface, negating the need for individual tailoring of the launch vehicle for each individual payload and allowing for more process innovation. Also, most RLV concepts will require construction of a new launch facility designed explicitly for high frequency, low-cost flight operations. New infrastructure will remove past constraints

to operations innovations and thus also enhance learning curve benefits. Economies of scale will also likely result in significantly lower propellant costs.⁴³⁷

There are other traditional business scale efficiencies a newly established RLV service provider could leverage. Continued technology and process improvements could lead to lower costs and lower launch risks, and therefore indirectly to greater market share. Subsequent increases in revenue lead to increases in profits, cash flows, and in company growth rate, which together increase the level of expected future earnings and thus the stock price. Increases in stock price lead to a higher market value relative to book value and lower the risk of default, which in turn reduces the firm's cost of capital. Reduction in cost of capital, or the cost of debt as measured by the premium over the prime interest rate charged by a lender, directly lowers launch costs. These improvements increase industry demand as well as market share in a reinforcing cycle.

Cost versus Price

Even if successfully developed and operated at significantly lower costs than current launch systems, RLVs do not necessarily lead to lower priced launch services.⁴³⁸ If demand for launch services is high enough and the new RLVs don't have a high enough capacity to meet this demand by themselves, some customers will be forced to employ other, more expensive launch services. Thus, an RLV company may have little incentive from a short-term perspective to offer launch services much cheaper than the current market price. Barriers to market entry are high and a firm will be tempted to maximize profit.

⁴³⁷ An RLV will most likely employ either liquid hydrogen / liquid oxygen or kerosene / liquid oxygen as propellants. Some studies claim a high enough launch rate would enable very cost effective production of liquid hydrogen at the launch site, either by leasing facilities from a supplier or by the launch company creating their own capability – a business vertical integration.

⁴³⁸ Henning, Garth, "Modeling Launch Vehicle Economics," *Aerospace America*, Vol 37, No 3, Pg 36, March 1999

Launch Vehicle - Payload Interface Standardization

Traditionally, payload integration in ELVs is time consuming and expensive. Because launch vehicle payload bays and interfaces are not standardized, and because satellites have historically been both very costly and physically unique, most ELVs have had to be significantly redesigned for nearly every flight. Launch and mission operations can account for up to 45% of the cost of each launch, and payload integration can be a major fraction of the cost of launch operations.⁴³⁹ Thus, switching costs to the customer have been traditionally rather low as long as the switch is to another launch provider of approximately equal reliability. This situation has changed with the relatively recent advent of LEO satellite constellations. Composed of numerous identical satellites, these constellations have enabled the satellite manufacturers to practice assembly line fabrication (in as limited scale as it may be) for the first time. Standardization of the satellites has also prompted some limited launch vehicle payload interface standardization, a practice that will increase switching costs.

Standardization of the payload bay and its interfaces with the launch vehicle, accompanied by automated checkout procedures and an off-line processing and testing capability, may be a source of significant competitive advantage for a future reusable launch vehicle. Standardization of launch vehicle - payload interfaces has tempted launch vehicle designers for decades but has not yet been carried out in a widespread manner due to customer reluctance to pay the associated penalties. These penalties are the additional initial payload design expense and, in many cases, an increase in payload mass leading to additional attitude control propellant mass requirements and an increase in orbit insertion booster weight.⁴⁴⁰ This could be a very expensive proposition if the customer is charged the typical fee of \$5,000 or more to place each of those extra pounds into orbit. However, standardized payload interfaces will greatly reduce the time required to conduct launch vehicle

⁴³⁹ United States Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28, Washington, DC, September 1988

⁴⁴⁰ Conversely, of course, the penalty could be absorbed as a decrease in payload functionality for a constant weight

payload design integration, mating, and testing. This practice would thus save RLV operators considerable money as well as significantly reduce turn-around time. A reduction in turn-around time may enable an increase in flight rate, which would boost an RLV operator's cash flows as well as amortize the huge development costs more quickly.

Proposed Market Entry Strategy for a New Entrepreneurial RLV

The above logically leads to a market entry strategy⁴⁴¹ for a new entrepreneurial 2nd generation RLV: (1) form an alliance with an aerospace prime (if not already done in the development phase, perhaps with an equity offering) to acquire needed complementary assets such as marketing and sales, brand, reputation and relationships with customers and suppliers, facility use, etc.; (2) combine aggressively low launch prices with a standardized launch vehicle - payload interface, subsidizing the customer's design costs and weight penalties where necessary; (3) grow flight rate as quickly as possible in order to leverage learning curve benefits and economies of scale; (4) conduct intensive research and development of launch operations processes and system hardware to increase efficiency, drive down costs, and build appropriability and barriers to entry with intellectual property protection and tacit knowledge; (5) once adequate market share is captured, focus on creating a strong brand and improving customer service.

The economic attractiveness of a reusable launch vehicle system is heavily dependent on its flight rate. Some studies indicate RLVs are not economically feasible without a flight rate at least one order of magnitude higher than for existing ELVs (e.g. one or two flights every two weeks versus six flights per year). Thus, the success of a new RLV market entrant is critically dependent on its ability to fill its flight manifest. Low prices, quality service, responsiveness, and a demonstrated

⁴⁴¹ Obviously a market entry strategy for a future new RLV is dependent upon the future competitive climate, unexpected technological breakthroughs, and a myriad of other factors that can't be foreseen. In this speculative context, the posed preliminary strategy assumes (1) that this RLV meets NASA's current SLI cost and reliability goals, (2) it is the first 2nd generation RLV to enter the market, and (3) market entry would occur within the next few years. The latter implies the primary competition would be either today's expendable launch vehicles or newly developed ELVs.

high degree of system reliability are essential to attract and retain customers. Low prices are especially important for attracting new customers, and even lower launch fees are needed to entice conservative customers to switch from their current launch services provider.

Rapid imitation of a new RLV by competitors would be difficult due to the lengthy development time and other barriers to entry. Depending on the maturity of the concepts of competing RLV developers, the first new successful 2nd generation RLV to reach the market will have a large advantage, and perhaps several years lead time over its competitors. One goal of the new entrant is therefore to grow as rapidly as possible, taking market share from established ELV services, in order to quickly begin accessing launch operations learning curve benefits and leveraging economies of scale. The new RLV market entrant will have to avoid the temptation to price its launch services near market prices, which may maximize profit but slow growth. Increased profits would be eventually realized by holding an increased market share as well as lower costs due to learning and scale economies. Because there may not be enough room in the commercial marketplace to support more than one or two RLV launch service providers,⁴⁴² it is imperative that the new RLV entrant acquire as much market share as quickly as possible in order to create even higher barriers to entry for follow-on RLV competitors. It will be a difficult enough task to wrest market share from government subsidized ELV competitors; a price war with an RLV competitor backed with significant investor capital could be untenable.

As noted above, use of a standardized payload – launch vehicle interface will reduce launch operations costs and may enable a higher flight rate. This change in the business model may be interpreted by some customers as disruptive and consequently may be difficult for them to accept without a sizable economic incentive. To acquire these reluctant customers the new RLV entrant must take on the burden of these switching costs, subsidizing them in the form of even lower

⁴⁴² At current market conditions. This may change significantly in the future if the launch price elasticity enables certain emerging markets

launch prices, at least for a period of time. Although initial profits would be far lower than necessary, product lock-in would be greatly enhanced once satellite designers switched to the new RLV entrant's standardized interface.

7. Summary & Observations

This thesis addressed several facets of the space industry that affect the development of reusable launch vehicles: the development of the space launch industry, supply and demand for space launch vehicles, and ELV and RLV system and technology development programs. ELV research focused on new entrants to the launch vehicle market and on entrepreneurial development efforts. RLV research focused on concepts under development by industry, the United States government, foreign nations, and especially by small entrepreneurial ventures.

This thesis also presented a number of observations of technology development trends and strategies from ELV and RLV technology and system development programs. Additionally, an introduction to barriers to entrepreneurial RLV development was offered, concentrating on legitimacy issues and the problems of financing such high-risk ventures. Finally, technology and market entry competitive strategies for entrepreneurial RLV ventures were investigated and recommendations made.

Summary

Responsive, affordable space launch, using reusable launch vehicles to place payloads into orbit at fraction of today's exorbitant costs, will become a reality within the next two decades. As the railroads unlocked the American West, and as the modern airplane shrank our planet, RLVs will open space with vast commercial, scientific, humanistic, and military payoffs. The nation that wins this economic space race will gain significantly through the growth of entirely new industries and new technological developments, reaping large financial rewards from increases in employment, corporate & personal tax revenues, and export revenues.

This transportation revolution will require responsive and affordable space launch costing an order of magnitude less than that of today's systems. The keys to responsiveness and low cost are operability, reusability, and their enabling

technologies; the keys to a successful business case appear to be successful government involvement in technology development and financing.

The space launch industry is characterized by a very high degree of risk, high costs, and very large barriers-to-entry, so large that nearly every successful launch system in use today was originally sponsored by its respective government. Barriers to entry into the launch service market include development of vehicles requiring very complex, risky, and costly technologies, large expensive infrastructure investments, and high market risk. Governments and their large aerospace contractors consequently dominate the industry.

The riskiness of space launch is legendary; the historical launch vehicle success rate over the past 40 years is only about 85%, and over the past decade, about 95%. Launch failures are unforgiving and almost inevitably result in loss of both the launch vehicle and its payload. Losses from a single launch can amount to more than a billion of dollars, and in case of the relatively rare manned flight, to loss of life as well.

Space launch costs are extremely high, with an industry average price tag in the range of \$5,000 - \$7,000 for placing one pound of payload into low Earth orbit. The prices charged by many launch services are competitively influenced by direct or indirect government subsidies, including investments in research and development, and launch infrastructure.

Initial outlays to develop a new generation launch vehicle are enormous and the development process itself is risky and time consuming. Rather than developing a completely new launch vehicle, manufacturers in the past have instead almost always incrementally upgraded the performance of their current rockets. After about half of a century, the result is a launch vehicle industry that exhibits many characteristics of a mature industry – incremental change, competition based

primarily on price, focus on manufacturing and process technologies rather than product technologies, etc.

Over the years the satellite industry has matured significantly as well. Payloads, once few in number, unique, temperamental, and technologically complex, have become routine, less risky, more robust, and increasingly fabricated using standardized, commercial off-the-shelf technologies. Ground-based support for space launch and on-orbit assets has also become more routine. Increased competition and, in some cases, technology maturation have caused both launch and payload costs to decline to the degree that small satellites, once the pride of nations, have become commonplace and owned by universities and even clubs.

The 1990s saw a large increase in global launch service competition as demand dramatically increased primarily due to growth in the communication satellite arena. Several multinational alliances were formed between the East and the West to launch and market low priced, reliable Russian and Ukrainian ELVs as well as create new ventures, such as Sea Launch, Eurockot Launch Services GmbH, Starsem, and International Launch Services. A number of new expendable launch vehicles have entered the market over the past few years or will soon enter, helping to create the greatest overcapacity of launch services ever. New ELV market entrants include Boeing's Atlas V, Lockheed Martin's Delta IV, Arianespace's Ariane 5, and Japan's H2A.

Except for the partially reusable Space Shuttle system, every orbit capable rocket today is an expendable launch vehicle (ELV). Reusable launch vehicles promise vastly increased reliability and lower costs over ELVs, and thus they have been earnestly pursued in research and development programs for more than 30 years. Yet to date, no developmental RLV program has succeeded. Despite this, in the last decade more than 15 small entrepreneurial RLV companies have formed, all vying to do what governments and the aerospace giants such as Lockheed Martin and Boeing have failed to do - develop a commercially viable RLV. This, in the face of a

Space Shuttle total development bill of about \$40 billion, the failure of the National Aero Space Plane program to the tune of over \$3 billion, the recent failures of the X-33 and X-34 programs at over \$1.5 billion, as well as a host of other formidable deterrents. And this, despite the fact that the past is littered with failed ELV entrepreneurial efforts, a much less challenging development effort than that posed by an RLV.

The entrepreneurial RLV firms examined in this thesis were Kistler Aerospace Corporation, Pioneer Rocketplane, Kelly Space and Technology, Rotary Rocket Company, and Space Access, LLC. Kistler received the most attention, due to its leadership over the others with respect to design maturity, management team, capitalization, and fabrication.

The odds are that most, if not all, of the current entrepreneurial RLV development efforts will fail. Regardless, there is always a chance one of the leading candidates will succeed. Certainly, the potential payoff is huge; a successful RLV (in terms of cost effectiveness, safety, and reliability) would be a disruptive product, revolutionizing the space launch and earning fame and wealth for the winners, as well as a well-deserved place in history books alongside the likes of the Wright brothers.

Financial markets have not favored commercial RLV ventures. A number of entrepreneurial RLV development businesses were started in the mid-1990s, bolstered by the then bullish, even exuberant, LEO communications⁴⁴³ satellite market that appeared to underestimate the threat of fiber optics. With the bankruptcies or deep financial straits experienced by Iridium, ICO, Orbcomm, Globalstar and others in the last two years, the LEO market has since drastically declined. Financing entrepreneurial launch vehicle system development is very difficult and will require large amounts of risk capital that far exceed venture capital

⁴⁴³ Telecommunications, digital television, radio, paging, tracking, telephone, earth observing, and Internet services satellites provided high demand for satellites and launches throughout much of the 1990s.

markets. Large corporate joint ventures, syndicates, the United States government, or other large funding sources will likely be necessary to capitalize some of these efforts.

Ironically, while demand has dropped launch capacity has reached an all-time high. Some view future demand for LEO launches very grimly. The 2000 ten-year satellite forecast by the FAA, for example, predicts about half the demand for LEO payload launches than it did in 1997. Still, some forecasts see the multimedia, remote sensing, weather, and navigation portions of the satellite market significantly increasing over the next decade. Spaceway, a geostationary constellation of 8 satellites, currently provides fixed telephone service for developing areas, fax, and broadband multimedia, and is thought by some to have a good shot at capturing a reasonable Internet broadband subscriber base. And Teledesic, the "Internet of the Sky," the most blatantly ambitious LEO constellation project of all those planned in the 1990s, still remained in a planning mode as of last year.

Motivated especially by the recent souring of the LEO communication satellite market, reusable launch vehicle developers are carefully scrutinizing other facets of the launch market. Several yet untapped commercial markets may increase demand for space transportation services in the future. Space tourism, for example, has been extensively studied with some supply and demand forecasts showing a potentially lucrative market – but only enabled by launch costs of a fraction of those of today's systems. Micro-, nano-, and picosatellites may offer a relatively inexpensive architectural option to the satellite industry in the future, perhaps enabling a resurrection of demand for LEO launches. Another area of high market potential is in very fast freight services where a company would provide nearly global package delivery in a mere few hours rather than overnight using RLVs with suborbital trajectories. Such an offering could obviously be extended to a suborbital passenger service. Other possible markets for RLVs are to launch payloads for space solar power, space-based manufacturing, satellite-aided agriculture, and even advertising and entertainment.

Observations

The following observations were made of technology development trends, issues, and strategies from ELV and RLV technology and system development programs examined in Chapters 4, 5, and 6.

RLV Dominant Design / Winner Take All Market

The future space transportation market will effectively be a niche market with perhaps less than a dozen RLVs sufficient to meet worldwide low Earth orbit launch demand for some time. With this in mind, the first successful⁴⁴⁴ RLV stands a good chance of being the de facto dominant design. With such lengthy development times, large required investment, and other barriers to entry, the first successful RLV fleet may tip the commercial market toward a “winner take all” situation. Although many commercial launch systems would be driven out of business, some of those subsidized by their governments would likely survive due to nationalistic and strategic considerations, and the reluctance of customers to rely on a sole source launch provider.

Entrepreneurial Launch Vehicle Development is Very Challenging

Entrepreneurial reusable launch vehicle development poses an extremely risky and difficult challenge. The past is littered with failed entrepreneurial launch vehicle development ventures, and to date no entrepreneurial ELV or RLV venture has succeeded. Further, the entire current crop of entrepreneurial RLV developers appears to be foundering, at least with respect to acquiring sufficient capital to complete development. Government and corporate programs have fared no better. NASA cancelled their X-33 and X-34 programs just a few weeks ago at a cost of \$1.5 billion due to technological problems and massive cost and schedule growth.

⁴⁴⁴ A “successful” RLV is one which meets NASA’s Space Launch Initiative 2nd Generation RLV program cost goal of \$1,000 per lb to LEO and reliability goal of 0.9999, respectively.

Entrepreneurial Developers Almost Exclusively Use Current Technology

Nearly all of the entrepreneurial designs employ current technology almost exclusively. Additionally, most ventures also emphasize their use of commercial off-the-shelf components wherever possible, notably Russian liquid oxygen / kerosene rocket engines. These companies generally hold little intellectual property protection other than on an architectural level or for special discriminating innovative designs, such as Kelly's patented tow-launch assist, Kistler's landing recovery system, or Pioneer's aerial propellant transfer. Most of the few entrepreneurial launch vehicle developers that did more extensive technology development perished (e.g. Beal, Rotary Rocket, Starstruck, American Rocket Company).

Stepping Stone, "Build a Little, Fly a Little" Approach

The large amount of financing required for commercial RLV development coupled with significant market risk, the employment of a myriad of high-risk technologies, the lack of Federal assistance beyond early stage RLV technology development, and numerous other barriers to entry have greatly undermined successful RLV system development. Historically, the U.S. government has stepped into the fray of past transportation technology and infrastructure development with investments and funding incentives. Over the past two decades, however, the U.S. government's performance in RLV development has been dismal, characterized by repeated attempts to leapfrog critical technologies rather than applying a pragmatic, stepping stone, "build a little, fly a little" approach that was so successfully utilized in experimental aircraft development a few decades before. This approach has resulted in the failure of the X-30, X-33, X-34, and other RLV development programs with an accumulated cost in the billions of dollars. In contrast, DoD's modestly funded DC-X and X-40A programs set challenging but practical goals which they very successfully achieved.

Legitimacy

Since reliability is such a primary concern to customers, legitimacy plays a major role in the sales of launch services, particularly for future market entry of a small entrepreneurial firm with no established brand image and little manufacturing or integration experience. Some legitimacy concerns could be mitigated if the small entrepreneurial firm contracts to established industry figureheads for at least all critical systems and subsystems, if not integration as well. Some in the current wave of RLV entrepreneurs are utilizing these resources as part of their strategy to use current technology and commercial off-the-shelf components wherever possible. RLV developer Kistler Aerospace, for example, has made extensive use of expert contractors to design and manufacture K-1 components, including Lockheed Martin, Northrop Grumman, GenCorp Aerojet, Draper Laboratory, AlliedSignal Aerospace, Irvin Aerospace, and Oceaneering Space Systems.⁴⁴⁵

Historically, small new entrants have essentially “bet the company” with each launch. A new entrepreneurial RLV market entrant will likely have neither the capital nor the brand to overcome an early catastrophic launch failure, which usually requires an extended period of further engineering and redesign. Only with customer-perceived legitimacy can the RLV venture wrest market share from well-established space launch incumbents in an economically viable period of time.

Legitimacy plays an even more critical role when the payload is human. Even with adequate reusable launch vehicle offerings, the space tourism market will never grow significantly until the customers’ perception of safety is satisfied. Public acceptance of a new space tourism business based on a new RLV concept will be obviously heavily influenced by the perceived legitimacy of the company offering the service. The company’s legitimacy and its ability to obtain investment capital, however, are also influenced to some extent by the overall industry’s safety and reliability records.

The legitimacy of NASA, DoD, the incumbent aerospace industry, and new RLV entrepreneurial ventures to develop an RLV have been eroded by the highly visible and costly failures in developing RLVs and RLV technology demonstrators. The false hopes and broken promises of NASP, X33, X34, and other poorly designed and executed programs may also have discouraged private sector investment in commercial RLV ventures.

Disruptive RLV Technologies versus Disruptive RLV Systems

The RLV research community has often implicitly assumed that revolutionary technology advances are required in order to create a revolutionary product. This is not the case with some very complex, highly nonlinear systems such as RLVs where integration of a myriad of evolutionary technology advances can sum to a revolutionary product, that is, a reusable launch vehicle having a revolutionary performance capability.

The more traditional approach towards RLV technology development, unfortunately, is that of isolated component specialization and optimization. This approach is strengthened by the high level of technological complexity of even the minutest components, resulting in laboratories where technology specialists are now the norm and generalists very rare. The professional interests of the researchers usually serves to strengthen their enthrallment with disruptive technologies; the lure of high technology is often dizzying for RLV development managers and engineers who succumb to the mirage of exciting, potentially disruptive, subsystem technologies, losing sight of overall system objectives. Such technologies might eventually prove to provide a disruptive performance capability for the subsystem in isolation, yet almost invariably present a suboptimal solution for the overall RLV system due to critical nonlinear integration issues. RLV designers found this to be

⁴⁴⁵ Mueller, George, Written Statement of Kistler Aerospace Corporation, Presented at the "Commercial Spaceplanes" hearing to the House Subcommittee on Space and Aeronautics, U.S. Congress, 13 October 1999, www.house.gov/science/

the case with the NASP program with the revolutionary, advanced airbreathing propulsion system, spending billions of dollars to discover their error.

Proposed Market Entry Strategy for a New Entrepreneurial RLV

A market entry strategy for a new entrepreneurial 2nd generation RLV was developed in Chapter 6: (1) form an alliance with an aerospace prime (if not already done in the development phase, perhaps with an equity offering) to acquire needed complementary assets such as marketing and sales, brand, reputation and relationships with customers and suppliers, facility use, etc.; (2) combine aggressively low launch prices with a standardized launch vehicle - payload interface, subsidizing the customer's design costs and weight penalties where necessary; (3) grow flight rate as quickly as possible in order to leverage learning curve benefits and economies of scale; (4) conduct intensive research and development of launch operations processes and system hardware to increase efficiency, drive down costs, and build appropriability and barriers to entry with intellectual property protection and tacit knowledge; (5) once adequate market share is captured, focus on creating a strong brand and improving customer service.

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