THE DECISION MAKER'S GUIDE TO ROBUST, RELIABLE AND INEXPENSIVE ACCESS TO SPACE

by
Gary N. Henry, Lieutenant Colonel, USAF

July 2004
Occasional Paper No. 37
Center for Strategy and Technology
Air War College

Air University
Maxwell Air Force Base, Alabama

The Decision-Maker's Guide to Robust, Reliable, and Inexpensive Access to Space

Gary N. Henry, Lieutenant Colonel, U. S. Air Force

July 2004

The Occasional papers series was established by the Center for Strategy and Technology as a forum for research on topics that reflect long-term strategic thinking about technology and its implications for U.S. national security. Copies of No. 37 in this series are available from the Center for Strategy and Technology; Air War College; 325 Chennault Circle; Maxwell AFB, Alabama 36112. The fax number is (334) 953-6158; phone (334) 953-6460

Occasional Paper No. 37
Center for Strategy and Technology

Air University
Maxwell Air Force Base, Alabama 36112

Contents

Disclaimer

Author

Lieutenant Colonel Gary N. Henry graduated from the United States Air Force Academy with academic distinction in 1984. Colonel Henry's varied career includes assignments in laboratory research, academic instruction, developmental flight test, and system acquisition. He began his career conducting high-energy laser vulnerability research under the auspices of the Strategic Defense Initiative from 1984-87 and then served as an Assistant Professor of Astronautical Engineering at the USAF Academy from 1989-93. While there he co-edited the textbook *Space Propulsion Analysis and Design* and received the 1993 USAF Science and Engineering Award for successfully launching the DOD's first land-based hybrid sounding rocket. He was then selected to attend USAF Test Pilot School and subsequently assigned to the 418th Flight Test Squadron as Chief of the Flight Dynamics Branch from 1994-1996 where he directed numerous MC-130H Combat Talon and AC-130U Gunship test missions. Colonel Henry later became the Chief of the Airborne Laser (ABL) System Program Office Air Vehicle Integration and Test IPT at Kirtland AFB, New Mexico, from 1998-1999, where he was responsible for preparing the ABL weapon system for first flight. In 2000, Colonel Henry was assigned as the Lead ABL Program Element Monitor in the Office of the Assistant Secretary of the Air Force for Acquisition at the Pentagon. He is currently the Chief, Advanced Space Systems Division, Space Superiority Materiel Wing, Space and Missile Systems Center, at Los Angeles AFB, California, and will assume command of the 1st Air and Space Test Squadron, 30th Space Wing, Vandenberg AFB, California, in the summer of 2004. Colonel Henry's academic credentials include a Bachelor of Science in astronautical engineering from the USAF Academy, a Master of Science in aeronautical and astronautical engineering from Stanford University, and a Master of Strategic Studies from the Air War College.

Illustrations

Page

Tables

Page

Preface

I naively began my research thinking that our failure as a nation to achieve truly robust, reliable, and inexpensive space access (*R^2ISA*) was simply the result of several misplaced technology bets, poor timing, and bad luck. I was wrong. I soon discovered that one cannot adequately address this complex topic without entering the realm of public policy, economics, and programmatics, as well as the technical complexity inherent with *R^2ISA*.

Although I am critical of NASA at times in this paper, without question, NASA is blessed with the services of some of the most brilliant and dedicated scientists and engineers this nation has to offer. However, if NASA was an organization in crisis before the tragic loss of Columbia, it will soon be under siege. This is wrong. Decisions spanning more than thirty years by the Executive Branch, Congress, the Department of Defense, and the entire aerospace community contributed to this tragedy.

The loss of Columbia brings some difficult issues to the forefront. NASA made a decision in late 2002 to defer pursuit of a second-generation reusable launch vehicle until at least 2009, and it instituted a shuttle life extension program to 2020. While I personally believed this to be a mistake prior to the loss of Columbia, I can now say so with absolute certainty. Keeping the shuttle flying until 2020 will almost certainly mean the loss of another vehicle and crew, as well as an abrupt and permanent grounding of the remaining shuttle fleet. Failure, due to a "lack of resources," to immediately begin the pursuit of the design and build-out of a new space transportation architecture that fails to include a solution for the shuttle not only puts a price tag on human life but seriously jeopardizes the future of manned space flight.

Recent Space Launch Initiative shuttle replacement cost estimates as high as $30-35 billion proved unaffordable for NASA. Further, the NASA staff was unable to make the business case to its own administrator for the long promised $1000 per pound to low-earth orbit. Meanwhile, the Department of Defense (DOD), unable to ride NASA's coattails, struggles to find solutions to its aspirations for an affordable, flexible, and operationally robust space launch system. Significant strides towards defining force enhancement, counterspace, and force application requirements are encouraging, but an enabling space launch system remains elusive.

The commercial space industry is on life-support with global capacity far outstripping demand for expensive and cumbersome launch services. The DOD and NASA pursuit of independent space launch solutions is inefficient and unaffordable. I believe the answer to this crisis demands a national solution to earth-to-orbit operations that is responsive to civil, military, and commercial requirements.

Is a national solution possible? Does it even make sense? Potential answers to these vexing questions were painfully slow in coming. This paper suggests that there are indeed national solutions that can deliver R^2*ISA*. There are also quicker, riskier, technology-leveraged alternatives than those suggested here that ***could*** work. However, as a nation we've been down that road before – placing several multi-billion dollar bets that failed to deliver. I am convinced that the approach promulgated here—followed to its logical conclusion—is ***guaranteed*** to deliver R^2*ISA*. There are likely to be similar solutions that can deliver R^2*ISA* even faster and cheaper; it is time for ***all*** stakeholders to focus our effort to defining those solutions.

One observation I've made is that it would be very helpful if the aerospace community could reach a reasonable consensus recommendation regarding a prudent road ahead. This would not only help lift the fog that has virtually immobilized us for more than thirty years, but also inspire some sorely needed confidence from American leadership and her people. Unfortunately, without a clear mandate from our senior leadership, such consensus is unlikely. Hence, the decisions of our most senior leadership within the executive, congress, DOD, and NASA will provide the direction and resources to make R^2*ISA* a—or not. This paper is a modest, unbiased attempt to help prepare them for that task.

My sincere thanks to the Center for Strategy and Technology and the unwavering support of Dr. Grant Hammond, Mr. Ted Hailes, and particularly, Col John Geis, who painstakingly reviewed numerous drafts of this paper and provided invaluable editorial comment. I am also sincerely grateful to Dr. Lanny Jines of the Air Force Research Laboratory and Dennis Bushnell of NASA Langley Research Center for providing personal insight as well as generous access to their respective organizations. Thanks to Dr. Kevin Bowcutt, Ramon Chase, Bill Claybaugh, Dr. William Heiser, Dr. Harry Karasapolous, Dr. John Olds, Russel Rhoades, Ming Tang, Neil Woodward, Edgar Zapata and others for challenging the thesis of this paper and providing invaluable advice and

assistance. Finally, I'd like to thank my beautiful wife Heather for her unselfish support as well as my two-year old son Patrick who never quite figured out where daddy went all those weekends.

Despite bleak characterizations of past failure, there is great hope for the future. As I researched this paper, I was struck by the sheer magnitude and diversity of the technical and programmatic discourse surrounding space exploration and exploitation. There is no shortage of brilliant people or great ideas. Once R^2ISA is achieved, I am convinced that we will witness a renaissance in space not unlike that experienced in aviation during the interwar years of the 20th Century. Today's earth-to-orbit operations are reminiscent of the challenges and risks of Charles Lindbergh's foray across the Atlantic. We have yet to build the space equivalent of the DC-3. Any personal agenda I may have brought to the debate amounts to nothing more than one day hoping to affordably buy a ticket to earth orbit—and one more thing. To inspire my son, and his generation, in the same way I was inspired by the men and women who built Apollo and safely delivered a dozen men to the lunar surface and brought them home again. I'd like to one day claim that I was part of the next generation who built the ships that permanently bridge the gap between air and space—both inspiring and enabling my son's generation to begin an awe inspiring journey of their own.

This paper is dedicated to Dr. Ron Humble, an aerospace enthusiast with whom I had the pleasure to co-edit a text entitled *Space Propulsion Analysis and Design*, who passed away in 2002 at 44 years young. We'll miss him.

Abstract

The principal barrier to unconstrained civil, military, and commercial exploitation of space is the high cost and elevated risk associated with access to low-earth orbit and beyond. The road ahead remains clouded and ambiguous despite thirty years of trying. This paper is intended to empower senior-level decision-makers with the insight and objectivity needed to ask tough, probing questions, as well as provide a course of action that illuminates a path toward truly robust, reliable, and inexpensive space access (R^2ISA) for the 21st Century. It will be made clear that: 1) R^2ISA will never be achieved with foreseeable expendable launch vehicle technology. Reusable launch vehicles are currently the only economically and operationally viable path toward achieving R^2ISA. 2) Existing technology limitations make pursuit of a single-stage-to-orbit solution imprudent at this time, while a two-stage-to-orbit reusable launch vehicle is the logical next step towards R^2ISA. 3) Despite conflicting requirements, a common "national" solution for civil, military, and commercial application is both possible and desirable. 4) Fundamental reforms are essential to make R^2ISA a reality.

This paper provides a concrete, quantifiable definition and a theoretical construct for R^2ISA. It then presents the historical context, divergent requirements, and disparate technical perspectives that comprise the confusing state of affairs engulfing the space transportation debate and concludes with a set of lessons learned. It will then explore the current physical, economic, and technological challenges associated with achieving R^2ISA. From this, it then outlines the technical solutions to R^2ISA focusing on rocket and air-breathing reusable launch vehicles. A set of proposed "national" space launch system architecture attributes are introduced as well as a proposed solution to the current impasse. Finally, this paper will present a set of conclusions and recommendations for the successful pursuit of R^2ISA. Along the way, this paper will frame the critical issues and key questions that must be asked and answered before the United States commits billions of dollars towards a future space launch architecture. A fundamental question considered is whether R^2ISA is best achieved through separate (but coordinated) Military, Civil, and Commercial endeavors, or if a single "national" solution makes sense. This question is vital to framing a debate that transcends technological

challenges, interagency rivalry, and political expediency, and may ultimately determine the difference between success and failure.

I. Introduction

> *The Air Force was born of a new technology – manned powered flight. Innovation will enable the Air Force to evolve from an air force to an air and space force on its path toward space…. We are now transitioning from an air force to an air and space force on an evolutionary path to a space and air force.*
>
> *—Global Reach—Global Power*

Robust/Reliable/Inexpensive space access (R^2ISA) is the holy grail of space transportation. It is universally accepted that the principal barrier to unconstrained civil, military, and commercial exploitation of space is the high cost and elevated risk associated with access to low-earth orbit and beyond. It is evident that the United States has yet to introduce a space transportation architecture that delivers R^2ISA despite numerous abortive attempts to do so. Equally disappointing is the clouded and ambiguous road ahead despite thirty years of trying. It didn't have to be this way.

This paper is intended to empower senior level decision-makers with the insight and objectivity needed to ask tough, probing questions, as well as provide a course of action toward truly robust, reliable, and inexpensive space launch for the 21st Century. It will be made clear that: 1) R^2ISA will never be achieved with foreseeable expendable launch vehicle technology. Reusable launch vehicles are currently the only viable path, both economically and operationally, toward achieving R^2ISA. 2) Existing technology limitations make pursuit of a single-stage-to-orbit solution imprudent at this time while a two-stage-to-orbit reusable launch vehicle is the logical next step towards R^2ISA. 3) Despite conflicting requirements, a common "national" solution for civil, military, and commercial application is both possible and desirable. 4) Fundamental reforms are essential to make R^2ISA a reality.

This paper will begin by providing a concrete, quantifiable definition and a theoretical construct for R^2ISA. It then presents the historical context, divergent requirements, and disparate technical perspectives that comprise the confusing state of affairs engulfing the space transportation debate and concludes with a set of lessons learned. It will then explore the current physical, economic, and technological challenges associated with achieving *R^2ISA*. From this, it will then outline the technical solutions to *R^2ISA* focusing on rocket and air-breathing reusable launch vehicles, propose a set of "national" space launch system architecture attributes, and conclude with a proposed solution to the current impasse. Finally, this paper will present a set of conclusions and recommendations for the successful pursuit of *R^2ISA*. Along the way, this paper will frame the critical issues and key questions that must be asked and answered before the United States commits billions of dollars towards a future space launch architecture. A fundamental question considered is whether *R^2ISA* is best achieved through separate (but coordinated) Military, Civil, and Commercial endeavors, or if a single "national" solution makes sense. This question is vital to framing a debate that transcends technological challenges, interagency rivalry, and political expediency, and may ultimately determine the difference between success and failure.

R2ISA DEFINED

Robust, Reliable, Inexpensive space access is a qualitative construct describing the essential characteristics of any successful civil, military, and commercial space launch system architecture. However, quantification is necessary to scope the problem, define usable metrics, and permit objective decision-making. Although any quantitative rationale is subject to debate, a *R^2ISA* definition is nonetheless provided.

Inexpensive

The term inexpensive is used in lieu of affordable with premeditation. "Affordable" is whatever a customer is willing to pay based upon overall mission value or imperative.[1] "Inexpensive" represents a threshold where there is no longer a cost disincentive in considering space-based alternatives to specific mission requirements. The complication arrives when attempting to define that threshold. Typically, between the civil, military, and commercial arena, the lowest cost threshold lies within the commercial realm. Thus, the commercial standard is used to define the threshold for "inexpensive" space launch.

The National Aeronautics and Space Administration (NASA) sponsored a collaborative government/industry Commercial Space Transportation Study in 1994 that is recognized as the most comprehensive and authoritative effort to date in quantifying the commercial space market.[2] It was intended to address the global perception that: 1) significant untapped commercial markets existed if the cost of access to space could be lowered an order of magnitude or more, 2) a new launch system could provide such a reduction in launch costs, and 3) such a reduction would result in a "space industrial revolution" with very large increases in users and traffic.[3] The analysis concluded that a non-linear change in demand relative to price (called market elasticity) begins to enter the commercial space launch market at around $1000 (FY93) per pound to low-earth orbit and is well established at $600 per pound.[4] For the purposes of this paper, the threshold for commercial viability begins at $1000 (FY02) per pound to low-earth orbit and is used as the threshold for a second-generation launch system.[5] Based upon the author's interpretation of Commercial Space Transportation Study estimates, $100 per pound to low-earth orbit can provide a sufficient return-on-investment to make the subsequent development of profitable commercial launch system architectures self-sustaining. Thus, the price threshold of $100 per pound is used for third generation launch systems.[6] However, this optimism does not negate the fact that another order of magnitude drop in costs to $10 per pound is necessary to approach "aircraft-like" costs. Further, the study concluded, "as a commercial investment measured at standard industrial return-on-investment levels, the investment cost for a new space launch system must be kept in the range of a few billions of dollars."[7]

Reliable

There are two distinct dimensions of reliability that have a large impact upon overall system cost and performance. The first is the probability of mission failure, which is relevant to both manned and unmanned systems. The second is probability of catastrophic loss of either a mission payload or crew. The former drives critical commercial considerations to include customer confidence and the cost of insurance (which can be a high percentage of launch costs) as well as directly impacting the probability of mission success in the military realm. The latter deals with crew safety and implies a "crew-rated" system demanding significantly higher safety margins than unmanned systems, adding weight, complexity, and cost. Higher margins for crewed systems can be addressed one of two ways. The first is to augment a non crew-rated vehicle with a crew-escape system to make the system safer. This approach can provide improved safety margins, but with a significant penalty (typically manifested as weight) to overall system performance. The second is to build a vehicle with sufficiently high reliability to make the crew-rated distinction irrelevant, as is the case with existing aircraft operations.

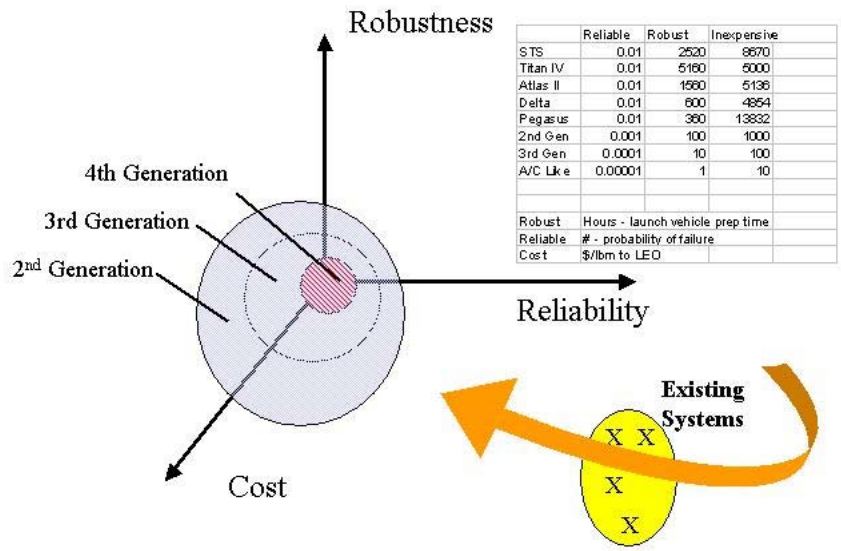
Space launch systems have historically operated at very low reliability and safety thresholds relative to aircraft operations. Based upon Bayesian reliability theory (where the benefit of learning is factored into statistical analyses), the first human launch of the Mercury Redstone (Alan Shepard) appears to have carried a 61 percent probability of vehicle launch failure. The first human launch of a Mercury Atlas (John Glenn) carried a 63 percent probability of launch failure. Both of these values are based upon the heritage of the their respective launch vehicle development to that date.[8] To deal with unacceptably low demonstrated reliability, a crew escape system was added with a five percent probability of failure. With crew escape, safety now becomes the product of the two numbers yielding a probability of both the launch vehicle and the crew escape system falling to three percent, or alternatively, a 97 percent probability of crew survival.[9] Although expendable launch vehicle reliability has improved dramatically since the early 1960's, demonstrated system reliabilities to this date range between 94 and 99 percent.

Current NASA shuttle reliability numbers vary, and there is a large disconnect between the desired reliability of its future generation reusable launch vehicles and reality. One unpublished NASA source projects shuttle reliability against loss of vehicle as "marginally higher" than the originally specified 98 percent reliability (implying a catastrophic loss of one vehicle in every 50 launches).[10] An internal NASA "bottom-up" failure analysis predicts the probability of catastrophic failure at 1 in 247.[11] The space shuttle, despite its overwhelming complexity, is without question the safest and most reliable space transportation system to ever fly. However, relative to aircraft operations, the shuttle is a very dangerous machine. NASA articulated a desire to achieve a two order of magnitude improvement with its second-generation reusable launch vehicle development under the auspice of the Space Launch Initiative to reduce the risk of crew loss to approximately 1 in 10,000 missions.[12] Note that another order of magnitude improvement to 1/100,000 probability of loss of vehicle is necessary to approach "aircraft-like" reliability.[13] A more realistic and achievable failure probability goal for a second- and third-generation reusable launch vehicle is 1/1000 and 1/10,000 respectively. One can safely conclude that aircraft-like reliability for space launch systems is well beyond existing state of the art.

Robust

The term "robust" is a multifaceted mission and system-dependent component of R^2ISA that can carry significantly different meanings in the civil, military and commercial realms. An important goal of a national solution to R^2ISA is an amelioration of these differences that is addressed in the following chapter. This axis of the R^2ISA parameter space can be defined in any fashion, to include the flexibility to readily select the mission, payload, flight path, and crew (if applicable) without significant configuration changes despite highly variable weather and/or operational conditions. For the purpose of this paper, robustness takes on the much narrower definition of responsiveness, which is simply the launch vehicle preparation or recycle time, measured in hours. Figure 1 below graphically depicts the R^2ISA parameter space for existing expendable and reusable launch vehicles, as well as second-, third-, and fourth- generation (aircraft-like) space launch systems.

Finally, a brief discussion of important definitions is in order. The FAA Office of Commercial Space Transportation defines four payload mass classes to low-earth orbit: small (5,000 lb or less), medium (5,001-12,000 lb), intermediate (12,001-25,000 lb), and heavy (more than 25,000 lbs).[14] For the purposes of this paper, medium and intermediate are merged into medium-class payloads. Low-earth orbits are used as the baseline for objective cost and performance assessments and to define some common terms. Low-earth orbits are defined as circular orbits in the range of 185 kilometers (100 nautical miles) to 460 kilometers (250 nautical miles) with the lower threshold used in this paper.[15] Orbital velocity is important because it represents the minimum speed and direction at which immediate active propulsive thrust is no-longer required to counteract the earth's gravitational acceleration and the trajectory can be sustained indefinitely (absent losses due to drag, gravitational anomalies, solar activity, etc.).



	Reliable	Robust	Inexpensive
STS	0.01	2520	8670
Titan IV	0.01	5160	5000
Atlas II	0.01	1560	5136
Delta	0.01	600	4854
Pegasus	0.01	360	13832
2nd Gen	0.001	100	1000
3rd Gen	0.0001	10	100
A/C Like	0.00001	1	10
Robust	Hours - launch vehicle prep time		
Reliable	# - probability of failure		
Cost	$/lbm to LEO		

Figure 1. Robust Reliable Inexpensive Space Access (*R²ISA*) "Trade Space"

R2ISA KEY LINKAGES

R²ISA is directly linked to the overall vehicle design that is in turn influenced by an overarching space architecture. Earth-to-orbit operations, of which *R²ISA* is directly concerned, is a part of this larger space architecture. Since a system-of-systems perspective is essential to achieving an optimized *R²ISA* solution, two important observations are now made. First, the successful oversight of these elements can only be accomplished by very senior level decision-makers. Secondly, these interrelationships can get very complicated very quickly. Figure 2 below graphically illustrates these relationships and can be considered a topical "roadmap" of discussion for this paper. Although the details of this figure are not discussed here, the reader is encouraged to refer to it often as more detailed information and actionable arguments are presented in this paper.

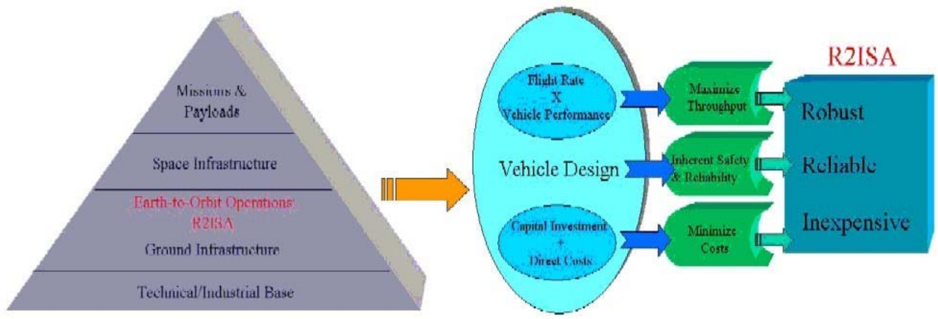


Figure 2. *R^2ISA* Linkages to Vehicle Design and Space Architecture

II. Background

The earth is covered by two-thirds water and one-third space launch studies.[16]

—Secretary of the Air Force Sheila A. Widnall
December 1992

Regarding his predecessor, Daniel S. Goldin's $1,000-per-pound-to-orbit goal: I'm not an archeologist; I'm not a forensic pathologist. I don't know where this stuff came from, and I'm really not interested in going through an excavation or a dig around the agency to figure out who came up with what number when. That is a bumper sticker, and I haven't found anybody who can attest that there is any technology that can achieve that.[17]

—Sean O'Keefe, NASA Administrator
November 2002

HISTORICAL PERSPECTIVE: THE ROAD TO NOWHERE

In the late 1960s, two very different approaches emerged as potential means of significantly reducing the cost of access to low-earth orbit. One approach proposed using simplified expendable boosters; the other a winged, fully reusable, manned launch system.[18] In 1972, the U.S. government officially came down on the side of the winged, fully reusable system. The space shuttle was established as America's future space launch vehicle and a solution to high cost. Although the ultimate shuttle configuration was only partially reusable, cost analysts at that time nevertheless predicted an order of magnitude reduction in launch costs to $162 per pound to orbit (FY71) relative to existing expendable systems.[19] The space shuttle proved to be an engineering marvel providing a wide range of on-orbit capabilities; however, as a launch system it was, and continues to be, an economic failure. In order to get the funds to build the shuttle during the lean 1970s, NASA was forced to trade higher operational costs in the future for lower developmental cost in the present.

The ramifications of that political trade-off eventually came home to roost, as shuttle operations have dominated and continue to dominate the NASA budget.[20] The shuttle is most expensive heavy-lift launch vehicle in the U.S. inventory, whether based on cost per launch or on dollars per pound to orbit.[21]

In 1987, the DOD began a cooperative effort with NASA to develop a new, simplified rocket booster called the Advanced Launch System that was intended to succeed where the shuttle had failed. Once again, the goal was to achieve order of magnitude reduction in launch costs. In November 1987, Congress specified that any Advanced Launch System request for proposal would include the target of $370 or less per pound of payload to low-earth orbit.[22] Budgetary and political pressures caused the original Advanced Launch System initiative to eventually be transformed into a follow-on program called the National Launch System. This system represented a family of simplified expendable boosters that depended on shuttle-derived hardware for some key components, and advocates claimed it held great promise for reliable, responsive space transportation. The National Launch System program de-emphasized the goal of $370 per pound to low-earth orbit. Program managers emphasized a simpler design approach to keep manufacturing and operating costs low, but cost projections for the development of the new launch vehicle continued to rise.[23] Congress cancelled the program in 1992 when non-recurring development cost projections for the National Launch System exceeded $10 billion.[24] The subsequent joint Space-Lifter program, dubbed "Shapeshifter" by some due to its ability to mutate according to changing political demand, survived only a year and was cancelled in 1993.[25]

The post-Challenger environment was a politically turbulent and uncertain one for space policy. Between 1987 and 1992, coinciding with the birth and demise of both the Advanced Launch System and National Launch System programs, this uncertainty manifested itself in an abundance of high-level space policy studies to include *Pioneering the Space Frontier*, the 1986 report of the National Commission on Space; the 1987 *Leadership and America's Future in Space* report generated by a panel chaired by America's first woman in space, Sally Ride; the *Space Architecture Study* done by DOD in 1988; the 1990 *Report of the Advisory Committee on the Future of the U.S. Space Program* (the Augustine committee); the 1991 *Synthesis Group Report* (the Stanford committee); the 1992 reports from the National Space Council and the Vice-Presidents

Space Policy Advisory Board, *The Future of U.S. Space Launch Capability and a Post-Cold War Assessment of U.S. Space Policy*, and the 1992 National Research Council report *From Earth to Orbit*. All examined, and most stated as a priority, the imperative of low-cost earth-to-orbit transportation.[26] The National Commission on Space stated, for example, "the most significant contributions the U.S. government can make to opening the space frontier are to ensure continuity of launch services and to reduce drastically transportation costs."[27] One concludes that the need for change within the existing space transportation system was recognized, yet interagency/political consensus proved elusive.

Meanwhile, an alternative to a rocket-based solution to low-earth orbit access was being pursued. The U.S. Air Force and NASA initiated the X-30 National Aerospace Plane program as a single-stage-to-orbit vehicle using a supersonic combustion ramjet (scramjet) and slush hydrogen propellant. This decision was made despite the fact that a scramjet had never flown nor had slush hydrogen propulsion ever been successfully demonstrated. The program plan allocated $3.33 billion over eight years (soon raised to $5 billion) to build and test two vehicles (later cut to one) by 1990. The National Aerospace Plane was to enable aircraft-like operations with a 24-hour turnaround time and a 100-person ground crew. As the program progressed, the scramjet technology, thermal protection system, and a host of integration challenges became problematic, causing Defense Secretary Richard Cheney to review the program in 1989. At this point, first flight had slipped a decade, and total costs estimates were as much as 500 percent over initial estimates. Secretary Cheney terminated DOD investment in the National Aerospace Plane, killing the program.[28]

In 1996, NASA began the X-33 competition for the next-generation Space Shuttle. The Lockheed-Martin Skunk Works was awarded the contract to build a wedge-shaped, vertical take-off horizontal landing lifting body powered by a linear-aerospike engine and incorporating a metallic thermal-protection system and composite fuel tanks (all unproven technologies). The sub-scale unmanned X-33 demonstrator was designed to reach Mach 15, a velocity adequate to validate the technology necessary to build an orbital reusable launch vehicle. The X-33's first flight was originally scheduled for March 1999; however, numerous technical challenges slipped the launch date and added costs. The failure of a composite liquid hydrogen tank forced the use of a heavier aluminum alternative and destroyed what little design margin existed. Scalability and traceability to the orbital reusable launch vehicle was in serious doubt. A September 2000 revision of the NASA-Lockheed-Martin agreement posited first flight in 2003, contingent upon the X-33 winning funding from the new Space Launch Initiative. Funding was not forthcoming, and the X-33 program died in late 2001 when the USAF, after a six-month review, chose not to resuscitate it. NASA had spent $912 million and Lockheed-Martin an additional $365 million on the X-33 before it was finally cancelled.[29] Also in 2001, NASA deferred further work on a smaller X-37 spaceplane prototype and killed the air-launched X-34 Mach 8 hypersonic demonstrator that had gone over budget.[30] However, The X-37 was resurrected in November 2002 when NASA awarded a $301M contract to Boeing Phantom Works to continue the development of the X-37 Approach and Landing Test Vehicle as well as the design of the long-duration orbital vehicle.[31]

NASA unveiled the $4.85 billion Space Launch Initiative, often referred to as the second-generation reusable launch vehicle program (shuttle replacement), in May 2001.[32] It was a near-term (2001-2006) business plan for NASA and its partners, to include DOD, to investigate new space transportation architectures and advanced technologies required to profitably implement them.[33] Stated objectives were: 1) "Invest in technical and programmatic risk reduction activities, driven by industry needs, to enable full-scale development of commercially competitive, privately owned and operated, Earth-to-orbit reusable launch vehicles by 2005; and 2) Develop an integrated architecture with systems that build on commercial Earth-to-orbit launch vehicles to meet NASA-unique requirements that cannot be economically served by commercial vehicles."[34]

NASA solicited and initially received hundreds of proposals and selected 15 for further consideration in April 2002. Among the 15 rocket-based concepts, five were based solely on hydrogen fuel, another five used a mix of hydrogen and kerosene, and the last five tapped hybrid mixtures and unconventional launch concepts.[35] On 21 October 2002, NASA indefinitely suspended a system requirements review slated for the following month that would permit a down select and pursuit of three Space Launch Initiative designs through 2005.[36] A total of $2.3 billion was cut from the Space Launch Initiative, with the decision on whether to develop the vehicle at all pushed back from 2006 to no earlier than 2009. The NASA justification says that they "had hoped to pay for the new vehicle by amortizing its estimated $10 billion development cost across the commercial and NASA launch market. The assumptions proved too optimistic given the declining launch market." Further, four independent cost estimates projected the total development cost of the new reusable launch vehicle at $30-35 billion.[37]

The USAF did a better job, albeit with a significantly more modest goal, to successfully upgrade the Delta and Atlas expendable launch vehicle families (Delta IV and Atlas V) to initial operational capability in 2002. In the 1994 Space Transportation Study chaired by Air Force Lieutenant General Thomas Moorman, roadmaps for four space launch options were developed: "maintaining the status quo; undertaking a limited evolution of current systems or components; beginning a new, clean-sheet expendable launch vehicle development; and developing a reusable launch vehicle."[38] However, no specific recommendations were presented with the report. Eventually, the Evolved Expendable Launch Vehicle—the evolutionary approach—was initiated as a politically acceptable response. The primary motivation was to provide responsive, "assured access" to space at reasonable cost. It was never intended to be a cure for the transportation problem, rather only a treatment to permit a cure to be found.[39] The Air Force awarded $500M to both Boeing and Lockheed-Martin in October 1998 to develop their respective launch vehicle families and supporting launch infrastructure. The contract also included options to purchase 19 launches worth $1.38 billion to Boeing and $650 million to Lockheed-Martin.[40] The Evolved Expendable Launch Vehicle program goals included: 1) reduce launch costs by 25-50 percent, 2) launch with 98 percent design reliability within 10 days of scheduled launch, and 3) capable of launching pre-integrated payloads within 45 days of government notification.[41] Current Air Force estimates are that it will pay between $75 and $150 million for medium and heavy-class payloads respectively.[42] Both the Delta IV and Atlas V had successful launch debuts in 2002.

Yet today the space transportation situation remains virtually the same as it was in 1985, with only the modest improvements of the Evolved Expendable Launch Vehicle as the notable exception. In fact, within the reusable launch vehicle arena, the situation has deteriorated considerably since the inaugural launch of the shuttle in 1981. The shuttle was the first attempt beyond totally expendable rocket designs, which initially became operational in the 1950s. If space transportation is assumed to drive and leverage cutting-edge technology, something is terribly askew. Clearly it is not another launch study that is needed.

Why has so little progress been made within the realm of space transportation for the past thirty years? First, a new space transportation system that truly delivers R^2*ISA* is not really necessary to continue limping along and perpetuating the status quo. Between the Shuttle, Titan, Delta, Atlas, and other international expendable launch vehicles in existence, the current payload manifest can be easily met. Second, "incrementalism"[43] has permeated U.S. space policy. Elements of the government bureaucracy remain locked in debate over policy, requirements, technology, and resources that derails efforts toward rational decision-making. Unfortunately, the aerospace community, to include government (DOD and NASA), academia, and industry, has done little to clarify the issues and help settle the debate. What is needed, more than all else is a rational, deliberative, and enduring effort to solve the space transportation mess. Outsourcing the problem to industry (discussed in detail in chapter 3) won't work. The systems are too expensive and the markets too thin to support this at present. Additionally, the status quo ensures that space launch maturation will remain stalemated, and future space exploration and exploitation will remain stagnant.

Until recently, the government was assumed to bear the burden of all serious space transportation solutions, with NASA playing the historical leadership role in that endeavor. Although NASA's agenda was not always synchronized with commercial or military needs, (as repeatedly demonstrated by strife over joint programs to include Advanced Launch System, National Launch System, Space-Lifter, X-30, and Space Launch Initiative to name a few) it was intended that it be endowed with the resources and technical expertise to lead these efforts. NASA has had great success with the latter, but the resource challenges have worsened dramatically. The continuing operational challenges associated with the shuttle and the international space station will continue to hobble NASA. Both are projected to consume more than 51 and 48 percent of NASA's annual $14+ billion FY03 and FY04 budgets respectively.[44] This results in an inability to fund its own proposed initiatives or demonstrate the wherewithal to see promising technology demonstrations to completion.

The recent Space Launch Initiative debacle, and NASA's decision to defer any decision on a second-generation reusable launch vehicle to no earlier than 2009, left unanswered, removes the possibility of R^2*ISA* for at least another 20 years. It is unclear whether this decision was based solely on current fiscal pressures, the agency's inability to articulate a clear and convincing case to its own administrator as to how $1000 per pound to low-earth orbit was possible, or the $30-35 billion price tag. In any case, there is no credibility to NASA's vision for a return to the moon and subsequent human exploration of the solar system until it effectively addresses the fiscal and managerial burden of the shuttle and the international space station and secures *R^2ISA* as the key enabler for its space exploration initiatives. Put simply, at least for now, NASA has been forced to abdicate its historical role as a catalyst for U.S. space launch system innovation and development.

The DOD could be allowed to pursue its own specific space launch systems that satisfy specific military requirements, and left to its own devices will likely do so. Based upon the Air Force's commitment to the Evolved Expendable Launch Vehicle program, there is reason to believe it would stay the course on whatever future solution it chooses. However, is this the most prudent path for the nation? Certainly a strictly military solution would have limited civil and commercial benefit. A successful national "compromise" solution to the stalemate may be the best way to permit NASA to regain its footing and deliver valuable military and commercial capability as well. Is a national solution to the current impasse possible? Does it make sense? The remainder of this paper will endeavor to answer these questions.

DIVERGENT REQUIREMENTS

There are unique requirements to civil, military, and commercial space launch. Differences in the areas of payload size and weight, launch rate, payload integration, mission turn-time, and cost can be significant. A military vehicle is driven to high sortie rates, smaller payloads with maximum mission flexibility, and minimum integration time. Civil (primarily NASA) requirements include medium to large payloads, lower launch rates, and deliberate/predictable payload integration. Although cost currently permeates all three sectors, not surprisingly, commercial launch vehicle service providers consider manageable costs the highest priority. Examination of all three sectors is intended to establish some "common ground" from which a national solution might prove possible.

Civil & Military Convergence?

Figure 3 highlights some of the important differences in civil and military requirements along functional lines. Taken at face value, one could quickly conclude that these "requirement" sets irreparably drive NASA and the DOD to two completely different system solutions, where collaboration beyond mutually supporting technology initiatives is both technically unfeasible and operationally unwise. Although this thinking is deeply entrenched in both the civil and military space communities, there are "joint" solutions that merit serious consideration. It will become evident later in this paper that the military's need for responsive operations, rapid turn time, and high sortie rate are the key operability elements that deliver order of magnitude reductions in cost. NASA's experience with the shuttle will clearly illustrate this point. Further, the apparent differences in payload delivery can be ameliorated through other elements of the space transportation architecture.

NASA's needs fall into two general categories: 1) launch of satellites for environmental monitoring and planetary exploration, and 2) launch of astronauts and payloads in support of the manned space flight program to include the International Space Station. Each of these currently require medium to heavy-lift payload capability to low-earth orbit. The added complexity associated with a crew-rated system may also need to be considered. At present, NASA is publicly committed to the development of an orbital space plane[45] and upgrades to the shuttle to keep it flying until at least 2012.[46] International Space Station logistical support may also require a heavy-lift capability that is currently being serviced by four Space Shuttle missions annually, at $800M per launch.[47]

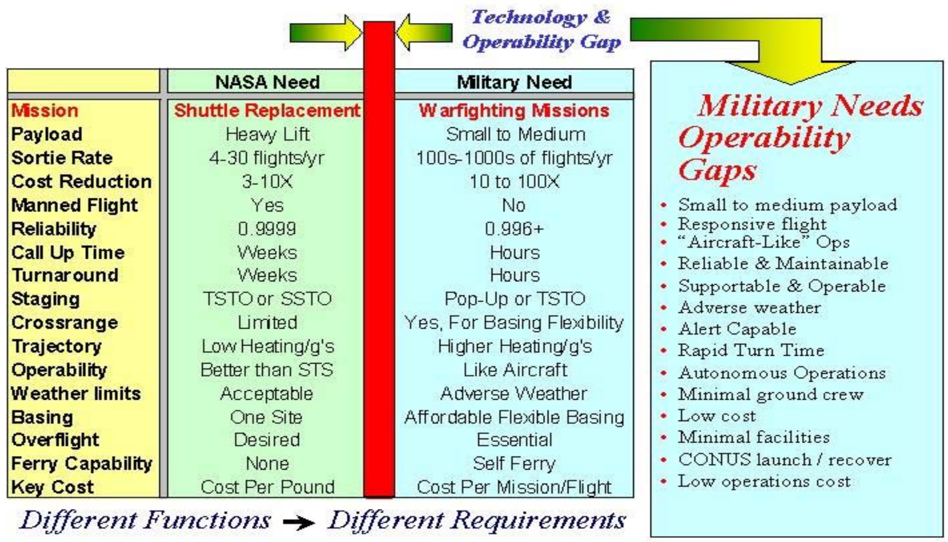


Figure 3. Civil and Military Requirements Comparison[48]

Military space mission areas include space force enhancement, space forces support, space control, and space force application resulting in a diverse set of specialized payloads.[49] DOD payloads often use commercially provided medium-payload-class expendable launch vehicles which deliver a wide variety of force enhancement systems to include navigation, communication, environmental, and information/surveillance/reconnaissance satellites. Future trends in the force support arena point to the proliferation of smaller satellite systems to include "gap filler" systems launched in time of crisis. Defining payload requirements for space control missions is problematic. The Air Force has publicly articulated its intention to develop offensive and defensive counterspace systems in the future.[50] Virtually all of these systems will be developed in a highly classified realm. However, it is generally accepted that these payloads will be relatively small (smallsat/microsat class), and RAND research studies indicate that there are a variety of useful small-launch-vehicle-class space control payloads possible.[51] Force application from or through space to effect the terrestrial battlespace—particularly lucrative, time-critical, remote, hardened, or heavily defended targets beyond the capacity of terrestrial-based aerospace forces—is an attractive option for space planners. Some proposed future systems that might accomplish these missions could be quite large, with space-based kinetic and directed energy systems requiring heavy-lift low-earth-orbit payload delivery and other concepts demanding small to medium-class capability.[52]

RAND concluded in 1996 that a military vehicle capable of a 1,000 to 5,000 lb payload delivery capability may be sufficient for most of the space control missions. Further, many of these military missions would require launch-on-alert within minutes to hours, lack launch predictability, and demand a rapid turnaround and launch reconfigurability to be most effective. These characteristics imply aircraft-like operations to include alert status in times of crisis. Finally, such levels of responsiveness demand aircraft-like supportability and reliability achieved with the smallest vehicle possible.[53] RAND considered the feasibility of a Trans-atmospheric Vehicle, or space plane, as a flexible approach to satisfying these requirements, where flexibility is defined as the capability of a space plane to deliver payloads to a variety of orbits and to operate from a number of different bases.[54] Other considerations included launch infrastructure, reentry cross-range capability, and ability to perform other missions, such as that of a long-range bomber. RAND concluded that a first-generation space plane, once demonstrating reliable operations, could provide significant long-term cost savings in terms of reduced launch costs.[55] Such a system currently appears attractive for an important segment of the future DOD space launch requirement. However, it fails to address some of the larger, more recently recognized payloads concepts such as the Space Maneuver Vehicle or Common Aero Vehicle that may follow.

Where might common ground between NASA and DOD exist? The "120-Day Study" chartered by the Secretary of the Air Force and the NASA administrator in October 2001 was a joint NASA-USAF effort to develop a "credible, comprehensive plan for the joint development of the next generation of reusable launch vehicles."[56] The subsequent "Red Team" study observation was that the study was chartered to address a "point solution," consistent only with overarching NASA second-generation Space Launch Initiative objectives and that a broader Air Force analysis of alternatives was prudent.[57] Although it must be conceded that such direction inevitably narrowed the trade space, NASA and the Air Force did find agreement in operational requirements to include: initial operational capability between 2012 and 2014, reliability between 1:750 to 1:1000 (probability of failure), full payload deorbit mass, abort to orbit, rendezvous capable, and full access to a full range of orbital inclinations (equatorial to polar and sun-synchronous). Overlap in the areas of payload mass and responsiveness is even more significant. USAF weapons and information, surveillance and reconnaissance preliminary requirements fell between ten and fifteen thousand pounds to low-earth orbit. NASA science and international space station support ranged between ten and fifty thousand pounds to low-earth orbit (or the equivalent of five to twenty thousand pounds delivered to the International Space Station).[58] The team concluded a common booster with a payload range between 25-45 thousand pounds to low-earth orbit was possible, and a wider payload range could permit a common orbiter.[59] NASA expressed a desire for a 48-hour call-up for crew rescue purposes in contrast to the Air Force's 12-24 hour call-up for contingency operations.[60] Overall, the team concluded that "architecture options were identified that meet USAF and NASA needs."[61]

The Air Force believes it needs to further refine space missions, requirements, and concepts of operations before it can commit to any joint DOD/NASA reusable program, although a NASA deferral of any decision regarding a next-generation reusable launch system appears to make this point moot. It is noteworthy however, that the 120-Day Study Red Team also observed that "multiple reusable launch vehicle development programs was most likely unaffordable and recommended that NASA and DOD leadership should both commit to some flexibility on requirements in order to control costs."[62] Certainly the RAND and 120-Day Study Team conclusions bound the Air Force payload requirement between one and fifteen thousand pounds to low-earth orbit. The articulated NASA requirement exceeds forty thousand pounds to low-earth orbit. However, NASA's decision to build an orbital space plane that is launched from an Evolved Expendable Launch Vehicle greatly reduces this requirement. The two remaining missions are cargo delivery to the International Space Station (currently Russian Progress missions delivering 4,000 pounds of cargo) and earth observing/interplanetary missions ranging from two thousand to twelve thousand pound payloads.[63] Exploitable overlap now exists between civil and military payload requirements.

Commercial

The most important attributes of any commercial launch system include 1) reducing costs to compete effectively in the worlds market, 2) performing to scheduled launch manifests, 3) developing payloads sized to the market, and 4) providing preplanned flight profiles without major anticipated changes. Most commercial satellites today require medium to heavy-lift launch vehicles. The relatively low global demand for commercial launch services (33 actual and 32 forecast worldwide commercial launches in 2002 and 2003, respectively)[64] and the crowded launch services market, which includes U.S., French, Russian, and Chinese, make the launch services industry very competitive. The vast majority of commercial missions require a geostationary transfer orbit in lieu of low-earth-orbit mission orbits that are the equivalent of a 20,000 to 45,000 lb low-earth-orbit class delivery.

The Commercial Space Transportation Study examined a plethora of potential commercial markets to include communications, space manufacturing, remote sensing, unique civil/military missions, transportation, entertainment, space utilities, extraterrestrial resources, advertising, and new missions.[65] Although there was significant variability among system architecture requirements between segments, some important common system attributes and requirements emerged and are summarized in Table 1.

Table 1. Commercial Space Transportation Study Attributes and Requirements[66]

Category	Attribute	Requirement Range
Dependability	High probability of launching on schedule	99% within scheduled hour 99.999% within scheduled day
Schedule	Minimum advanced booking time	6 months to 24 hours
Reliability	Equal to or greater than existing system	1/100000 probability of loss
Cost	Minimum cost per launch	Less than $1000/lb to orbit minimum $10,000 per

		event
Operations	Standardized and simplified payload interfaces	Maximize payload capability with customer base
Capabilities	- Support multiple payload classes - Provide delivery to multiple destinations - Provide on-orbit rendezvous and docking - Provide delivery and return capabilities	3000 pounds sub-orbital package delivery to 7,000 pounds to geostationary transfer orbit
Availability	High probability that the system will be in an operational rather than stand-down state	90% to 99.9%
Responsiveness	Minimum response time for launch on need	30 days to 24 hours

There is a striking similarity between these commercial requirements and those articulated for the military case. For example, fast package delivery was the most operationally stressing case examined by the study and drove the most aggressive requirements captured in Table 1. It was estimated that a 3000-pound cargo capability with a 10,000 nautical mile capability could capture between 70,000-1,000,000 pounds of cargo delivery at $1000/lb and 1,000,000–100,000,000 pounds at $100/lb based upon 1991 prices and markets.[67] One can reasonably conclude that a militarily suitable reusable launch vehicle that pierced the $1000/lb to low-earth-orbit cost threshold may have significant commercial viability.

BROKEN PROMISES and LESSONS LEARNED

Three experiences with reusable launch vehicles, one resulting in a flight vehicle (shuttle) and two that did not (X-30 and X-33), provide a unique opportunity to learn some important lessons. Closer examination of these programs will make it apparent that there is much more to high shuttle costs than complexity and a lack of true reusability, just as immature technology is not the only culprit behind the demise of the X-30 and X-33.

Space Shuttle

As the Apollo program was approaching its zenith, NASA's next goal was to first build and deploy an already mature space station design while simultaneously beginning the development of a fully reusable two-stage-to-orbit space shuttle. Shrinking budgets forced NASA to postpone space station development when it became apparent that it was not economical without a low-cost supply system. Hence, shuttle was at the forefront of development in the 1970's, with the space station shelved for at least a decade. In July 1970, NASA awarded contracts to North American Rockwell and McDonnell Douglas to design a shuttle with a 25,000 lb to low-earth orbit payload and 200-1500 nautical mile cross-range capability. Further in-house studies that year prompted NASA to opt for a delta-winged orbiter with a 65,000 lb low-earth orbit payload and 1500 nautical mile cross-range capability in 1971. This configuration came under intense criticism in both congress and scientific communities. The $10 billion developmental cost for this configuration was considered too expensive, so alternative booster designs were studied. NASA decided to scrap the fully reusable shuttle for political, technical, and economic reasons and scrambled to complete a new plan within six months in time for fiscal year 1973 appropriations. The final "thrust assisted orbiter concept" selected in 1972 consisted of a manned orbiter, expendable external tank, and reusable solid rocket motors characteristic of today's shuttle system. [68]

Cost analyses conducted in 1971 at the request of the Office of Management and Budget (OMB) estimated development costs of a fully reusable shuttle at $12.8 billion ($56.8B FY02) and stated that the development of a less expensive $5.15 billion ($22.9B FY02) partially reusable system was justified within a level of space activity between 300 and 360 flights between 1979 and 1990.   The estimated cost per flight was $10.5 million (FY71) ($46.6M FY02) based upon a flight rate of 50 per year and a first launch in 1978. By 1980, development costs had increased 20 percent to $6.2 billion (FY71) ($27.5B FY02) and a cost per flight to $15.2 million (FY71) ($67.5M FY02). The spectacular first-flight of Columbia occurred on 12 April 1981. A maximum annual flight rate of nine had been demonstrated in 1985 before the catastrophic loss of

Challenger and her crew on 28 January 1986. Extensive redesign and system improvements/upgrades were incorporated into shuttle, resulting in maximum payload reduction from 65,000 lbs to 53,700 lbs.[69]

The fundamental question is this: How could initial 1971 shuttle launch cost estimates of $46.6 million (FY2002) equating to $717 per pound to low-earth orbit have been more than an order of magnitude in error? At the risk of oversimplification, the answer lies with a large annual flight rate shortfall illustrated in the Figure 4 below. Once the magnitude of this impact is understood, attacking its root causes goes a long way towards enabling *R^2ISA*. The original shuttle orbiter maintenance turnaround operations envisioned a simple to operate and maintain vehicle, very little infrastructure, simple payload integration, and low labor intensity enabling a flight rate of forty per year.[70] This "vision" of operations was rendered circa 1974, prior to a detailed systems definition. The shuttle flight and ground support architectures matured as first flight approached and grew in complexity to meet the servicing, inspection and checkout required by the vehicle design. As a result, spacelift performance expectations (top of the graph which is a product of the flight rate multiplied by the single mission lift capability) versus its actual performance (the lowest area on the graph) in Figure 4 diverged radically.[71] Emblematic of this performance shortfall is the current need to remove and replace 50-100 line replaceable units between each flight due to failures found in flight (10 percent), on the line (55 percent), or while under test or inspection (35 percent), respectively.[72] A stable flight rate of about eight per year for a fleet of four vehicles had been achieved through 1997 with a decline to four per year by 2002. Likewise, the single lift capability had not met expectation, dropping from the original 65,000 lbs concept to 50,000 lbs actually fielded for operation. Although the vehicle performance shortfall was small compared to the flight rate shortfall, the combined effect had tremendous implications on the shuttle flight and ground architectures, undermining total spacelift performance.[73]

The flight rate shortfall can be attributed in part to the design compromises made to lower developmental costs as well as the NASA approach to forgo "Y-prototype" development that permits the rigorous testing and experience necessary to inject operability and maintainability improvements into the objective system design. Hence, an important design parameter that should be examined, estimated, and ultimately verified before production of the objective system is the "single vehicle" capability. Verification is accomplished with frequent flights of the

Y-prototype in an operationally stressing environment. Arguments that a "stressing" high single vehicle capability rate drives unnecessarily high cost into prototype development fail to recognize the importance of flight rate capability and fall into the same trap graphically illustrated by shuttle. These issues emphasize the importance of the conceptual design phase as the first opportunity to establish first-order-of-magnitude ground infrastructure and cycle turn-around time requirements that are ultimately verified in a Y-prototype. Any launch system's total flight rate and vehicle performance (payload capacity) drives total payload throughput and defines a system's overall spacelift performance capability.[74]

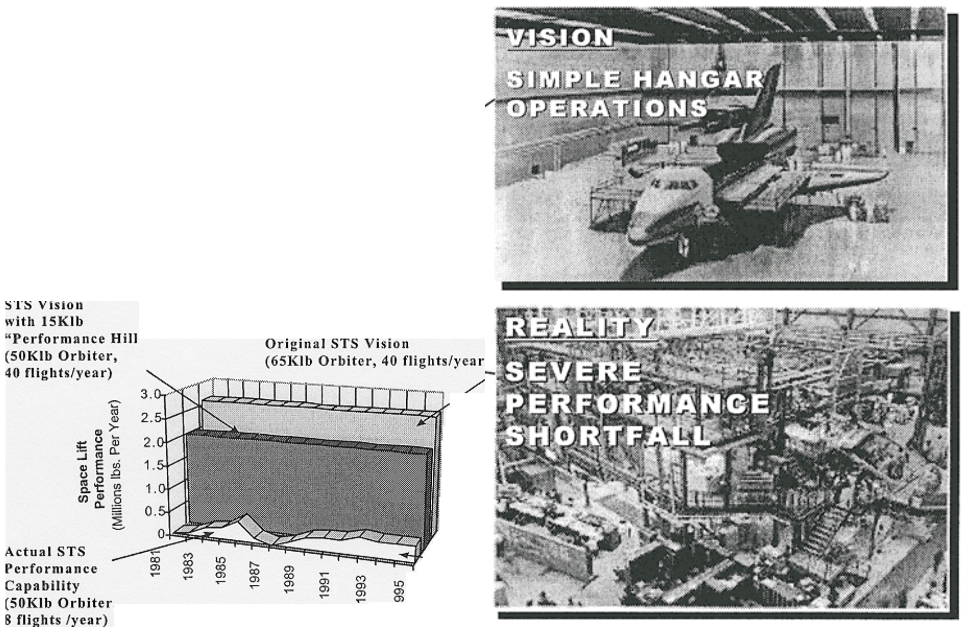


Figure 4. Shuttle Spacelift Performance —Vision vs. Reality [75]

X-30 and X-33

The X-30 National Aerospace Plane program of the late 1980's and early 1990's was preceded by a program of the same name in the late 1950's and early 1960's; both were cancelled before a flight vehicle was ever built. The first program demonstrated a number of important technologies such as real-time air liquefaction and hypersonic refueling.[76]

The second program, X-30, called for a single-stage-to-orbit, fully reusable system based upon a complex combined cycle propulsion concept with several air-breathing components. The original program goal was to insert a manned, air-breathing, single-stage-to-orbit vehicle into low-earth orbit. However, the high risks associated with the propulsion concept, as well as other vehicle design aspects, prevented it from proceeding beyond the technology development phase.[77] At the time, computational fluid dynamics was not sufficiently advanced, nor were ground test facilities sufficient (upper limit was Mach 10) to preclude the need for extensive flight-testing. Further, the vehicle's depressed ascent profile (to permit air ingestion) resulted in high skin temperatures and potential heating of internal structure and components. This environment demanded an advanced thermal protection system that included active cooling of leading edge surfaces. The combined cycle engine was to provide smooth transition from a slower subsonic/transonic mode to ramjet and eventual scramjet mode of operation to achieve orbital velocity. The Defense Science Board Task Force reviewed the program in 1988 and found six critical technology areas: aerodynamics, supersonic mixing and fuel-air combustion, high temperature materials, actively cooled structures, control systems, and computational fluid dynamics. The Defense Science Board concluded that the development schedule for all of these technologies was unrealistic.[78] The program was cancelled after $1.7 billion was spent and it became clear that an operational prototype would cost $10 billion or more.[79] Remnants became an advanced technology program.[80]

NASA initiated the X-33 program in 1995 with the goal of demonstrating key single-stage-to-orbit technologies by the year 2000, leading the way for an eventual operational vehicle that could replace the space shuttle as well as existing expendable launch vehicles.[81] The X-33 was a subscale technology demonstrator intended to show scalability and traceability to a full-scale single-stage-to-orbit reusable launch vehicle. Lockheed-Martin Skunk Works was awarded an $837 million contract on 4 July 1996 to design a lifting body vertical-take-off/horizontal-land vehicle using a linear-aerospike engine. NASA had budgeted an additional $104 million to support its own program infrastructure, with Lockheed-Martin investing an additional $212 million for X-33 development. Lockheed-Martin had estimated a fleet of two to three full-sized vehicles would cost between $4.5-5.0 billion at the successful conclusion of the X-33 program.[82] The significant technical risks outlined by the Lockheed-Martin program manager, Dr. David Urie, at the outset of the program included vehicle integration, structures, propulsion, and thermal protection. To achieve single-stage-to-orbit capability, Lockheed-Martin would have to successfully overcome specific design challenges in the X-33 that included flight stability and control (the Lockheed-Martin design was aerodynamically unstable); a very lightweight, structurally efficient vehicle; and highly efficient, performance driven propulsion.[83]

Economics played a dominant role in X-33 development. Lockheed-Martin intended to transform the X-33 into a commercially viable single-stage-to-orbit reusable launch vehicle that could compete successfully against expendable launch systems. Corporately, Lockheed-Martin had to achieve revenue and profit objectives within corporate capital investment constraints and reasonable reusable launch vehicle market demand. This included recouping sub-scale X-33 and full–scale Venture Star development costs within a reasonable time frame at an acceptable investment rate of return.[84] The following business objectives had to be satisfied to make a reusable single-stage-to-orbit vehicle economically viable: 1) having the first reusable launch vehicle to enter the marketplace; 2) building a reliable launch vehicle that had a successful first flight; 3) meeting market-based "cost-per-pound-to-orbit" pricing targets; 4) designing for low operations costs; 5) establishing long-term cash flows and a predictable launch rate; 6) lining up customers; and 7) establishing good returns on a space-port type launch services.[85] The X-33 began development at a time where a fairly robust demand for launch services prevailed and was expected to continue. Based upon the aggregate of all three competitors' mission models, average demand varied between 32 and 46 space launches per year. At that time, this represented nearly the combined U.S. government and commercial launches projected by the 1994 Moorman panel and implicitly assumed an anchor tenancy (guaranteed market access) for NASA and DOD payloads.[86] There was also agreement among the three competing contractors that DOD payloads in excess of 20,000-pound low-earth-polar orbits fell within the Titan-IV heavy-lift vehicle class and was outside the design limits of a marketable reusable single-stage-to-orbit concept. All three X-33 concepts were designed to capture the majority of the Delta and Atlas class payloads.[87]

By 1999, technical problems with the vehicle's internal composite fuel tanks, linear-aerospike rocket engine, and thermal protection system had, in turn, precipitated cost increases, revision of key performance objectives, and significant delays in the vehicle's flight test schedule.[88]

After the failure of a composite liquid hydrogen tank in ground testing, NASA restructured the program as a competitor for Space Launch Initiative bidding. The X-33 failed to secure NASA funding after an agency-wide review concluded that the costs of continuing the program outweighed the benefits they were expected to produce. Mr. Art Stephenson, director of NASA Marshall Space Flight Center concluded, "One of the lessons learned is that our technology has not yet advanced to the point that we can successfully develop a new reusable vehicle that substantially improves safety, reliability and affordability."[89] Dennis Bushnell, Chief Scientist of NASA Langley Research Center, concluded that a key lesson learned from both the X-30 and X-33 programs is that "revolutionary goals require revolutionary technology and a 'going in' large 'cushion' in terms of expectations versus metrics."[90] Both of these perspectives place a premium on technology and claim that the technology isn't ready. Technology is indeed a key enabler for *R²ISA*; however, there are other equally important facets of space launch vehicle design directly impacting system maintainability and operability that cannot be ignored. The space shuttle space-lift performance shortfall is a case in point.

Additional Lessons Learned

A recent paper from Booz Allen Hamilton[91] cast a larger net by examining the experience base from a broader set of past reusable launch vehicle projects,[92] as well as other successful aerospace endeavors,[93] to make a set of technical/programmatic and "environmental" project comparisons. The analysis and conclusions from this paper not only reinforce the shuttle, X-30, and X-33 experiences, but also add additional insight as well. A synopsis is highlighted in Tables 2 and 3 below.

The most intriguing observation that can be made regarding these technical/programmatic lessons learned is that they could describe any high-risk government acquisition program, many of them successful. This in turn implies that the space shuttle performance shortfall and the X-30 and X-33 program failures were avoidable. Either the "system" should have permitted a better risk assessment and more realistic funding, or they should never have been funded in the first place.

Table 2. RLV "Technical/Programmatic" Development Lessons Learned

Characteristic	Discussion
Technology	In every case, including both successful and canceled RLV programs, the technology required was more difficult to develop than most proponents had originally forecast. Successful programs exceeded original budget estimates to solve technology challenges and were supported to completion.
Risk	Cost, schedule, and performance are inextricably linked. Sufficient trade space must exist between them to be successful. Low failure tolerance by management negatively impacts cost and schedule. Incremental versus substantial leaps in technology or performance is the prudent path.
Requirements	Solid mission requirement and/or clear market demand must exist.
Credibility	Overselling the capabilities of a vehicle results in loss of credibility, leading to much more difficult funding. Shuttle, X-30, and X-33 were all oversold.
Realistic Cost & Schedule Estimates	Part of the overselling problem. Sometimes the result of honest underestimation but also from deliberate dishonesty. Typically, the largest cost overruns are associated with immature technology where precise cost estimating is not possible.
Organization Matters	Successful X-vehicles have traditionally been produced by organizations that were kept "lean" and co-located as the scope of the project allowed.

Table 3. RLV "Environmental" Development Lessons Learned

Lesson Learned	Discussion
Credible and Compelling Need	A clear, credible, and compelling mission is essential. A solid business case to justify the substantial investment in lieu of technical and business risk associated with the development.
National Commitment	Top-level, enduring commitment at the national level is necessary, as well as significant commercial and public support to ensure project stability.
Recognize Competing Interests	A radical departure from the status quo can be viewed as threatening to organizations and institutions that benefit most directly from established approaches. Very real political and industrial base considerations must be addressed.
Realistic Expectations	The vehicle cannot be oversold. Although design variations may address additional missions, claiming at the outset that it will do all or most related space missions will result in another Space Shuttle.
Parallel Approaches	Parallel approaches to mitigate higher risk elements of the supporting technology base are essential for program success.
Small Steps versus Giant Leaps	Unreasonable to expect too much from a demonstrator. No X-vehicle ever completed has had operational capability. Smaller steps associated with a clear, sustainable evolutionary path are the proven approach.
Focused Leadership	While many organizations may contribute, leadership must be in the hands of a single organization, one not bound to legacy systems. History is clear that breakthrough aerospace projects have a program office or other organization with real authority and long-term commitments from the agencies and contractors involved.

The environmental factors highlighted above are political and institutional in nature. Due to the high front-loaded developmental costs inherent in R^2*ISA*, one must ask if indeed there is a compelling need—and whether an enduring national commitment can be reasonably expected. With the tragic loss of Columbia, the entire civil space program is under review, with the future of NASA's manned space flight program at the center of the debate. The DOD is clear in its position: "Space transportation represents the sine qua non of space power: unless sufficient lift capability becomes readily available at significantly less cost, U.S. capabilities to place its projected systems on orbit in sufficient quantities to achieve mission objectives will increasingly lag behind demand. Major technological advances leading to improved launch capability will be needed to achieve the very first of USSPACECOM's objectives for the future—Assured Access to Space—without which its other objectives may remain beyond reach."[94] American commercial space launch is in siege mode, with the current glut of global expendable launch capacity exceeding demand by a factor of 300-400 percent. The compelling need exists, but it must now be recognized, communicated, and acted upon by senior leadership. Experience has taught us that a successful reusable launch vehicle development program hinges as much upon a national commitment to a politically sensitive, realistic, focused, evolutionary solution as it does to making the appropriate design choices responsive to a compelling mission/market defined by clear and unambiguous requirements.

III. Defining the Problem

> *The last ten percent of performance generates one-third the cost and two-thirds of the problems.*
>
> —Augustine's Law Number XV

> *I think that if I'd been at Kitty Hawk in 1903 when Orville Wright took off, I would have been farsighted enough, and public spirited enough—I owed this to future capitalists—to shoot him down. I mean, Karl Marx couldn't have done as much damage to capitalists as Orville did.*[95]
>
> —Warren Buffet

This section introduces two key underlying elements of R^2*ISA*, namely: the Newtonian physics and thermodynamics that define the fundamental limits of space technology, and the linkages between the inelastic space transportation market (broadly defined as civil, military, and commercial) and the prohibitively expensive space technology upon which it is based.

ROCKET SCIENCE 101

The past thirty-year history of space transportation indicates that there has been a basic misunderstanding by some who should have known better that the laws of gravity and thermodynamics are non-negotiable. Ignore or defy them at your own peril. This section endeavors to briefly introduce, in as plain English as the subject will permit, the basics that ***must*** be understood and mastered to permit any meaningful technical discourse on the subject of R^2*ISA.*

The introduction of several basic equations is necessary to best explain fundamental concepts and commonly used measures of merit. English units are used throughout the text and in the tables to maximize familiarity and comfort with these topics. Unfortunately, English units are ill-suited for use within the context of modern science and engineering, as the recent loss of the Mars Climate Orbiter in September 1999 will attest. Hence, only metric units are used in the equations below.[96]

Energy is the Key

The challenge associated with delivering any payload to its final mission trajectory/orbit can be reduced to two fundamental activities: first, the acceleration of a payload from the earth's surface to orbital velocity; and second, the subsequent energy added to "raise" the orbit to its final state. Both elements involve adding large amounts of energy to the system, kinetic energy with the former, potential energy with the latter. Equation 1 quantifies this relationship.

$$\text{Orbital Energy} = m\left[\frac{v^2}{2} + \int_{r_0}^{r} g\,dr\right] \text{ and}$$

$$oe = \frac{OrbitalEnergy}{m} = \frac{v^2}{2} + \int_{r_0}^{r} g\,dr$$

where oe = specific orbital energy

v = velocity (m/s^2)

g = acceleration due to gravity (m/s^2)

r_0 = Earth radius, 6370 kilometers (km)

r = $r_0 + altitude$ (km)

Equation 1. Specific Orbital Energy

Figure 5 illustrates graphically that objects in a reference 100 nautical miles (nm) (or 185 km) altitude low earth orbit (where r/r_0 is a mere 1.029) have specific orbital energy that is overwhelmingly comprised of specific kinetic energy. In fact, the ratio of kinetic versus potential energy is about 20 to 1. Alternatively, moving from low-earth to geostationary-earth orbit (36,200 km from the center of the earth where r/r_0 is 5.68), specific orbital energy is comprised mostly of specific potential energy. The ratio of kinetic to potential energy is less than 0.1, or 1 to 10 for this case. This has profound implications for space transportation architectures. The challenge of earth-to-orbit launch systems is a kinetic one, where enormous energy is required to generate high levels of propulsive thrust in a short period of time to accelerate a payload to very high velocity (in excess of 7800 m/s). This is an inherently inefficient and potentially dangerous process due to the high energy densities required. Alternatively, additional energy added after orbital velocity is achieved can be accomplished in a much more deliberate fashion. Lower thrust systems operating at much higher efficiencies for longer duration provide invaluable flexibility (as well as innovation) in space propulsion that is not typically enjoyed in earth-to-orbit launch systems. Ideally, any intelligent, optimized space transportation architecture built from the ground up would minimize the burden on the launch vehicle while fully leveraging the benefits of on-orbit space propulsion to the maximum extent possible. For a wide variety of reasons, mostly historical, today's space "architecture" is woefully sub-optimized. For example, geostationary satellite delivery typically uses the launch vehicle upper stage in a direct ascent into a geostationary transfer orbit. This is done despite the fact that a wide array of space propulsion technologies could do so much more efficiently. However, due to a sub-optimized architecture, these options are either impractical or simply do not exist. Any future space transportation architecture must address this issue directly.

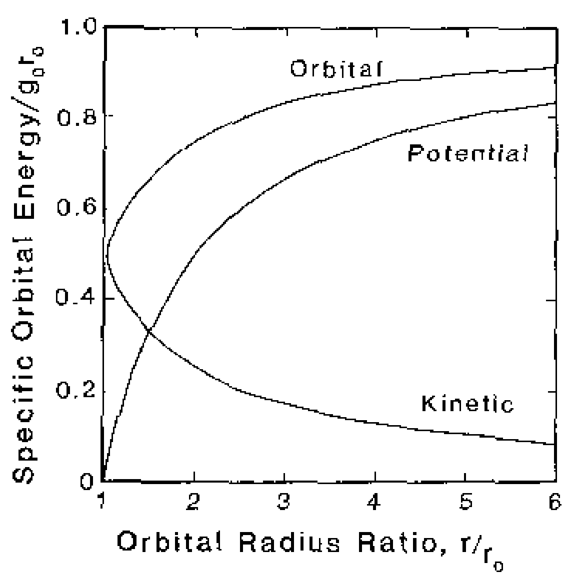


Figure 5. Specific Orbital Energy[97]

Measures of Merit

The most common propulsion performance parameter is specific impulse (I_{sp}), with higher values indicating greater efficiencies. It compares the thrust generated by a propulsion system to the propellant mass flow rate and can be considered a measure of thrust generation efficiency (much like gas mileage in your car).

$$I_{sp} = \frac{F}{\dot{m} g_0}; \quad c = I_{sp} g_0$$

where I_{sp} = specific impulse (s)

F = thrust magnitude (N)

$\dot{m}$ = propellant mass flow rate (kg/s)

g_0 = acceleration due to gravity, 9.807 (m/s^2)

c = effective exhaust velocity (m/s)

Equation 2. Specific Impulse and Effective Exhaust Velocity

Specific impulse permits the direct comparison of propulsion systems using different types of propellant (such as a hydrogen versus kerosene fueled liquid rocket engines), or dissimilar systems (such as a hydrogen/kerosene fueled liquid rocket and a supersonic combustion ramjet). The unit of seconds is disconcerting to some, but the concept is not that unlike miles per gallon as an efficiency measure for automobile internal combustion engines or specific fuel consumption of aircraft turbojet engines. However, the mass flow component of specific impulse is different for rocket systems (where all of the propellant is contained within and consumed by the vehicle) and airbreathing systems (where internal fuel is mixed with external air). The specific impulse calculations for airbreathing systems do not need to account for the external air flowing through the engine, thus resulting in much higher effective specific impulse.

Table 4 presents a synopsis of applicable propulsion technology for both earth-to-orbit as well as on-orbit applications. While more versatile chemical systems operate over a wide range of thrust levels, they do so at low to moderate specific impulse. Alternatively, high specific impulse electric systems deliver very low thrust, while nuclear systems carry sufficient political and environmental concerns to make approval for their use in a near-earth environment unlikely. Solar thermal propulsion is representative of a developing class of on-orbit space propulsion technologies where thrust levels are high enough to make them attractive as orbital transfer vehicles that operate at specific impulse levels two to four times higher than traditional chemical systems.

Table 4. Propulsion Technology Performance Summary[98]

Technology	I_{sp} (s)	Thrust (lbs)	Advantages	Disadvantages
Cold Gas - N_2 - H_2	 60 250	0.02-10	• simple • safe • low contamination	• low specific impulse
Chemical - Liquid - Monopropellant - Bipropellant - Solid - Hybrid	 140-235 320-460 260-300 290-350	0.02 to 2,700,000	• high thrust • heritage	• moderate performance • combustion complications • safety concerns
Nuclear - Solid Core - Liquid Core - Gas Core	 800-1100 3000 6000	Up to 2,700,000	• high specific impulse	• unproven • politically unattractive • expensive • low thrust/weight
Electric - Electrothermal - Electromagnetic - Electrostatic	 500-1000 1000-7000 2000-10000	0.00002 to 5	• very high specific impulse	• high system mass • low thrust levels • limited heritage
Solar Thermal	700-1000	1-10	• high specific impulse	• limited heritage

Another useful performance parameter is effective exhaust velocity "c" where the force of thrust "F" in the specific impulse equation is replaced with "$\dot{m}c$" and appropriate substitutions yield $c = I_{sp} g_0$. Thrust, whether aircraft, rocket, or from a deflating toy balloon is generated through the acceleration of the exhausted propellant. Thrust is maximized for a given mass of propellant by accelerating it to the highest velocity possible, hence higher exhaust velocities typically indicate more highly efficient propulsion and provides another method of direct comparison between propulsion systems. Engine thrust-to-weight is an intuitively straightforward parameter that captures the "engineering" efficiency of an engine. It is the total thrust generated by the engine divided by the engine weight, where higher ratios are desirable.

Table 5 highlights the range of performance both within and between chemical rocket and airbreathing propulsion systems suitable for terrestrial and earth-to-orbit applications. The very large increases in specific impulse in airbreathing versus pure rocket-based systems make their use in space launch systems highly desirable. However, hypersonic airbreathers remain technologically immature, and the benefits of higher specific impulse are partially offset by lower thrust, thrust-to-weight, and limits to its operating range.

Table 5. Key Propulsion Performance Characteristics

Demonstrated Technology	*Isp (s)	Sea Level Thrust (lbs)	Thrust to Weight	Range of Operation
Chemical Rockets				
- Liq Oxy/Hydrogen (SSME)[99]	454	418,000	59.8	No Restrictions (Sea Level to Vacuum)
- Liq Oxy/Hydrogen (RS-68)[100]	410	608,000	41.8	
- Liq Oxy/Kerosene (RS-27A)[101]	302	200,000	79.1	
- Solid	260-300			
- Hybrid	290-350			
****Airbreathers**				
- CF6-80C2B6 (B-767)[102]	10770	60,800	6.3	0-Mach .9
- F100-PW220(F-15C)[103]	1713	23,770	7.3	0-Mach 2+
- Notional Hydrogen Scramjet[104]	1-3000			Mach 5-20
- Notional Kerosene Scramjet[105]	1000			Mach 5-8

*Note that rocket I_{sp} values are ideal vacuum performance. Seal level (launch) performance is typically only 80% of the ideal value.
** Includes the mass of fuel only

Other important vehicle "technology" metrics are the inert and propellant mass fractions as well as the structural ratio. The vehicle mass relationships are highlighted both graphically and mathematically in Figure 6.

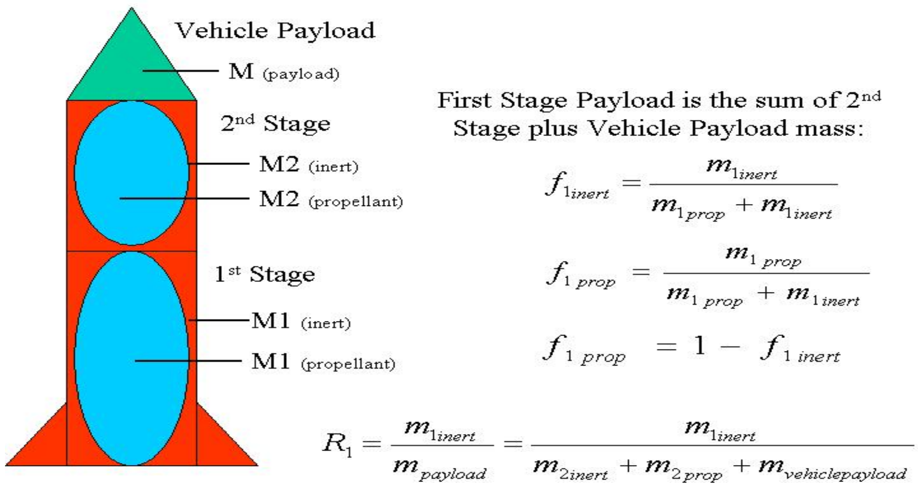


Figure 6. Two Stage Vehicle Mass Contributors

$$f_{inert} = \frac{m_{inert}}{m_{prop} + m_{inert}}; \quad f_{prop} = \frac{m_{prop}}{m_{prop} + m_{inert}}; \quad f_{prop} = 1 - f_{inert};$$

$$R = \frac{m_{inert}}{m_{payload}}$$

where f_{inert} = inert (structural) mass fraction
f_{prop} = propellant mass fraction
R = structural ratio
m_{inert} = inert (structural) mass (kg)
m_{prop} = propellant mass (kg)
$m_{payload}$ = payload mass (kg)

Equation 3. Launch Vehicle Mass Fractions

The inert mass fraction (f_{inert}) is an excellent indicator of the overall structural efficiency of a launch vehicle, or any aerospace vehicle. Lower values indicate higher efficiency. The structural ratio (R) is the ratio between inert vehicle mass and payload mass, with lower numbers approaching unity most desirable. Structural ratio is a direct measure of how efficiently overall vehicle dry weight is allocated to useful payload.

Table 6 below shows representative mass fractions and vehicle structural ratios for both expendable and reusable launch vehicles as well as aircraft.

Table 6. Mass Characteristics of Aerospace Systems

Vehicle				**1st Stage**		**2nd Stage**	
	f_{inirt}	f_{prop}	$*R$	f_{inirt}	f_{prop}	f_{inirt}	f_{prop}
Delta II	0.06	.91	2.4	.055	.94	.137	.86
Atlas II	0.06	.91	1.8	.062	.94	.11	.89
Titan II 23G	0.04	.96	3.6	.033	.96	.092	.91
Pegasus (L-1011 stage 0)	0.10	.90	5.0	.084	.92	.096	.90
Space Shuttle System	.134	.85	11.2	.15	.85	.12	.87
Space Shuttle Orbiter	.73	.16	2.8				
X-15[106]	.42	.54	24				
X-33	0.09	.88	3.3				
F-15[107]	.46	.28	1.7				
B-777-300[108]	.52	.21	1.9				
*Launch Vehicle payloads normalized to 100 nm 28.5 deg incl except Titan II (polar) **Sum of vehicle inert and propellant mass fractions do not add to unity due to inability to fully extract payload and wet vs dry weights from data sets							

There are some important trends revealed in Table 5 that warrant comment. First, all of these are or were operational vehicles, with the exception of the X-33, which did not fly. Note how expendable, single use, space launch vehicles tend to have inert vehicle mass fractions between 0.04 and 0.10, indicating very highly structurally efficient systems. At the other end of the spectrum you find highly reusable aircraft with inert mass fractions between 0.42-0.52. The higher mass fractions are primarily the result of heavier (less expensive) structural materials, higher margins of safety, and the operability and maintainability inherent with high reusability. When one considers the amount of design work and resources that are allocated to keeping an aircraft as light as possible, one can begin to appreciate the implications of inert mass fractions below 0.10. Now consider the required inert mass fraction required for the performance driven X-33. The technologies envisioned for this vehicle were beyond existing state-of-the-art, with virtually no design margin available for future weight growth. The wide disparity between demonstrated mass fractions of expendable and reusable systems imply that there are some formidable technological challenges in transitioning from expendable to reusable launch vehicles as well as making reusable launch systems "aircraft-like."

The ideal rocket equation is an elegantly simple equation that provides powerful insight into the first order concerns surrounding launch vehicle design and performance:

$$\Delta V = g_0 I_{sp} \ln\left(\frac{m_i}{m_f}\right) = g_0 I_{sp} \ln\left(\frac{m_{inirt} + m_{prop} + m_{payload}}{m_{inirt} + m_{payload}}\right)$$

where ΔV = change in velocity (m/s)
$m_{initial}$ = initial mass (kg)
m_{final} = final mass (kg)

Equation 4. Ideal Rocket Equation

Here, ΔV represents the change in velocity (without accounting for losses due to gravity, steering, atmospheric drag, and earth's rotation) that a vehicle can attain based solely upon specific impulse and initial/final vehicle mass. This equation, coupled with a velocity budget associated with a given mission, defines the boundary conditions for launch vehicle design. An example of such a budget for ascent into selected low-earth orbits for rocket based launch systems is summarized below in Table 7.

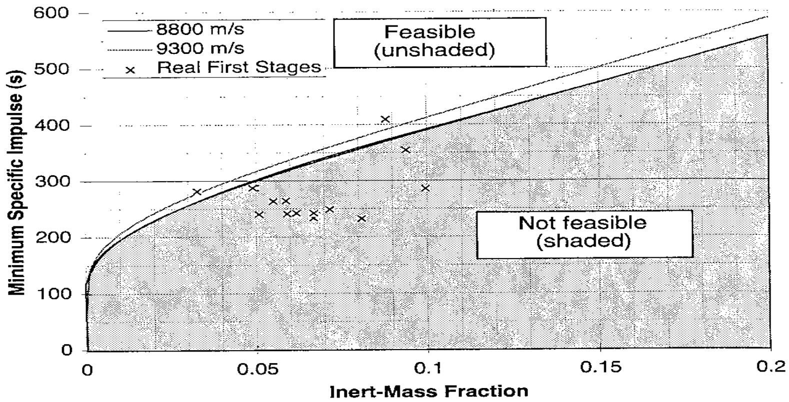
Table 7. Velocity Budgets to Low-Earth Orbits for Selected Launch Vehicles[109]

Vehicle	Orbit: $h_p x h_a$ Inclination (deg)	ΔV_{LEO}	ΔV_{grav}	$\Delta V_{steering}$	ΔV_{drag}	ΔV_{rot}	$\Sigma\Delta V$
Delta 7925	175x319 33.9	7842	1150	33	136	-347	8814
Atlas I	149x607 27.4	7946	1395	167	110	-375	9243
Titan IV/ Centaur	157x436 28.6	7896	1442	65	156	-352	9207
Space Shuttle	196-278 28.5	7794	1222	358	107	-395	9086
Units of ΔV in m/s.							

The first term (ΔV_{LEO}) is calculated using the ideal rocket equation. The additional values are added velocity required to overcome gravity, steering, and drag. Note relative magnitudes of these values with both the ideal velocity required and the relative uniformity in the gravity and drag losses among pure rocket trajectories. These losses increase for airbreathers that spend more time in the atmosphere before attaining orbital velocity. Also note that ΔV_{rot} is negative because of the benefit these trajectory flyouts receive from the earth's west to east rotation. Hence velocity budgets can be built and used to determine basic vehicle requirements (initial and final mass, propulsion efficiency, etc.) that deliver a desired capability (payload to a desired orbit).

Figure 7 shows inert mass fraction as a function of specific impulse with two curves derived from the ideal rocket equation, representing ΔVs of 8800 and 9300 meters per second (28,900-30,500 ft per second), that bound the velocity change required to achieve low-earth orbit insertion. Real first stages (those on existing or historical launch vehicles) are plotted against these curves. The shaded region represents the trade space that is not feasible for single-stage-to-orbit vehicles.

Figure 7 illustrates the impact of higher inert mass fractions demanding higher specific impulse to attain orbital velocity. For example, a single-stage-to-orbit with an average specific impulse of 430 seconds (typical liquid oxygen/hydrogen rocket) must have an inert mass fraction of at least 0.125 (no more than 12.5% structure) to achieve orbit with no excess margin to deliver any useful payload. An added payload requirement would drive this number even lower. However, reusable launch vehicles must be much more structurally robust than their expendable cousins, demanding inert mass fraction of at least 0.20-0.30. This would imply a requirement for a propulsion system with an average specific impulse in excess of 550 seconds, a technology not yet available for practical chemical rockets. Unfortunately, a reusable launch vehicle with an inert mass fractions below 0.10 has yet to be demonstrated either. This type of basic analysis graphically illustrates the challenges inherent with any single-stage-to-orbit program and puts the technical hurdles confronted by the X-30 and X-33 into proper perspective. Thus, in proposing these two programs, either someone wasn't asking the right questions, or someone else wasn't telling.



Feasible Regions for Launch Systems. The two curves shown here represent the minimum possible specific impulse, given a certain structural technology (f_{inert}), to perforn a launch mission. Data for existing or historical (real) first stages is overlaid [Isakowitz,1991] and is listed in Table C.1. Several existing first-stage systems are feasible for a launch mission alone, based only on specific impulse and inert-mass fraction (other conditions may make these impractical or impossible).

Figure 7. Feasible Regions for Launch Systems[110]

Staging

The ideal rocket equation makes it clear that certain specific impulse and vehicle inert mass fraction combinations make earth-to-orbit missions impossible. One way to overcome this limitation is through staging. For example, from Figure 7, one could surmise that a single-stage-to-orbit vehicle with a specific impulse of 290 seconds (a liquid oxygen/kerosene combination) and aggressive inert mass fraction of 0.05 cannot achieve orbit. However, staging permits the “discarding” of inert vehicle mass at some point in the trajectory. So, what is the right number of stages for a specific combination of technology and mission constraints? Figure 8 is based upon the ideal rocket equation and illustrates the benefit of staging for an orbital mission requiring a ΔV of 9000 meters per second (29,527 ft/sec), inert (structural) mass fraction of 0.08, and specific impulse of 420 seconds.

Notice that in this example overall system mass is decreased by 54 percent when adding a second stage and the marginal benefit of three or more stages. This is typical for a wide range of specific impulse/inert mass fraction combinations for earth-to-orbit launch vehicles and is why most launch vehicles use two stages to achieve orbital velocities. Additional parallel first stages (such as solid strap-on boosters) are used to increase the initial vehicle thrust to weight ratio as well as payload capacity to low-earth orbit.

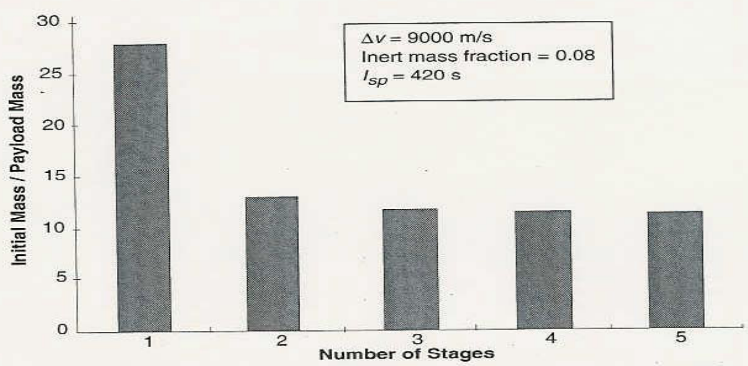


Fig. 2.11. **Varying the Vehicle's Initial Mass versus the Number of Stages.** Mass decreases greatly (54%) as we shift from one to two stages. The initial mass continues to decrease as we increase the number of stages, but the payoff is not as significant.

Figure 8. Staging Impact Upon Vehicle Mass[111]

Launch Vehicle Technology

Technology and system integration are the "brick and mortar" upon which R^2*ISA* is built. It is universally acknowledged that the most challenging element to the development of any complex system is system integration—the creation of new system that is greater than the sum of its parts. Surprisingly, there is also consensus within the space launch community where the bulk of the enabling technology development remains. As previously discussed, advances in four areas to include propulsion, advanced materials and structures, thermal protection (not relevant to expendable launch systems), in addition to vehicle integration are critical to achieving R^2*ISA*.

Table 8 is a top-level structural, propulsive, and mechanical comparison of existing aircraft and reusable/expendable launch vehicles. This table lists some of the inherent engineering design characteristics of aircraft and space launch vehicles and highlights a few of the challenges in developing more "aircraft-like" space launch vehicles. The wide disparity in performance is in part an artifact of the inherent demands of space launch, but much of it is a direct result of the performance maximization mindset permeating U.S. launch vehicle development since the early days of intercontinental ballistic missiles in the 1950's. Performance maximized systems typically lack design margin, or the difference between designed and demanded performance, that in turn has a very large impact on vehicle reliability, robustness, and cost.

Table 8. Aircraft to Launch Vehicle Comparison[112]

Characteristics	Aircraft	STS (Orbiter)	ELVs
Structures:			
- Factors of Safety	1.5	1.4	1.25
- Gross Liftoff Weight (Klbs)	618	4,426	1,888
- Design Life (Missions)	8,560	100	1
Propulsion:			
- Thrust (Vacuum, Klbs)	30-60	470	200 to 17,500
- Thrust/Weight Ratio	4.5	74	60 to 140
- Operating Temperature (°F)	2,550	6,000	500 to 5,000
- Operating Pressure (PSI)	140	2,970	500 to 1,200
- Cruise Level Power	25%	109%	100%
Mechanical:			
- Specific Horsepower (hp/lb)	2	108	3 to 18
- RPM	13,450	35,014	5,000 to 34,000

The reasons for the wide range of structural mass fractions between expendable and reusable systems can be seen here. Lower factors of safety,[113] volumetric efficiency, and single use, are characteristics that result in highly specialized, highly efficient expendable launch vehicles. Much smaller aircraft represent the opposite end of this spectrum, demanding higher factors of safety and structural mass fractions (refer to Table 5) up to an order of magnitude greater. The inherent nature of earth-to-orbit operations demands very powerful (thrust) and lightweight (high thrust-to-weight) propulsion, which in turn requires demanding performance maximization that includes much higher operating temperatures and pressures as well as operation at or on excess of design limits (cruise level power) to accomplish the mission. The impacts of cruise power are well documented. For example, the operational life the Space Shuttle Main Engine is reduced by nearly a factor of ten when operated at 109 percent of rated thrust. Reusable launch vehicle propulsion will need to operate well beneath its design limits to permit aircraft-like operations in the future. The disparity in the mechanical demands placed upon rocket-based turbomachinery (pumps) versus aircraft (turbines) is truly remarkable. The high rotational velocities coupled with the power that drives rocket turbo-pumps makes them the single most failure prone and potentially dangerous component on a space launch system. The development of space launch vehicles that approach aircraft-like operations will need to have large performance margin built into its systems to minimize "redline" operations.

Propulsion. The most important performance related propulsion characteristics are high thrust at high total system performance (specific impulse), high structural efficiency (thrust to weight), accomplished with the highest density propellants possible (smaller vehicle size), and robust performance margin. The operability requirements for rapid turnaround and low cost operation demand durability, damage tolerance, ease of inspection, and capability for rapid and safe shut-down. Performance and operability inevitably come into direct conflict with each other.

The highest specific impulse and thrust-to-weight rocket propulsion systems commonly used in space launch are liquid hydrogen/oxygen (LH_2/LO_2) fuel/oxidizer systems. There are several drawbacks to this propellant combination. First, the cryogenic properties of liquid hydrogen create unique fuel handling and storage problems. It is difficult to contain, prone to leaks, and always an explosive hazard. Further, its very low boiling point (-423° F) introduces unique material compatibility issues. Although all of these problems have been successfully addressed since the earliest days of modern rocketry, the added complexity makes a flexible, responsive launch vehicle and ground support system problematic. The second drawback to liquid hydrogen is its very low density, demanding much larger and often complex propellant tanks manifesting themselves into larger, heavier vehicles. Hence, despite their lower performance, alternative higher density oxidizer/fuel combinations such as liquid oxygen combined with kerosene (RP-1), methane, as well as hydrogen peroxide (oxidizer) and kerosene are attractive alternatives. Other more exotic and even higher density materials (HEDM) are under investigation. A synopsis of these propellant combinations is summarized below.

Table 9. Properties of Candidate RLV Propellants[114]

Propellant		T_{fp} (°K)	T_{bp} (°K)	P_{vap} (Mpa)	Density (kg/m^3)	Stability / Handling/ Storage Characteristics	(O/F) I_{sp} (sec)
Oxygen	O_2	54	90	5.07 @ 154°K	1142	Good/ Good/ Cryogenic	N/A
Hydrogen	H_2	13.8	20.3	1.29 @ 32.8°K	71	Flammable/ Flammable/ Cryogenic	(3.8) 435 w/O_2
Kerosene (RP-1)	$CH_{1.97}$	229-291	445-537	2275 @ 344°K	810	Flammable/ Flammable/ Good	(2.2) 321 w/O_2
Hydrogen Peroxide	H_2O_2	267.4	419	345 @ 298°K	1414	Unstable >414°K Flammable/ 1%/yr decomp	(7.5) 298 (w/RP-1)

T_{fp} = freezing point; T_{bp} =boiling point; P_{vap} =vaporization pressure;

(O/F)= oxidizer to fuel ratio;

I_{sp} = Vacuum Specific Impulse; 0°K=-460°F// 72°F=295°K

Hence propellant selection is a very important design parameter for launch vehicle design consideration. When different propellant combinations are used in a staged vehicle, the maximum ΔV is derived from higher specific impulse upper stages. Higher density propellants can have a very large impact upon vehicle size (note that kerosene is 11.4 times denser than liquid hydrogen) making the denser propellants most attractive in the larger first stage.

One of the best first-order indicators of conventional rocket engine design complexity is chamber pressure. Higher chamber pressures equate to higher overall performance, but unfortunately, also demand heavy, complex, and often failure prone turbo-pumps as well. Further, higher pressures equate to higher operating temperatures, often driving an engine from passive cooling to much more complex active cooling. Rocket engines operate at maximum performance when the exit pressure equals ambient pressure, a condition present during a very small segment of the engine's operation. Conventional rocket engines typically have fixed bell nozzles resulting in sub-optimal performance. Variable expansion nozzles are typically heavy, complicated and cumbersome, rarely making their implementation worthwhile. However, the linear-aerospike engine, like that pursued on the X-33, uses a fixed-center "spike" constraining the flow between nozzles but permitting the outside flow to freely expand to ambient pressure. Hence, the nozzle can be optimized to operate at a high altitude or vacuum condition without experiencing significantly degraded performance at low altitude.[115] Despite some minor performance drawbacks at certain flight transients, these engines can operate at much lower chamber pressures and can be designed to be modular, greatly enhancing propulsion integration with the remaining vehicle structure.[116]

In the final analysis, rocket propulsion is on the performance edge of demonstrating single-stage-to-orbit capability at current specific impulse and thrust-to-weight ratios. They also currently lack the operability and maintainability necessary for R^2*ISA*. A combination of higher specific impulse and thrust to weight with proven reliability and durability is necessary for rockets to become an attractive alternative for either single or two-stage-to-orbit vehicles.

Advanced Materials and Structures. Minimizing inert mass fractions is key to maximizing the payload capability of space launch vehicles. Development of advanced materials, particularly reinforced composites and metal matrix composites for both structural and thermal performance are central to this success. These advanced materials exhibit strength-to-weight and stiffness-to-weight ratios two to five times higher than aluminum or titanium, the current staple for aerospace vehicles.[117] These materials include graphite epoxy (five times stronger per unit weight than aluminum, which is the primary shuttle structural material), aluminum/lithium alloys, and others. According to some analyses, advanced composite materials and lightweight metal alloys may permit launch vehicle structure weight to be reduced by up to 35 percent.[118] Despite some unique flight vehicle environmental challenges, (temperature, material compatibility, etc.), intelligent application of these advanced materials is a prerequisite to building design (in this case structural) margin and robustness onto future reusable launch vehicles.

Thermal Protection. Load bearing structures such as aluminum and titanium cannot survive the severe thermal loads associated with reusable launch vehicle atmospheric reentry. None of the classic solutions of the past, to include missile reentry vehicle ablative ceramics, or space shuttle silica glass tiles are suitable. Light, inexpensive, low maintenance, launch systems with rapid mission turnaround and high payload mass fractions require a durable, robust, and lightweight thermal protection system. Reusable launch vehicle aerodynamic design can be optimized to reduce peak heating and overall thermal loads on the vehicle, thereby decreasing the degree of thermal protection required. RAND concluded that the technology is sufficiently mature to fabricate a thermal protection system that is more reliable and less expensive to maintain than the current shuttle ceramic tile system that requires 17,000 man-hours for refurbishment after every flight.[119] Provided reentry temperatures less severe than those encountered on the shuttle, existing advanced thermal protection materials, have the potential to provide the robustness and durability required for a next generation reusable launch vehicle.[120] Peak temperatures generating the highest thermal loads would still likely require reinforced carbon-carbon, but combinations of metallic panels are suitable for most other vehicle locations. The thermal regime referenced is summarized in Table 10. Temperatures associated with the Boeing Reusable Aerodynamic Space Vehicle are consistent with the RAND conclusions discussed above. RAND further observed that "although metallic panels have higher density than ceramic tiles, a metallic TPS may be lighter and simpler by eliminating the need for a complex adhesive system such as that used on the space shuttle. The panels may also serve as aerodynamic load bearing structures, eliminating the necessity for an underlying airframe."[121]

Table 10. Selected Temperature Distributions[122]

	National Aerospace Plane	**Boeing RASV**	**Space Shuttle**
Nose, leading edges	3000-4000 °F	1800-2770°F	2300-2800°F
Lower fuselage/ wings	N/A	**1200-1800°F**	1800-2300°F
Upper fuselage/ wings	N/A	**900-1200°F**	600-1800°F

Note that the two most common Shuttle thermal protection materials, namely reinforced carbon-carbon found on the shuttle nose and leading edges as well as the silica glass tiles on the lower fuselage and wings, have single-mission and 100-mission temperature ratings of 3300/2700°F and 2600/2300°F respectively.[123] Even the moderated Boeing Reusable Aerospace Vehicle temperature regime described above exceeds the 100-mission life temperature of reinforced carbon-carbon. This punctuates the challenges and importance of reentry energy management and an appropriate thermal protection schema.

Vehicle Integration. Structurally efficient and maintainable vehicles demand the effective integration of lightweight, high-strength composites and metal alloys into vehicle structures to include the dual role of tanks and metallic thermal protection systems as structural load bearing elements. The efficient integration of propulsion elements into the vehicle structure, particularly airbreathing hypersonic propulsion solutions is also a major design challenge. The success of these integration efforts is essential for minimizing inert vehicle mass and maximizing design margin or useful payload delivery to low-earth orbit. Further, vehicle design integration must ensure simple subsystem interfaces and maintenance accessibility to minimize labor intensity, ground handling, and mission-turn time. Careful design trades between operationally desirable but structurally parasitic wings in lieu of structurally efficient but control limited lifting bodies must also be carefully considered.[124]

EXIT STAGE RIGHT

This section addresses the present technology limitations that drive any existing space launch vehicle to a two-stage-to-orbit-solution.

Challenges of Single-Stage-to-Orbit Vehicles

Historically, single-stage-to-orbit designs of the 1960's and 1970's had been considered more technically challenging than two-stage-to-orbit designs due to technological limits on achievable vehicle inert mass fractions and propulsion specific impulse. These limitations resulted in extremely performance sensitive single-stage-to-orbit designs with large gross lift-off weights and hypersensitivity to any performance shortfall. The National Aerospace Plane unsuccessfully attempted the development and integration of very high specific impulse, airbreathing scramjet technology into a reasonably sized single-stage to orbit vehicle until it was abandoned in 1992. The development of modern composite materials, advanced lightweight alloys, and thermal protection systems in the 1980's and early 1990's indicated that vehicle structures might be reduced by as much as 35 percent.[125] This reassessment did not go unnoticed by NASA, prompting pursuit of the X-33 program in 1996.

A single-stage-to-orbit space launch system holds the promise of providing the simplest reusable space launch architecture possible, yet the enabling technology to achieve it remains beyond the state-of-the-art. As previously discussed, a viable singe-stage-to-orbit vehicle is challenging because of the high ΔV and aggressively low inert mass fraction required. Efforts such as X-33, shown conceptually in Figure 9 and outlined in Table 11, heavily leveraged technology to push the performance envelope with high performance rocket propulsion, advanced lightweight high-strength materials, and innovative thermal protection systems. The X-33 program was intended to demonstrate technology scaleable and traceable from a subscale vehicle to a full-scale single-stage-to-orbit rocket.[126] Since the X-33 design competition was so keen (a successful X-33 design was considered an inside track to the build the successor to the space shuttle) and the design approaches so varied, it is instructive to examine the vehicle "vital statistics" for the all three proposed objective reusable launch vehicle systems.

Figure 9. X-33-Based SSTO RLV Design Concepts

Table 11. X-33 Based Single-Stage-to-Orbit Design Concepts Description

Characteristic	**Lockheed-Martin**[127]	**McDonnell Douglas**[128]	**Rockwell**[129]
Type	Lifting Body VTHL	Ballistic VTVL	Winged VTHL
Length (ft)	127	185	213
Width (ft)	128	48.5	103
GLOW (lb)	2,186,000	2,400,000	2,200,000
Empty Weight (lb)	197,000	219,000	296,000
Propellant Weight (lb)	1,929,000	2,136,000	1,861,000
Payload Weight (lb)	59,000	45,000	43,000
Propulsion	7 RS2200 Linear Aerospike Engines	8 Rocketdyne RS-2100 Engines	6 Rocketdyne RS-2100 Engines
Propellant	LH2/LOX	LH2/LOX	LH2/LOX
Engine Vac. I_{sp} (sec)	445	450	450
Engine T/W		83 to 1	83 to 1
Chamber Pres. (psia)	2250	3250	3250
Payload Size (ft)	15x45	16.5x35	15x45
Inert Mass Fraction	0.090	0.091	0.135
Propellant Mass Fraction	0.882	0.890	0.846
Payload Mass Fraction	0.027	0.019	0.020
RDT&E COST	2-3 vehicles@ $5B	1 vehicles@ $4-7B	1 vehicles@ $5-8B
VTHL=Vertical Take-off Horizontal Land; VTVL=Vertical Take-off Vertical Land; GLOW=Gross Lift-off Weight; T/W=Thrust-to-Weight; RDT&E=Research Development Test & Evaluation; LH2/LOX=Liquid Hydrogen/Oxygen			

Although the vehicles depicted above are very different in outward appearance, they share many common underlying characteristics. The most notable but predictable characteristic common to all three vehicles is the aggressive application of "cutting-edge" technology to expand the performance envelope sufficiently to make a single-stage-to-orbit vehicle practical. As previously discussed, existing technology resulted in vehicles cursed with very small payload fractions and razor thin performance margins that, in turn, demanded very aggressive inert mass fractions and high performance propulsion. The inert mass fractions ranging between 0.09-0.135 for the proposed X-33 is reasonable for an expendable launch vehicle, but unrealistic for reusable systems. Unreasonable demands on the propulsion side of the equation were no different. The thrust-to-weight ratios for the X-33 design proposals are consistent with the National Research Council conclusion that a single-stage-to-orbit reusable launch vehicle would require a minimum thrust-to-weight value between 75 and 80.[130] The Space Shuttle Main Engine Block II+ with a sea-level thrust to weight ratio of 58 remains the most advanced liquid hydrogen/oxygen rocket engine ever built. NASA is planning to improve to thrust-to-weight to near 70 in the Block III version. Hence, all proposed X-33 propulsion solutions reside beyond the existing state of the art. Any performance shortfall of the already aggressively specified RS-2100 or revolutionary linear-aerospike engine would drastically reduce payload capacity for any of these designs. Not surprisingly, high performance liquid hydrogen/oxygen is incorporated into all three designs despite the low propellant density (and increased vehicle mass) associated with it. Lockheed-Martin chose to accept additional risk by incorporating the then unproven linear-aerospike engine to gain a five to eight percent performance improvement.[131]

Aggressive inert mass fractions also have significant design implications. The vertical take-off mode proposed by all three designs effectively constrains vehicle launch operations to a well-equipped spaceport. This design choice is made to eliminate the need for a robust landing gear (it supports an order of magnitude less vehicle mass at landing) and structurally inefficient but beneficial wings (also useful for significant cross-range), both necessary for a horizontal take-off. Neither a launch-certified horizontal take-off and landing gear nor wings appear realistic for single-stage-to-orbit application until much improved inert mass fractions and structural margin is demonstrated. Also, despite successful incorporation of current state-of-the-art materials technology, low inert mass fractions will make it difficult, in the foreseeable future, for the vehicle to compete with single stage expendable rockets for the launching of heavy payloads (i.e. 25,000 pounds or more).[132]

All three designs were emblematic of a performance-driven solution. A slight miscalculation or performance shortfall results in the elimination of useful payload capacity. Squeezing out the last drop of specific impulse or shaving off the last pound also costs money and reduces system reliability and robustness. It cannot be overemphasized that performance-driven designs are ill suited to deal with the inevitable

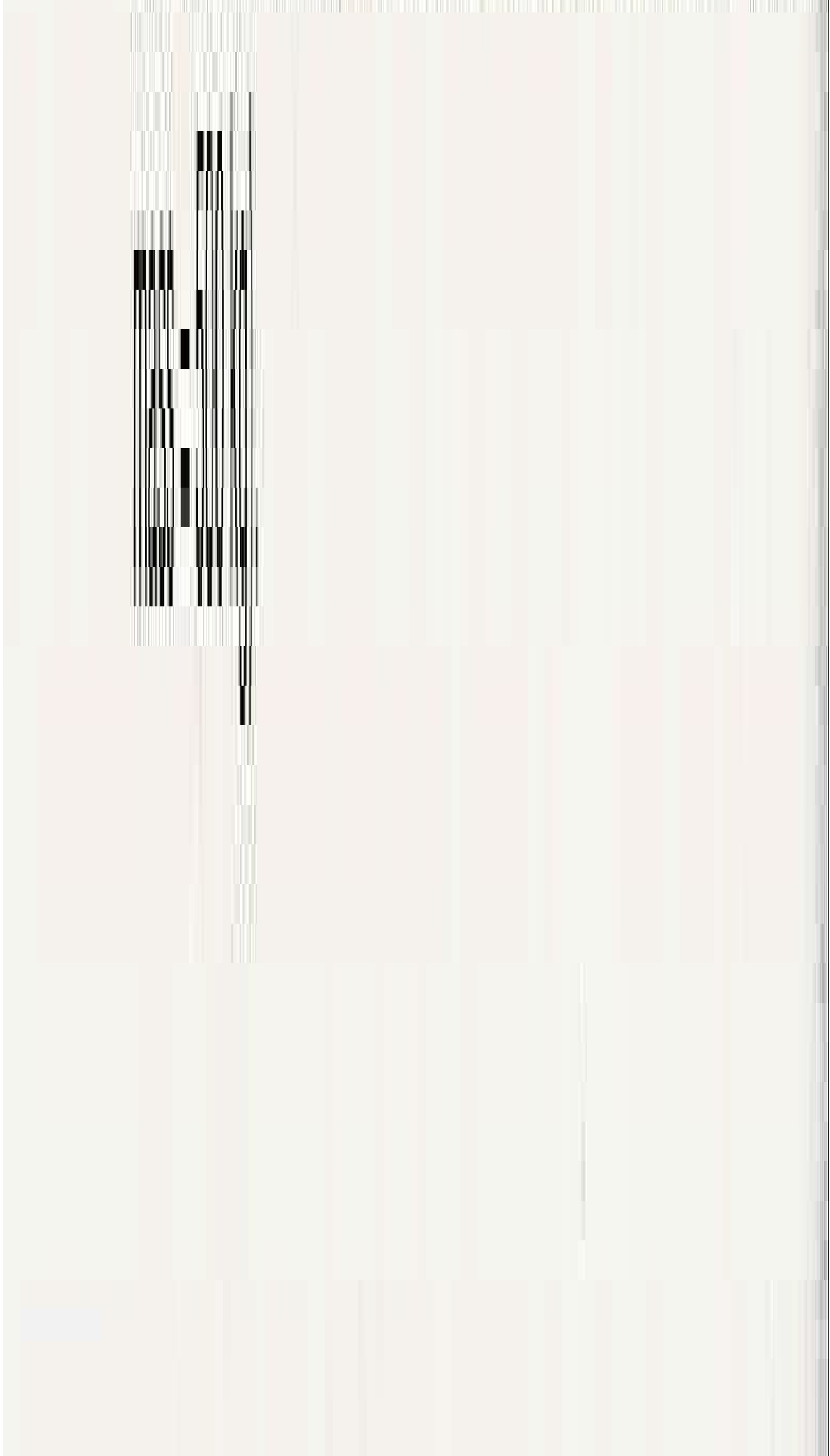


Figure 10. Parametric Analysis of a Single-Stage-to-Orbit Vehicle

Single Stage vs. Two-Stage-to-Orbit Solution

The single-stage-to-orbit example previously discussed demands beyond current state-of-the-art technology to deliver useful payloads to low-earth orbit. As mentioned earlier, a rocket-based solution continues to require liquid hydrogen/oxygen propellant resulting in volumetrically larger vehicles and a minimum thrust to weight ratio between 75 and 80, very light structures delivering a vehicle inert mass fraction below 0.10, as well as a very robust thermal protection system. All of these demands become tradable design margin with two-stage-to-orbit solutions.

The idea of a fully reusable two-stage-to-orbit system is not new. The original World War II German Sanger concept proposed a supersonic Mach 6 first stage, with a rocket-based orbital vehicle as the second stage.[133] The Sanger had both the first and second stages optimized and fully integrated into a combined vehicle configuration. Today, the Sanger II upper stage designed to achieve orbital velocity is rocket powered, while the first stage can be either rocket powered, airbreathing, or both. A two-stage-to-orbit vehicle could be launched either horizontally or vertically, with both first and second stages typically landing horizontally. First and second stage engines can operate concurrently at launch/take-off to provide additional thrust, but these designs require fuel and/or oxidizer transferred from the first to the second stage as propellant is consumed in the latter. Subsonic vehicle separation has been demonstrated between a highly modified B-747 and the space shuttle orbiter, and supersonic separation up to Mach 3 speeds with an SR-71 air-launched ramjet powered drone.[134] The reusable two-stage-to-orbit second stage will still require a robust thermal protection system to withstand the full rigors of reentry with minimal maintenance, but permits a much smaller orbital vehicle as well as eliminating the need for a complex thermal protection system for the first stage. Given similar technologies (i.e., the same propulsion system and inert mass fraction), a two-stage-to-orbit vehicle will always have a better payload mass fraction than a single-stage-to-orbit vehicle designed for the same mission. Only when the single-stage-to-orbit inert mass fraction approaches zero does its payload mass fraction approach that of a two-stage-to-orbit vehicle.[135]

SPACE ECONOMICS 101

The Space Launch Market

The U.S. space transportation market is a $7 billion industry comprised of 39 percent civil (manned) low-earth orbit missions; 28 percent commercial geostationary-earth-orbit; 16 percent military geostationary-earth-orbit; six percent military low-earth orbit; six percent civil low-earth orbit, and the remaining five percent to civil earth escape and commercial low-earth orbit missions.[136] Estimates in forward demand are historically both highly variable and optimistic. Much of the geostationary spacecraft launch demand is being offset by dual launch capability, and commercial low-earth-orbit demand remains uncertain. The 1994 Commercial Space Transportation Study indicates that present demand is linear (inelastic) to price down to approximately $1000/lb to low-earth orbit. Interestingly, tourism is the one new market that appears to dominate all others, indicating a highly elastic demand curve. There are undoubtedly others that are yet unidentified and will remain so until price barriers are lowered. Historical market conditions (high price, low volume) maximize industry revenue when demand is linear (or nearly so) with price. This is emblematic of a classical market failure, which ventures into the realm of a private cost, public benefit problem. If the price is halved, volume doubles, and total revenue remains constant, hence there is no market incentive to invest. Reality to date supports this assessment, as no investment in a new space launch system has returned that investment in real terms.[137]

Transportation industries have bedeviling contradictions in the past and remaining today. On the one hand, they are a vital part of a robust economy. On the other, they are historically government subsidized, money losing propositions for investors. Any government policy maker, corporate CEO, or entrepreneur who believes that the current economic state of affairs in space transportation is amenable to profitable commercial enterprise (outside of very limited niche markets) is sorely mistaken. However, that said, there is nothing unusual about this, and certainly nothing inherently "wrong" with the future potential space transportation market. The trick will be finding the right chemistry to unlock that potential.

Warren Buffet cites the automobile and the airplane as two illuminating examples of 20th Century transportation market failures with his commentary on the latter below:[138]

> The other truly transforming business invention of the first quarter of a century, besides the car, was the airplane—another industry whose plainly brilliant future would have caused investors to salivate. So I went back to check out aircraft manufacturers and found that between the 1919-39 period, there were about 300 companies, only a handful still breathing today. Move on to airline failures. Here is a list of 129 airlines that in the past 20 years filed for bankruptcy. Continental was smart enough to make that list twice. As of 1992, …the money that had been made since the dawn of aviation by all of this country's airline companies was zero. Absolutely zero.[139]

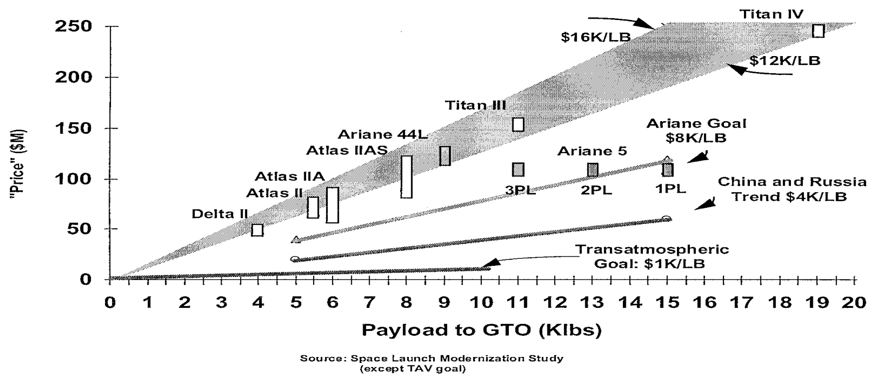
One conclusion that can be drawn from Mr. Buffet's observations are that access to public capital markets for the billions of dollars required for space launch system development will be very difficult. The potential for an attractive return on investment simply does not yet exist. More than $1 billion has been privately invested in various space launch startups since 1980, excluding the Evolved-Expendable-launch Vehicle. The cumulative "return" on this investment of social resources is less than $600 million from 35+ revenue launches of Pegasus and Athena vehicles. Even ignoring the time value of money, it is evident that private investment in new space transportation assets has not been justified by the return on investment. This is exactly what we would expect if the 1994 Commercial Space Transportation Study data were broadly correct.[140] Note that the only "successful" new entrant into the industry (Orbital) undertook private development of the Pegasus vehicle following the implied government endorsement of an "anchor tenancy," a form of government incentive.[141] All of this implies that access to U.S. government demand may be required for private or partly private financing of new launch assets.[142]

This situation is not at all unusual. There has been significant subsidization of railroad, automobile, commercial aviation, and space launch infrastructure. Further, within the aviation and space industry, national security imperatives were responsible for absorbing the cost burden of technological advance as well as flight vehicle development. This was the case from 1910 through 1960 in the aviation industry to include the enabling technology for the development of the DC-3 and B-707. The same was true for the space launch market. Once President Eisenhower made ICBM development a national priority in 1954, it would ultimately dwarf that of the Manhattan Project in both size and funding. The Thor, Atlas, Titan, (forerunners of the Delta, Atlas, and Titan launch vehicles) and Minuteman missiles would be successfully developed in just eight years.[143] The latest Evolved Expendable Launch Vehicle systems, namely the Delta IV and Atlas V, are direct descendants and beneficiaries of the immense capital investment made nearly fifty years ago. The only other major U.S. launch systems since that time, namely Saturn and Shuttle, were also government-financed systems. This will not change until there is a robust commercial space transportation industry to support.

Consequently, any illusion that the "smart money" from either the largest aerospace corporations or venture capitalists will finance future-generation launch systems before the government paves the way for several orders of magnitude reduction in launch costs is an exercise in wishful and unrealistic thinking. This problem is compounded by the fact that the space transportation market has no incentive to grow until the cost savings from an advanced space transportation architecture is demonstrated. The current state of affairs is a classic "chicken or the egg" scenario emblematic of a market failure.

Launch Vehicle Economics

Figure 11 provides a macro-view of existing expendable launch vehicle space launch cost trendlines of geosationary-transfer-orbits for U.S., French, Russian, and Chinese launch services. It also captures the operational partially reusable 1st Generation RLV launch systems (namely Pegasus and Shuttle). This section will provide the economic detail that drives these cost trendlines for Western systems.



Source: Under Secretary of Defense for Acquisition and Technology, *Space Launch Modernization Plan*, Office of Science and Technology Policy, 1995.

Figure 11. ELV Space Launch Cost Trendlines[144]

One approach to space launch system cost accounting is to describe total system costs as the sum of direct and investment costs:

$$C_{system} \equiv [C_{hardware} + C_{propellant} + C_{operations}]_{DIRECT} + [C_{infrastructure} + C_{development} + C_{money}]_{INVEST}$$

Equation 5. Total System Cost Elements

where investment costs include infrastructure (spaceports and support equipment), vehicle development costs, and cost of money (all costs to be recouped via vehicle operations). Direct costs include vehicle hardware, propellant, and vehicle operations costs. Propellant costs are generally insignificant and will not be discussed further.[145] Cost comparisons between systems is difficult due to the proprietary nature of data associated with commercial systems. However, in spite of these limitations, some important observations regarding launch system costs can be made.

Investment costs are typically the subject of intense scrutiny due to the upfront commitment of capital and the seemingly unavoidably large price tag that comes with it. Although this paper only briefly addresses infrastructure costs and the cost of money, it is important to recognize that these factors weigh heavily on any commercial decision to develop a space launch system. Developmental costs often dominate investment costs and are critically important because they are usually constrained by an upper threshold that, if breached, results in elevated managerial and political scrutiny, often putting the entire development effort in jeopardy. Subsequent design compromises, often made during the developmental phase as a consequence of constrained funding, come home to roost later as much higher production and operations and maintenance costs.

Direct costs typically dominate the overall system cost. Not surprisingly, hardware costs comprise the lion's share of expendable launch vehicle direct costs while operations and maintenance costs may comprise as much as 70 percent of the total direct costs for reusable launch vehicles.[146] Much of the reusable launch vehicle direct costs can be traced back to underlying technology, design, manufacturing, operability, and maintenance choices that are made during system design and development. Hence, insight into direct costs can guide decisions regarding the entire launch system architecture. Table 12 provides specific data highlighting some relevant launch vehicle cost data.

Table 12. Launch Vehicle Costs

System	"Dry" Mass (lb)[147]	Payload to Low-Earth Orbit (lb) (ref)[148]	Price to Low-Earth Orbit ($/lb)[149]	Specific Develop-mental Cost ($ per lb)[150]	Specific Hardware Cost ($/lb)[151]	Specific Operational Cost ($/lbm)	Labor Intensity (hrs/lb)[152]
SSTS	615,679	63,433 (127)	15,000	114,000	18,900		1
Pegasus	5395	976 (115)	13,500	Not Avail			
X-15	13,873	N/A	N/A	102,000	8960		0.5
X-33	76,534	N/A	N/A	20,000	3340	See Figure 11	N/A
X-34	16,500	N/A	N/A	14,000	1190		N/A
Delta II	36,388	11,330 (115)	4854	9,500			10
Atlas II/ Centaur	22,100	18,982 (115)	5136	31,600			40
Titan IV/ Centaur	132,800	41,000 (110)	4951	Not avail			40
Notes		(alt) nm 28.5 deg incl	FY2000	FY2002	FY2002		

Direct Launch Costs. Launch vehicles are, pound for pound, more expensive than almost any other manufactured product—significantly higher than the cost of aircraft. Table 13 depicts a relative cost comparison between several different transportation systems. These high specific costs are directly tied to technical complexity, design decisions, and manufacturing processes.

Table 13. Transportation Vehicle Hardware Costs per Pound[153]

Vehicle	**Relative Cost**	**Cost (FY02 $/lb)**
Space Shuttle Orbiter	11.1	16,473
Atlas IIA	2.5	3,708
Delta II 7925	0.97	1,438
F-15 Fighter Aircraft	1.0	1,488
Commercial Jet Airliner	0.33	496
Automobile	0.005	7.27

Table 13 is a graphic illustration of how the demands of increasing performance result in increased cost. Two root causes are implied, namely, system complexity and technology. Expendable launch vehicle single-use permits inert mass fractions as low as five percent of total dry vehicle mass contrasted with 13 percent for shuttle and a "stage-equivalent" inert mass fraction above 50 percent for a front-line fighter.[154] Reusable systems are typically more expensive than expendable systems because they simply weigh more, typically by a factor of five to ten. However, note the radical departure of the space shuttle orbiter from this trendline. This departure speaks directly to the technical complexity argument. The requirement to minimize inert mass fractions and maximize useful payload capability drove U.S. launch vehicle development to maximize system performance. This approach minimized performance margin and added complexity that ultimately manifested itself into expensive expendable launch vehicles (Delta, Atlas, Titan) and reusable launch vehicles (Pegasus and Shuttle).

Operational launch costs can represent a very large fraction (up to 70 percent) of overall direct costs of low-earth-orbit payload insertion. Claybaugh makes the case that labor intensity L* (man-hours/lb) is a useful surrogate for relative comparison of operational costs between systems. Figure 12 identifies two distinct trendlines between military and commercial aircraft ("sonic trendline")[155] and space launch vehicles ("orbital trendline") that are independent of vehicle mass.

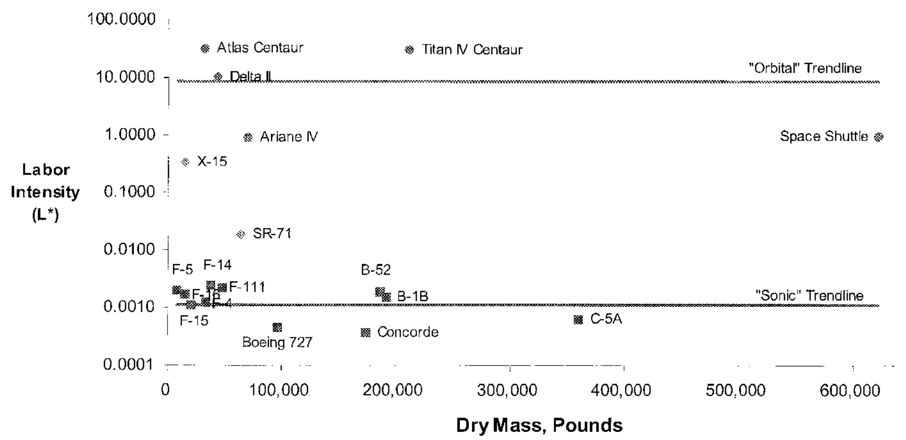


Figure 12. Labor Intensity of Aerospace Systems[156]

Note that both existing expendable and reusable space launch systems exhibit prohibitively high labor intensity, implying a lucrative area to pursue in any effort to reduce overall launch costs. The sonic trendline indicates a labor intensity (L*) of 0.0010, while the orbital trendline suggests 10 man-hours/lb. This approximate five order of magnitude difference in labor intensity between aircraft and space launch systems implies that operation and maintenance costs must be a paramount consideration in any future designs. Contemporary Ariane IV and space shuttle[157] launch systems are two notable departures from the orbital trendline showing a one order of magnitude improvement in labor intensity over more venerable launch systems to near one man-hour/lb. Two other systems of note falling between these two trendlines lines are the SR-71 and X-15 with an L* of 0.013 and 0.5 man-hours/lb respectively.[158] Arguably, both vehicles should deviate upward from the sonic trendline as they begin to more closely resemble spacecraft rather than classical aircraft. This data begins to quantify the very large disparity that exists between existing space launch and aircraft system labor intensity and provides a technique to bound operational costs as a function of vehicle mass. However, this approach begs the question: is labor intensity merely a surrogate for the increased vehicle complexity that inevitably migrates into larger aerospace systems? If so, it may suggest that other metrics can measure this phenomenon more directly.

Investment Costs. Investment cost estimates can "make or break" a launch system development decision. Although little data exists to support a strong statistical correlation between vehicle dry mass and facility costs, one does exist for vehicle dry mass and development costs. Sixty years of aerospace company proprietary data shows the impact of technological progress. Cost per unit mass tends to remain about the same as vehicle performance increases over time, or alternatively, similar performance vehicles cost less per unit mass over time.[159] Historical U.S. expendable launch vehicle development, all with a governmental development legacy, demonstrate developmental costs ranging from $10-40 thousand (FY02) per pound. Although developmental cost data for reusable launch vehicles is sparse, Claybaugh calculated costs for the government-developed X-15 and space shuttle systems at $102 and $114 thousand (FY02) per pound respectively. He reports costs of $25, $20, and $14 thousand per pound for the Boeing-777 (modern reusable benchmark), X-33, and X-34 respectively. The fact that neither X series vehicle actually matured to flight status likely biases these values significantly downward. Claybaugh concludes from this data that government-developed reusable launch systems are much more expensive than commercially developed vehicles.[160] However, when you consider the fact that governmental subsidization was involved in the development of virtually all U.S. expendable and reusable launch systems, this conclusion may be incomplete. The cost of money comes into consideration when infrastructure and developmental costs must be amortized over some meaningful period of time. Within the realm of the commercial world, investment decisions are dominated by maximizing return on investment. Hence, the need to recoup initial outlays as quickly as possible, often in as few as five but no more than ten years, must occur to permit any space launch development venture to be deemed commercially viable. The bottom line is that the calculations embedded in investment cost estimates are based upon assumptions—assumptions that often do not withstand the test of time—as the space shuttle clearly illustrates.

Expendable Launch Vehicles. How cheap can expendable launch vehicles get? Empirical cost estimating data previously presented can be applied to a very simple linear cost model to provide an answer to this question.[161] The following examples all assume investment costs (infrastructure, development, and cost of money) are zero, and that propellant is free to leave the following:

$$C_{system} \equiv C_{hardware} + C_{operations} = RfC_h + R_L * C_L = R(fC_h + L*C_L)$$

where C_{system} = specific system cost to deliver low-earth-orbit payload ($/lb)

R = structural ratio (inert structural mass/payload mass)

f = expended hardware mass fraction (1.0 for an expendable launch vehicle)

C_h = specific hardware cost ($/lb)

C_L = specific labor cost ($/hr)

$L*$ = labor intensity (man-hours/lb);
($75 U.S. burdened rate)[162]

Equation 6. Simplified Expendable Launch Vehicle Cost Expression

Example A in Table 14 is representative of a typical present day commercial booster delivering payloads to low-earth orbit for around $5000 per pound. For further simplification, ignore all operations costs for Examples B and C. Example B shows that a $2000/lb cost using typical present day structural ratios and hardware costs implies that the system must be one third reusable. Alternatively, Example C illustrates the reduction of the structural ratio to two, implying the highly unlikely scenario of single-stage-to-orbit technologies at present day hardware costs.[163] Example D considers the "Big Dumb Booster" as some proponents affectionately call it, where a very simple pressure-fed, all composite structure yields a "heavy" design with a structural ratio of six. (Note that liquid pump-fed systems operate with tank pressures in the tens to hundreds of pounds per square inch, while pressure-fed systems demand tank pressures in the thousands of pounds per square inch. You are trading the complexity of the pump for a savings in weight versus the simplicity of design for increased structural weight to accommodate the high tank pressure). Using a specific hardware cost of $300/lb (where $1000/lb is typical) that has been demonstrated by some solid rocket motors, yields $2250/lb to low-earth orbit. Claybaugh concludes that when including propellant, a best case, minimum cost (not price) expendable launch vehicle might demonstrate $2000/lb to low-earth orbit.[164] To emphatically make the case that expendable systems will never achieve R^2ISA, Example E illustrates the unachievable low structural ratio necessary for the high pressure "big dumb booster" to achieve $1000/lb. Example F shows the lowest possible cost that might be achieved in the distant future with as yet unknown ultra-high strength, inexpensive structures, free labor, free (or subsidized) propellant, and no investment costs (amateur rocket builders?). Note that the NASA Highly Reusable Space Transportation Study evaluated a Highly Evolved Expendable Launch Vehicle in 1995 using aggressive, highly innovative designs and concluded that the lowest cost attainable was about $800 per pound ($944 FY02) to low-earth orbit.[165] This reasonably approximates the Example F "Low Ball Booster."

Table 14. Simplified Expendable Launch Vehicle Cost Excursions

Description	Tag	C_{system}	=	R	(	f	C_h	+	$L*$	C_L	)
Current	A	5250		3		1	1000		10	75	
$2000/lb goal	B	2000		3		.67	1000		0	0	
$2000/lb goal	C	2000		2		1	1000		0	0	
Big Dumb Booster	D	2250		6		1	300		1	75	
Super Cheap & Sleek	E	1000		2.7		1	300		1	75	
Low Ball Booster	F	1050		3.5		1	300		0	0	

Space Shuttle. The space shuttle merits detailed discussion as it represents not only a first-generation reusable launch vehicle but has been subjected to very detailed "root-cause" analysis, particularly in the areas of cost and flight regeneration or cycle time. Figure 13 highlights the $3.27 billion resource allocation that generated four shuttle missions in Fiscal Year 2002. Nearly two-thirds of the shuttle budget is allocated toward fabrication, refurbishment, or flight preparation of the physical flight vehicle. Surprisingly, only about one quarter of the budget supports the highly visible ground and flight operations at Kennedy and Johnson Space Centers respectively. It also suggests that calling the shuttle a reusable launch vehicle is a misnomer, as clearly, more than one-third of the budget is directed at the refurbishment and reloading of the solid rocket motors and external tank/main engine production.

Considered alone, Figure 13 might suggest that hardware dominates the shuttle budget. This is not the case. A functional breakdown of shuttle costs using NASA definitions of direct (landing/recovery, vehicle assembly/integration, launch, payload/crew preparation, and turnaround), indirect (vehicle depot maintenance, traffic/flight control, and operations support infrastructure), and support (shuttle logistics and operations planning management) comprise 10, 20, and 70 percent of the total shuttle budget respectively. The latter is comprised of very labor-intensive activities across all of the NASA Centers to get the shuttle prepared for the next launch. The nature of these activities is highlighted in Figure 14.

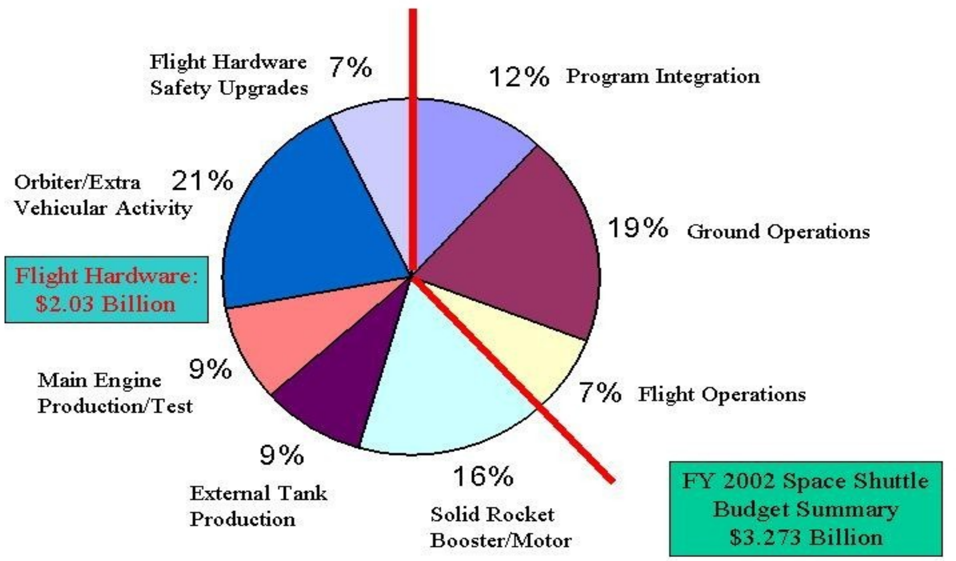


Figure 13. Fiscal Year 2002 Space Shuttle Budget Summary[166]

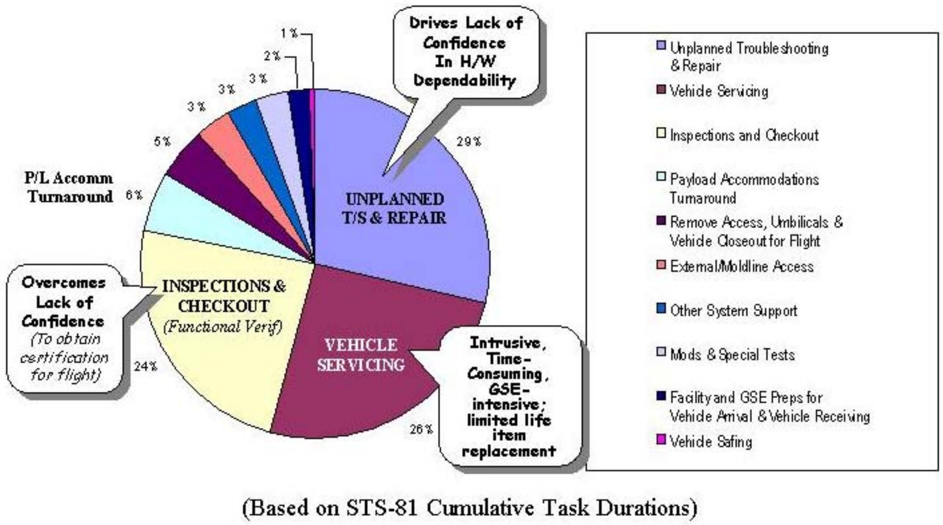


Figure 14. Time Allocation at the Space Shuttle Orbital Processing Facility[167]

Figure 14 suggests that the unplanned troubleshooting and repair of hardware drives a lack of confidence in the system that is not restored until required inspections and checkouts for flight certification are completed. These activities combined with complicated, manpower intensive, vehicle servicing are responsible for over 75 percent of shuttle cycle time. The cycle times for shuttle mission STS-81 represents the lowest post-Challenger annual recurring cost per pound achieved by the shuttle program.[168] Another insightful perspective on STS-81 task durations is to examine time allocated to subsystems that include structural/mechanical, propulsion, power management (mechanical and electrical), thermal management (active and passive) comprising 26, 18, 16, and 16 percent of orbital processing facility time respectively.[169] Not surprisingly, these areas correlate with the key reusable launch vehicle technology enablers previously discussed in chapter 3 to include materials and structures, propulsion, thermal protection.

Other Launch Cost Considerations. The expense of launching payloads into space today is very high. Launch vehicles and their operation -- whether expendable or reusable, small or large -- cost tens of millions to hundreds of millions of dollars per flight. These costs are in addition to the usually very expensive payload the launch vehicle is carrying. A payload budget planner must allocate such a significant portion of the budget to launch services that these considerations can have a powerful ripple effect on all aspects of the space mission. The cost of space vehicles has become almost inextricably linked to the cost of launch, and reducing the cost of space systems and missions is largely dependent on achieving lower space transportation prices.[170]

The nature of space launch has wide-ranging, pervasive impacts on the design and operation of spacecraft. Launch costs often are a large portion of space system lifecycle cost and hence heavily influence satellite capability, weight, volume, and complexity, as well as mean mission duration, deployment options, constellation quantities, and cost. A retired TRW executive stated that because launch systems cost so much, satellite designers always take the smallest and least expensive launch system possible and spend large amounts of effort and money trying to get their space vehicles to meet booster weight and volume constraints. He cited instances where designers spent up to $230,000 per pound (FY02) in taking the last few pounds out of a satellite so they could meet the selected launch vehicles orbital lift capability.[171] [172] There are also more subtle interactions between payload and launch costs. As launch costs increase, so do payload costs. To reduce risk of on-orbit failure and the probability of re-launch, some payload subsystems are made triple redundant, increasing the cost and weight of the satellite. If launch costs can be reduced significantly, it may no longer be necessary to design to such high levels of redundancy. In addition, a capability such as an orbital space plane or orbital transfer vehicle could recover payloads in orbit, and if payloads were designed modularly, they could be quickly repaired on-orbit. Such payloads could cost considerably less than existing satellites. An orbital space plane and/or orbital transfer vehicle linked to R^2ISA might enable a new era of low cost access to space.[173]

IV. The Search for Solutions

> *Everything should be made as simple as possible, but not simpler.*
>
> —Albert Einstein

This chapter explores key design attributes and enabling technology necessary to deliver R^2*ISA*. Consider the reinforcing relationship between vehicle design and R^2*ISA* illustrated in Figure 15 below. Robustness, as defined in chapter 1, is determined by the vehicle performance (maximum payload mass per flight) and sustainable flight rate (flights per year). These two factors multiplicatively determine the maximum vehicle throughput (measured in payload mass/year) that a launch vehicle can deliver to low-earth orbit. Recalling the flight rate capability shortfall experienced by the shuttle in chapter 2 speaks directly to this relationship. Reliability also has direct, traceable linkages to vehicle design. Space launch vehicle reliabilities today typically gravitate towards 98 percent (1/50 probability of failure) for both expendable and reusable launch systems, with a goal of 99.9 percent (1/1000 probability of failure) reliability for a second-generation reusable launch system. Costs, both direct and investment, were addressed at length in chapter 3. Design decisions directly impact developmental, infrastructure, hardware, and operations costs to such an extent, that arguably, the upper limits of vehicle affordability are determined (although impossible to precisely quantify) before the first piece of system hardware is ever fabricated. These annual costs ($/year) are balanced against payload throughput (payload mass/year) to determine overall cost effectiveness ($/lb) of payload delivery to low-earth orbit. This construct emphasizes the internally reinforcing nature of robust, reliable, and inexpensive systems and operations. As the shuttle clearly illustrated, robust operations characterized by high throughput are a prerequisite to affordability. Pursuit of one at the expense of the other is sheer folly. This chapter will address the key design attributes and enabling technology that delivers R^2*ISA*.

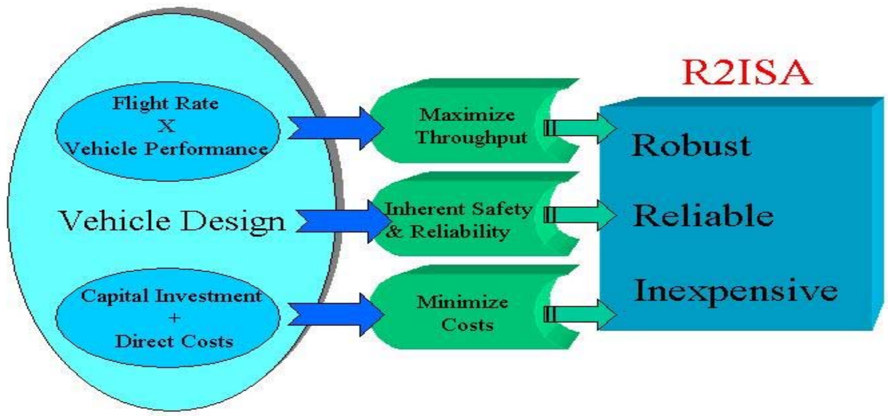


Figure 15. Space Launch Design Linkages to R^2*ISA*

THREE CAMPS

There is no overwhelming consensus within the aerospace community regarding the most promising and lowest risk approach to R^2*ISA*. In fact, there is no universal agreement on a definition for robust, reliable, and inexpensive operations. This is not surprising when considering the political, economic, and social dimensions coupled with the technical, programmatic, and engineering complexities and resource constraints shrouding space launch. At the risk of oversimplification, the debate falls within three general camps: 1) the expendable "big dumb booster" contingent; 2) rocket-centric reusable launch vehicle proponents (who presently appear to be in the majority); and the airbreathing, hypersonic reusable launch vehicle advocates. Overlaid upon this debate are numerous agendas and divisions to include manned versus unmanned; single-stage versus two-stage-to-orbit; civil versus military, etc. Despite these complexities, it is helpful to briefly examine the arguments, both pro and con, promulgated by each camp.

Expendable Launch Vehicles

The venerable expendable launch vehicle has been and remains the dominant method for earth-to-orbit operations and has consistently demonstrated the lowest costs. Medium to heavy lift Western systems are in the $4-5,000/lb cost range, while Russian/Chinese systems are in the $2,000/lb cost range for payload delivery to low-earth orbit. Economic dislocations and inexpensive manpower rather than differences in technology or vehicle complexity largely explains this price discrepancy.

The qualitative argument suggests that applying simple design practices, leveraging "off-the-shelf" technology, and using readily available inexpensive materials can produce the "big dumb booster" as an affordable low cost alternative. A simple design means fewer parts and interfaces, translating into lower first unit and recurring manufacturing costs as well as lower operating costs. Inexpensive boosters could create a greater market demand for launchers, permitting increased production runs that translate into even greater economies of scale. Further, economies of scale are one area in which expendable launch vehicles always have an advantage over reusable ones.[174] The longer-term evolution of expendable vehicles is driven by development of ultra high strength-to-weight materials and more powerful and efficient propulsion. Advances in materials will result in lighter and stronger vehicles and improve structural efficiency. Stronger structures permit higher operating pressures that in turn permit the transition from pump-fed liquid rocket systems to much simpler pressure-fed systems. This transition would permit a dramatic reduction in propulsion system complexity and a marked improvement in reliability and manufacturability. Further, advances in new propellant technology, to include High Energy Density Matter,[175] could be leveraged to significantly improve rocket performance (both specific impulse and thrust-to-weight) and significantly reduce vehicle size and gross lift-off weight. Advocates claim order-of-magnitude cost reductions from current prices to low-earth orbit are possible at much lower developmental risk and cost than any reusable system.

Expendable launch advocates also provide quantitative cost arguments supporting its advantage over reusable systems. Basically, expendable launch vehicle proponents concede an advantage to reusable systems in direct launch vehicle hardware costs, but argue advantages in nearly all other cost factors to include: 1) becoming cheaper with time (learning curve); 2) free of recovery and refurbishment costs making vehicle operations less expensive; 3) lower required vehicle reliability permitting less demanding performance and reliability margins; 4) easy accommodation of technological/performance upgrades; 5) simpler flight operations; 6) much lower up-front development (due to lower complexity) and production costs. James Wertz recently developed a purely analytic economic model permitting useful direct comparisons between expendable and reusable launch vehicles. He concludes that expendables remain somewhat lower-cost than the reusables over flight rates ranging from 10 to 10,000 flights per year and that the result is relatively insensitive to the input assumptions.[176] He indicated that a factor of five to ten near term reduction in expendable launch vehicle costs and a far-term reusable cost reduction of two to three from current costs are achievable.[177] The former implies expendable launch costs between $500 and $1000 per pound to low-earth orbit. There is no known exploitable technology known to date to enable this. Wertz' analysis is flawed in that it identified development costs as the principle reusable cost driver but over-weighted the increased manufacturing efficiencies associated with the learning curve, skewing the expendable launch vehicle results.[178] This type of well-intended but flawed economic argument is not uncommon and illustrates the pitfalls of purely econometric analyses that lack sound technical grounding and fail to leverage known empirical cost estimating relationships.

Reusable Rocket and Airbreathing Launch Vehicles

The latter two camps both advocate the reusable launch alternative, but paths quickly diverge from there. Rocket proponents are quick to point out that a reusable earth-to-orbit system is in operation, and what is required to achieve R^2ISA is the integration of a set of technology advances in materials, propellants, propulsion cycles, "designer-aero," and launch assist.[179] These technologies can significantly reduce vehicle inert mass fractions, provide higher specific impulse and thrust-to-weight propulsion systems, potentially via High Energy Density Materials propellants, as well as lower the aggregate vehicle ΔV requirement to orbit via reduced drag or fixed ground launch assist. A look at the aborted Space Launch Initiative second-generation shuttle replacement is instructive in that the rocket-based solutions proposed were large (millions of pounds at launch) and expensive ($30-35 billion in development costs).

Hence, recent experience implies that a pure rocket-based reusable launch vehicle as NASA envisioned is currently unaffordable.

A very attractive alternative to rockets is air-breathing propulsion. The two first-order potential performance benefits of this approach are much smaller vehicles operating at extremely high specific impulse. Figure 16 clearly illustrates that nearly two-thirds of shuttle's 4.5 million pound gross lift-off weight is oxidizer. A mere four and one-half percent mass reduction in liquid oxygen carried within its external tanks doubles the payload capacity to low-earth orbit!

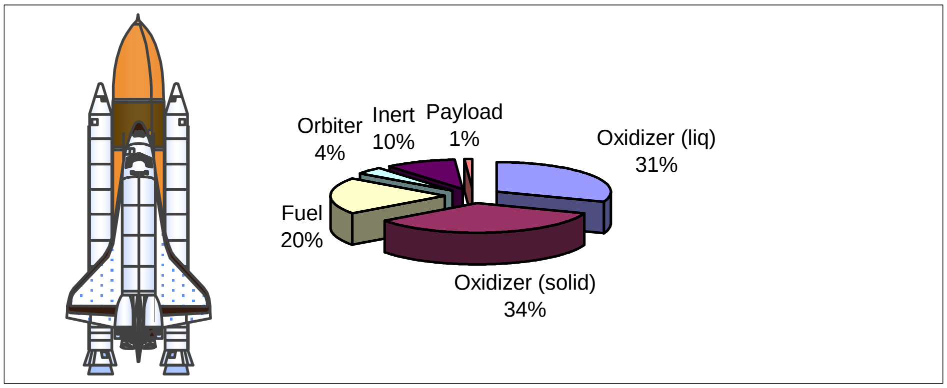


Figure 16. Space Shuttle Mass Distribution

Air-breathing propulsion gets its oxidizer from the surrounding atmosphere in lieu of carrying it internally, resulting in much smaller vehicles. The effective specific impulse of hydrogen and hydrocarbon-based airbreathing systems as a function of Mach number is captured in Figure 17.

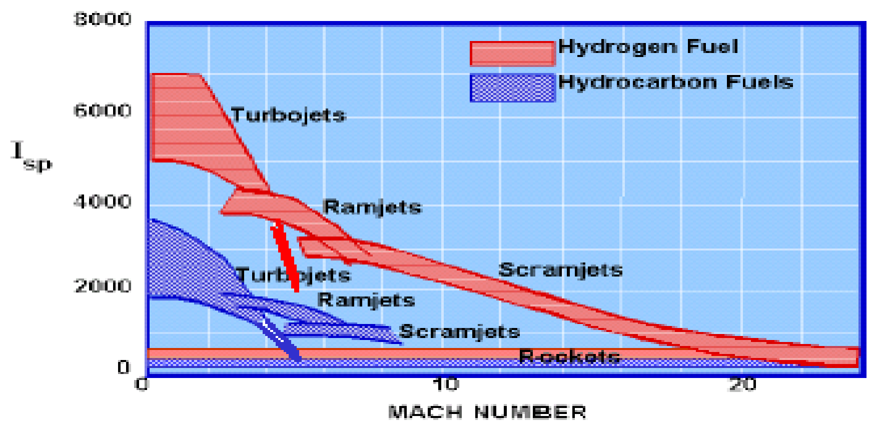


Figure 17. Airbreathing versus Rocket Performance[180]

Turbojets compress the incoming air to high pressure with turbomachinery prior to fuel mixing and combustion. Ramjets slow incoming air to subsonic velocities (with no moving parts) before the mixing of fuel and subsequent combustion, while supersonic combustion ramjets (scramjet) do this while the flow remains supersonic. The potential performance benefit over pure rockets is enormous. However, three remaining challenges associated with airbreathing technology include lower thrust, low engine thrust-to-weight, and vehicle integration challenges relative to rockets.

Airbreathing propulsion successfully applied through most of the Mach range to orbit (0-25) can have a very substantial improvement over rockets in vehicle robustness and reliability. Steve Cook, Deputy Program manager for NASA Next Generation Launch Technology cites a 10 to 25 percent improvement in structural ratio, increased inert mass fraction to 0.15 from 0.05, a factor of four to five reduction in total thrust required, less than half of the total gross weight (permitting horizontal take-off), and a factor of three decrease in performance sensitivity to weight growth.[181] Reliability and safety are improved through increased abort options, powered landing capability, and more benign failure modes due to lower power densities. Further, mission flexibility is enhanced through a factor of two to three increase in launch windows, a factor of 2.5 improvement in cross-range, self transport/ferry, orbit rendezvous two to three times faster, and increased basing options.[182] Unfortunately, hypersonic airbreathing propulsion technology is not sufficiently mature today for use on a second-generation launch vehicle. Further, only an aggressive research and development effort can make it available by 2010.

Despite the promise of air-breathing hypersonics, there are many skeptics. Among them is Mr. Dennis Bushnell, Chief Scientist at NASA Langley Research Center, who was deeply involved in the X-30 National Aerospace Plane program. His views include:

> Regarding rocket alternatives: The usual commentary regarding such is that Rockets are (forever) evolutionary, "not much left there," and therefore, Air-breathing systems of various persuasions, even with all of its warts, is the "only way ahead." (This may be true for the military flexibility metrics, *but not the NASA cost metrics*.) There are, in fact, a plethora of advanced concepts which could seriously revolutionize rockets – IF – we spent the time/treasure to go there. Overall, these technologies offer much more performance and a greater return on investment than air-breathing systems over similar time frames. These open up the design space and offer the opportunity to truly revolutionize space access (as opposed to the known agonies/disastrous sensitivities of air-breathing systems).[183] Airbreathers will, in all probability, increase the cost(s) and reduce overall safety for routine space access. Maintenance requirements for airbreathers is wholly unknown. Particularly worrisome are thermal/acoustic fatigue problems.[184] A higher I_{sp} does not necessarily imply reduced costs. There are no system studies which indicate airbreathers will/are expected to come anywhere near even an idealized factor of two, much less orders of magnitude improvement. Available estimates on idealized systems predict an approximate 35 percent cost reduction; this will disappear as we "get real."[185]

Once again, at the risk of oversimplification, consider the R^2ISA trade space. Expendable launch vehicle advocates are comfortable with the "disposable" nature of their systems and believe that technology can deliver an order of magnitude improvement in cost at the same levels of robust/reliable operations experienced to date. The rocket-centric reusable launch vehicle proponents believe that the successful maturation of a small subset of promising technologies will enable *R^2ISA*. Meanwhile, the hypersonic advocates make a compelling case for robust operations, a potentially strong but as yet unproven cost benefit, and a wholly unproven reliability argument. The truth is out there.

PROPULSION: THE KEY ENABLER

The previous chapter introduced four key enabling technology areas to include propulsion, advanced materials and structures, thermal protection, and vehicle integration. However, propulsion technology has traditionally been the most important pacing factor in flight system development since the Wright brothers, and it is especially true for space systems. This is not surprising when one considers the enormous amount of power generated by these systems to accelerate payloads to orbital velocity. Fundamentally, the means by which this is accomplished and the efficiency of the energy conversion process in turn drives the vehicle design and supporting system architecture more than any other single factor. A brief assessment of both rocket and airbreathing propulsion and the types of vehicles they enable is presented to permit an objective assessment of current capability and establish what currently lives within the realm of the possible, the improbable, and the impossible.

Rocket –Based Reusable Launch Vehicles

Modern rockets have dominated space transportation for nearly half a century, but their performance still fails to enable *R^2ISA*. The most important elements of rocket performance that directly impact vehicle performance are total thrust, specific impulse, and engine thrust-to-weight. Improved performance for both kerosene and hydrogen-based engine technology is valuable, particularly the latter's use as an enabler for a rocket-based single-stage-to-orbit vehicle. However, the more immediate need is for demonstrated operability, maintainability, and reliability that permits dozens of relights with little or no human intervention. The liquid oxygen/hydrogen Space Shuttle Main Engine[186] is the most advanced "reusable" engine of its kind. While it has seen substantial use in an operational environment, it has yet to fly on successive shuttle missions without removal after each flight.[187] The latest 7,480 pound block IIA version can produce a maximum of 418,660 pounds of thrust at a specific impulse of 363 seconds at sea level (512,950 pounds, 452 seconds in vacuum) resulting in a 56 to 1 thrust to-weight ratio. Performance is sufficient for a two-stage-to-orbit vehicle, but it is unlikely its underlying technology will ever permit the level of reusability necessary for *R^2ISA*. Proposed systems by major rocket engine developers are pursuing development of 100/50 (total mission life/missions to overhaul) systems with thrust to weight ratios in the mid-seventy range.[188] More subtle design parameters that directly influence engine reliability and reusability include operating pressures, combustion cycles, combustion efficiencies, and active versus passive cooling techniques. Rockets with these characteristics would be an invaluable *R^2ISA* enabler, but will not come cheap. The Apollo-Saturn expendable F-1 and J-2 engines and the reusable Space Shuttle Main Engine cost between $1.7-2.5 billion to develop and flight qualify, with one quarter of these costs attributable to the basic development program and the remainder in the "fail-fix" test mode. Boeing Rocketdyne recently demonstrated a much lower overall cost and more favorable development-to-test cost ratio with the RS-68 expendable rocket engine that may indicate a sustainable trend for a new reusable design.[189] However, there can be no mistake that such an engine will cost multiple billions of dollars to develop and qualify for flight. Continuing advances in performance and operability and maintainability are necessary to successfully demonstrate highly reliable and reusable rocket propulsion as a "threshold" enabler for *R^2ISA*.

One system concept that bridges the gap between rockets and airbreathing hypersonics is the air-augmented rocket. In this concept, the rocket engine is placed in the flow path of an airbreathing engine. At take-off the rocket engine, operating fuel rich, ejects this fuel-air mixture into the airbreathing engine duct. Analysis indicates a 15 percent increase in thrust at zero velocity and a 50 percent thrust enhancement at Mach 2.[190] This approach is one of many that might be used in a rocket-based combined cycle engine that is discussed in the next section.

In light of aborted X-33 single-stage-to-orbit and Space Launch Initiative two-stage-to-orbit programs, is there a rocket-based solution leveraging existing technology that can deliver *R^2ISA*? A 1996 RAND study investigated the utility, feasibility, and cost of procuring a trans-atmospheric vehicle, or orbital space plane, capable of accomplishing military missions.[191] A wide range of potential candidates were studied, to include three X-33 candidate designs, the X-34, and numerous commercial and government air launched space planes (to include the Air Force Phillips Laboratory Black Horse). The study considered the Northrop

Grumman two-stage-to-orbit space plane particularly promising. Estimated developmental costs of $677 million (FY96) would be required to build one sub-scale prototype X-vehicle and one full-scale operational prototype.[192] The vehicle concept included an air-launched "mini-shuttle" second stage with a Boeing-747 first stage. The mini-shuttle was an 180,000 lb horizontal take-off horizontal land system with liquid oxygen/hydrogen engines delivering one to six thousand pounds to low-earth orbit (significantly lower payloads to polar orbits).[193] More importantly, however, total system life cycle costs, when compared to an existing Pegasus expendable system, were very favorable. Despite a large disparity in developmental non-recurring engineering costs ($149 million to $677 million), a total life cycle cost of $7.9 billion for six trans-atmospheric vehicles delivered 600 launches (100 launches per vehicle) at a cost of $2,900 per pound to low-earth orbit, while an equal sum applied to Pegasus expendable launches would buy 290 launches at a cost of $34,000 per pound to low-earth orbit for the same overall life cycle cost. The level of detail of this analysis strongly suggests that a rocket-based reusable launch vehicle architecture delivering routine operation and a significant cost savings can be achieved *if* a high vehicle flight rate can be sustained.[194] However, it also further reinforces the conclusion that breaking the $1,000 per pound to low-earth-orbit threshold remains highly unlikely within existing rocket performance constraints.

RAND came to the following conclusion in its 1996 report on Military Trans-atmospheric vehicles (space plane):

> The X-33 competition, much like the NASP program, has focused attention on SSTO vehicles. RAND believes TSTO TAV concepts deserve equal attention if delivering small to medium sized payloads to LEO is viewed as a primary mission need. Air-launched TSTO TAV concepts appear particularly promising from a cost standpoint because the first stage aircraft could be based upon a commercial civil transport. In addition, they may provide an evolutionary development path to full reusability and aircraft-like levels of responsiveness for orbital vehicles. In contrast, SSTO systems may be more challenging technically, much more costly to build, and would be so large they could not meet military responsiveness needs.[195]

These conclusions are not only fundamentally sound, but perceptive in the sense that it anticipated the elevated risks associated with the single-stage-to-orbit X-33 program that was ultimately cancelled in 2001. NASA reached a similar conclusion when it pursued a two-stage-to-orbit solution to its short-lived Space Launch Initiative second-generation reusable launch vehicle. Finally, it suggests that if a flexible and affordable vehicle might be possible with a subsonic first stage, then a two-stage-to-orbit vehicle with a higher staging Mach number (6 to 10 for example) might deliver heavier payloads to low-earth orbit with similar benefits. Yet an air launched "mini-shuttle" that delivers one to six thousand pounds to low earth-orbit satisfies a smaller niche focused on military payloads. Since the preliminary Space Launch Initiative designs intended to deliver 50,000 pounds to low-earth orbit had a $30-35 billion developmental price tag, the question remains: can a rocket-based earth-to-orbit system that satisfies military, civil and commercial requirements deliver R^2ISA? Answer: Not with existing technology, and certainly not based upon NASA's acquisition philosophy.

Airbreathing Reusable Launch Vehicles

The chequered history of hypersonics is one of underlying promise pursued in a series of "fits and starts" that has never permitted the formation of a stable and coherent long-term technology development process. Current interest in hypersonics falls into three general categories: hypersonic missiles (engaging time-critical targets) operating between Mach 4-8; a hypersonic cruiser (global reconnaissance/strike and commercial transport) operating between Mach 4-10; and reusable launch vehicles (Mach 8-15 and higher) for space access.[196]

Hypersonic propulsion relies on a steady air within a suitable band of dynamic pressure that defines an atmospheric flight corridor that is illustrated in Figure 18. There are three primary regions of hypersonic operations. Region 1, which includes operations up to about Mach 8, requires the least complex hypersonic vehicles from a technical perspective, and appears reasonably achievable and tolerable for sensor operation and weapon delivery.[197] Region 2, between Mach 20-25 and outside the sensible atmosphere, is the most attractive area for hypersonic missions because of launch flexibility, short flight time, ease of maneuverability, and the relatively benign space environment.[198] Region 3 involves sustained cruising flight in the atmosphere between roughly

Mach 8-20. Operation within this region is plagued with high skin temperatures, control and maneuverability difficulties, ionized boundary layers that make sensor operations difficult, and high infrared signatures.[199] Hence, it is advisable to avoid Region 3 as a steady-state operating or "cruise" environment to minimize exposure to this harsh environment.

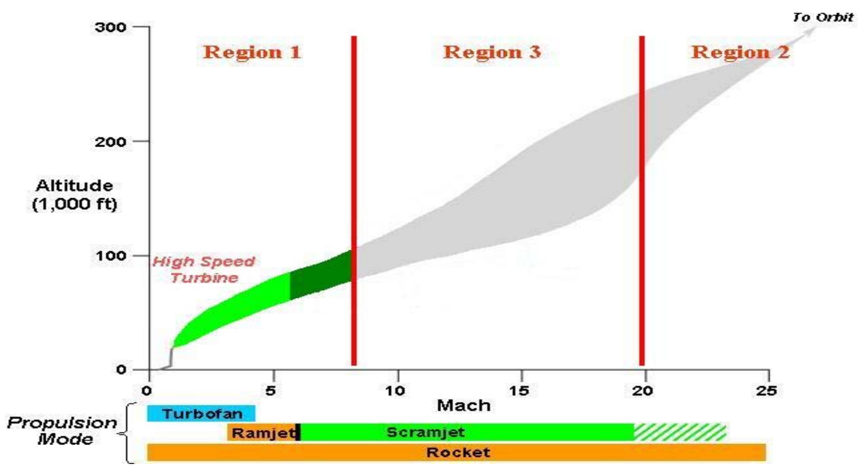


Figure 18. Notional Hypersonic Corridor

Leveraging the benefits of the atmosphere at hypersonic velocities comes at a price. The stagnation temperature of air rises dramatically with increasing Mach number.[200] For example, a vehicle traveling at Mach 4, 6, and 8 encounters corresponding stagnation temperatures of 1,100°F, 2,500°F, and 4,200°F respectively. With heat addition due to propulsive combustion, even higher temperatures of about 4,000°F, 4,400°F, and 5,100°F must be endured.[201] No known or projected materials with a practical scramjet application could survive these temperatures without active cooling at or near Mach 8.[202] Supersonic combustion also introduces some propulsion/vehicle integration challenges. High airflow velocities leave very little time for the introduction, mixing, and combustion of the fuel. Hydrogen is an ideal scramjet fuel choice because it provides higher specific impulse (relative to hydrocarbon-based fuels), enables very rapid combustion, can be used for active cooling where high temperatures are encountered, and indeed, is the only viable propellant choice above Mach 8. However, even with hydrogen, scramjet operations approaching orbital velocities (above Mach 15) typically demand that the entire vehicle act as an integrated inlet/mixer/combustor. The much denser hydrocarbon alternative (more appealing for lower stages and/or Mach numbers) reaches a stoichiometric limit[203] at Mach 8 and becomes unusable above these velocities.

Two classes of rocket propulsion alternatives, namely turbojets and ramjets/scramjets and their respective performance envelopes are illustrated in Figure 19. Combined cycle engines couple low speed turbines with ramjets, scramjets, or rockets to provide thrust throughout the entire vehicle flight regime. Airbreathing propulsion concepts currently under development and their associated flight regimes to include: Air Turbo-Ramjets, Mach 0-6; Hydrocarbon Scramjets, Mach 5-8; Hydrogen Scramjets, Mach 5-20+; Hydrocarbon/Hydrogen Turbine-Based Combined Cycle Engines, Mach 5-10; Rocket or Turbine-Based Combined Cycle Engines (with hydrogen scramjet), Mach 8-15.[204] The wide variety of concepts is emblematic of immature technologies where no clear-cut "winners" have yet emerged. However, the current scattershot of development activity is at least partially due to either the lack of a direct linkage to a developmental flight vehicle or the meager funding the hypersonics community has historically endured. The efficient combination of propulsive technologies into a single reliable system is critical to hypersonic vehicle development.

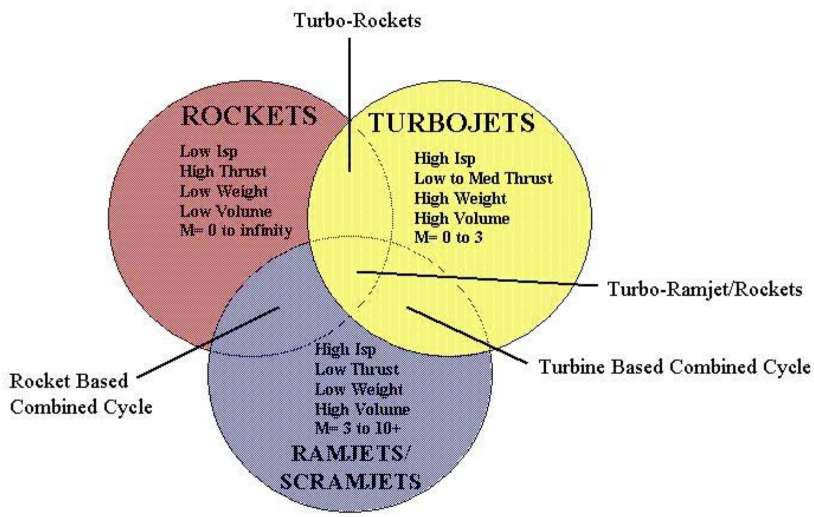


Figure 19. Rocket/Air-Breathing Propulsion Options/Characteristics

The most successful combined cycle engine to date is the Pratt & Whitney J-58 Air-Turboramjet developed in the late 1950's to power the SR-71 Blackbird until the 1990's. This 6,000-pound powerplant was rated at 32,500 lbs maximum sea-level thrust and flew in excess of Mach 3 at 80,000 feet. Any subsequent military air-turboramjet development is classified, but theoretical performance in excess of Mach 6 at altitudes of 120,000 feet is possible.[205] NASA is pursuing either solely or in partnership with DOD and industry the development and demonstration of high-speed turbine, hydrogen/hydrocarbon scramjets, as well as turbine and rocket-based combined cycle engines. Recent combined NASA/DOD funding for all of these efforts has been at a modest $65-85 million per year and is slated to drop sharply.[206] Limited testing is scheduled through 2005, with the bulk of testing occurring in the 2006-2010 timeframe.[207] Available funding overlaid upon program schedules suggests most of these planned tests are in jeopardy.

There are other ongoing hypersonic technology development activities targeted at both missiles and flight vehicles. The NASA Langley experimental hypersonic ground and flight test program called Hyper-X demonstrated hydrogen-fueled scramjet operation on the X-43A test vehicle on 27 March 2004. The 12-foot long X-43A was dropped from a B-52B and launched to its operational altitude of 95,000 feet by a Pegasus booster rocket. The scramjet ignited as planned and operated for ten seconds, the duration of its hydrogen fuel, reaching the targeted top speed of Mach 7 before gliding back and impacting in the Pacific Ocean.[208] The ongoing X-43 Program represents the largest and most advanced hypersonic test program to date and is part of a plan to flight test many of the ongoing engine systems under development. The current status of the FY03 X-43 test series is summarized below in Table 15.

Table 15. X-43 Series Hypersonic Tests[209]

	Sponsor	Funding ($M)	Goal
X-43A	NASA	185 (FY01-06)	Flight test of Hyper-X engine to demonstrate hydrogen powered scramjet to at Mach 7 in 2003 and to Mach 10 in 2005[210]
X-43B	NASA +RBC3		Flight test ISTAR strutjet engine to demonstrate a hydrocarbon rocket-based combined-cycle engine in 2006-2008.[211]
X-43C	NASA+ USAF		Flight test of HyTech engine and demonstrate hydrocarbon scramjet performance with TBD flight dates.[212]
X-43D	NASA		Flight test hydrogen powered scramjet to Mach 15

The NASA Marshall integrated systems test of an air-breathing rocket (ISTAR) has prompted a consortium between Aerojet, Rocketdyne, and Pratt & Whitney called RBC3. It is a rocket-based combined-cycle engine that employs a hydrocarbon-powered liquid rocket system for initial acceleration, with a ramjet that ignites at about Mach 2.5, followed by a conversion to scramjet mode at Mach 5 to accelerate to Mach 7. The engine can then revert back to rocket mode to continue acceleration to higher velocities as required.[213]

In the wake of the cancelled X-30 National Aerospace Plane program, the Air Force Hypersonic Technology (HyTECH) program was established in 1995 with modest funding.[214] Pratt & Whitney and the U.S. Air Force successfully demonstrated a hydrocarbon-fueled scramjet engine under this program operating between Mach 4.5 to 6.5 in January 2001. The next milestone is a full-scale system designated the Ground Demonstrator Engine that will weigh less than 200 lbs and result in a flight-worthy engine as early as 2004.[215] NASA selected General Electric in 2002 to begin a turbine-based combined cycle ground demonstration of a Mach 4+ turbine engine suitable for a future turbine-based combined-cycle engine with testing planned in the 2006-2008 timeframe.[216] Finally, the Defense Advanced Research Project Agency and the U.S. Navy plan to air launch a powered prototype hypersonic missile in late 2004. The four-year Hypersonic Flight (HyFly) program established in January 2002 plans to demonstrate a Mach 6 dual combustion ramjet[217] integrated into a missile with a 400-600 nautical mile range.[218] The U.S. Air Force Scientific Advisory Board in 2001 was highly critical of the lack continuity and requirements-driven systems engineering driving U.S. Air Force hypersonic research. Since that time, an ongoing effort to harmonize hypersonic research across all of DOD and NASA appears to be coalescing into a "national hypersonic strategy."[219]

The ultimate success of a hypersonic airbreathing propulsion system on a missile, hypersonic vehicle, or earth-to-orbit launch system depends upon its seamless integration with the overall vehicle structure. There are three major vehicle design classes to include the most common winged-body (space shuttle), the familiar lifting body (X-33), and the less familiar waverider (X-30). The latter deserves special attention since any hypersonic aerospace vehicle will likely be a waverider.[220]

In simplest terms, a waverider is any vehicle that uses its own shock wave to improve its overall performance, and a correctly designed vehicle can ride this wave to produce greater lift (compression lift) and less drag, resulting in higher lift to drag ratios and improved performance. For example, the delta-winged XB-70 Valkyrie experimental aircraft used compression lift to increase overall lift by 35 percent at Mach 3 and 70,000 feet altitude. Range was so dependent upon this benefit that in the event of a loss of one of its engines, it was more economical to go to afterburner than to fly in off-design conditions.[221] Waveriders only begin to become practical at Mach 4 or higher where the shock wave remains close to the surface of the vehicle.[222] The maximum lift to drag ratio naturally decreases with Mach number, but actual flight test experience has shown that actual measured values fall substantially below even what theory predicts. This phenomenon has been dubbed the Lift over Drag "L/D" barrier. The waverider design regains performance much closer to theoretical limits through compression lift that results from designing a vehicle to take advantage of the vehicle's own shock wave as illustrated in Figure 20 below. The precise vehicle shape is primarily dependent upon the Mach number and the shock angle that provides the best performance (maximum lift over drag ratio). Figure 21 illustrates waveriders optimized for Mach 6, 14, and 25 flight.

In addition to improved performance through a higher lift to drag ratio, waveriders also present a shape that can accommodate airbreathing propulsion integration. As previously discussed, the high flow velocities result in very short residence times for compression, mixing, and combustion. This problem is addressed most effectively by leveraging the entire integrated propulsion/vehicle system to efficiently perform this task.

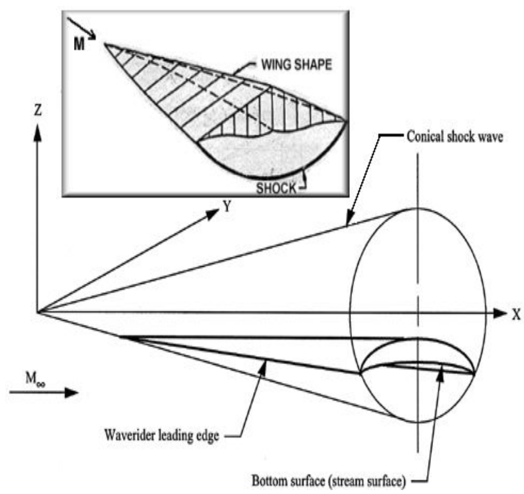


Figure 20. Construction of a Body "Waverider" Producing a Conical Shock[223]

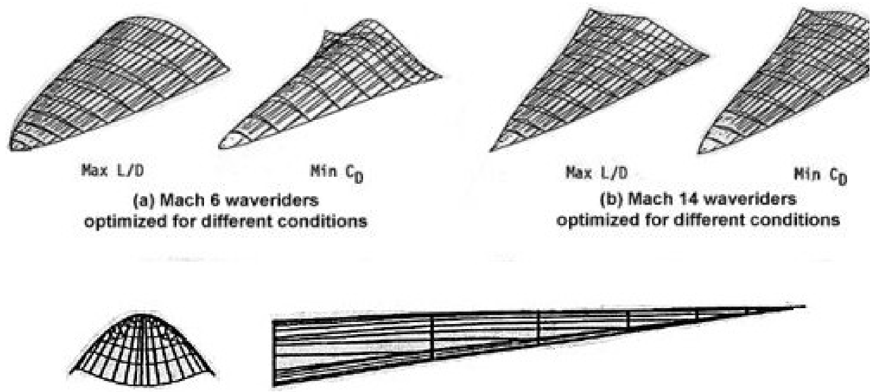


Figure 21. Waveriders Optimized for Different Mach Numbers and Conditions[224]

Dr. Kevin Bowcutt and others at the Boeing Phantom Works in Huntington Beach, California, are collaborating with Air Force Space Command and NASA on a horizontal takeoff, two-stage-to-orbit waverider concept known as FASST (Flexible Aerospace System Solution for Transformation).[225] The concept would operate from a standard runway with a waverider first stage using a hydrocarbon-fueled, turbine-based combined-cycle propulsion system (based upon the NASA Glenn Research Center Revolutionary Turbine Accelerator (RTA) program) and operate to at least Mach 4 and 70,000 feet altitude.[226, 227] The second stage orbital vehicle is also a waverider design using a hydrogen-fueled rocket-based combined cycle engine transitioning to a pure rocket mode at Mach 12.[228] Upon separation, the orbiter stage proceeds to conduct on-orbit operations. Both stages are recovered with an autonomous horizontal runway landing.[229] The FASST concept can deliver significant military capability to include rapid flexible global strike to any global position within 90 minutes, replenishment, augmentation, and integration of surface/air/space Intelligence, Surveillance, and Reconnaissance assets, as well as offensive and defensive space control capability. The concept would deliver 25,000 lbs to low-earth orbit, suitable for civil and commercial payloads. The first stage boost vehicle used in a standalone configuration as a Mach 4 strike/reconnaissance penetrator has significant commercial potential as well.[230] This specific FASST design concept (smaller payload delivery capable vehicles were studied) has a 1.2 million pound take-off gross weight (less than either the Antonov-225 or planned Airbus-380) with 550,000 and 650,000 pounds allocated to the first and second stages respectively. It would be approximately 200 feet in length, 45 feet in height, with a wingspan of 90 feet.[231] Takeoff speed is 250 knots based upon an initial thrust-to-weight of 0.4 with a first stage fly-back range of 130 nautical miles. Design characteristics such as these begin to approach the "aircraft-like" operations necessary for *R^2ISA*. The vehicle concept is presented in Figure 22.

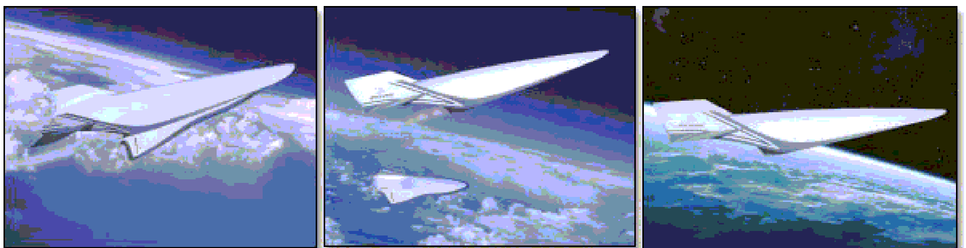


Figure 22. Boeing FASST Concept[232]

There are some notable advantages as well as concerns regarding this concept. Nine advantages of this approach include 1) a design supporting a national (civil/military/commercial) solution to *R^2ISA*; 2) an inherently robust system architecture that provides significant performance and design margin; 3) the ability of the first stage to accommodate alternative orbital stage solutions (such as a pure rocket); 4) the availability of the first stage for a host of adjunct missions; 5) a horizontal takeoff and landing capability that provides important flexibility and robustness over vertically launched systems; 6) a single propulsion system in each stage that significantly reduces the complexity of engine integration and access; 7) elimination of first stage thermal protection requirements precipitating greatly reducing operations and maintenance costs; 8) utilizing technology of direct benefit to a potential future single-stage-to-orbit successor, 9) inert mass fractions of 45 and 22 percent for the first and second stages, respectively, with an additional 15 percent design margin, represent very reasonable mass assumptions for existing state-of-the-art. However, there are also some deficiencies with this concept that deserve noting. First, the use of densified "slush" liquid hydrogen for the second stage increases risk and degrades operability and maintainability. Second, the higher dry vehicle mass relative to pure rocket-based solutions implies a higher developmental cost that can only be recovered through significantly lower total system life cycle costs. Finally, the advantages of a low staging Mach number are partially offset by an additional performance penalty assumed if the second stage propulsion system reverted to a pure rocket-based solution with a higher optimum staging Mach number. However, despite these concerns, the FASST concept is fundamentally sound. More importantly, such a design successfully "closes" while simultaneously delivering more than 20,000 lbs to low-earth orbit. Its first stage can accommodate military, civil, and commercial upper stages with the potential to evolve into a third-generation space transportation system. Such an approach is one that should be seriously considered as a second-generation reusable launch system in the pursuit of a national solution to *R^2ISA*.

The generation-after-next reusable launch system may no longer need to be a two-stage-to-orbit system. The NASA Highly Reusable Space Transportation Study completed in 1997 was intended to seek innovative concepts and identify advanced technologies to further reduce earth-to-orbit launch costs to \$100-\$200/lb—numbers that included development, production, operations, and amortization costs.[233] Approximately twenty concepts were examined in varying levels of detail that mapped various operational approaches (to include vertical takeoff/ horizontal & vertical landing and horizontal takeoff/horizontal landing) to propulsion approaches (to include all-rocket, rocket-based combined cycle, and scramjet). The "Argus" concept was the most promising "near-term" (within10 years) approach that emerged from the study and was a horizontal takeoff/horizontal landing vehicle consisting of a largely axisymmetric, cylindrical-winged body using a hydrogen fueled rocket-based combined cycle engine and a ground–based catapult launch assist.[234] The concept vehicle body is 171 feet in length and 17.1 feet in diameter with a total wingspan of 53.1 feet.[235]

The baseline Argus vehicle assumes an 800 feet per second (545 mph) subsonic launch assist with a 0.6 g acceleration and 1.2 g launch abort requiring a five mile track. The liquid oxygen/hydrogen supercharged ejector ramjet engine accelerates the vehicle to Mach 2 under supercharged ejector ramjet power. Argus transitions to a fanramjet mode between Mach 2-3 and intercepts a constant 1,500-pound per square foot dynamic pressure corridor to Mach 6. The engine operates in ramjet mode from Mach 3 to 6 and transitions to pure rocket mode at Mach 6 to accelerate a 20,000-pound payload into a circular 100 nautical mile, 28.5 degree inclined mission orbit.[236] Argus assumed the availability of very aggressive materials and subsystems technologies to include Titanium-Aluminide used as structure and embedded in metal matrix composites reinforced with Silicon-Carbide fibers. These materials permitted a vehicle dry weight (with 15 percent margin) of 75,500 pounds and a takeoff gross weight of approximately 597,000 pounds yielding a very aggressive inert mass fraction of 12.6 percent.[237]

Advantages to this approach include 1) the underlying technology that would support development of an operable supersonic ejector ramjet engine is well understood; 2) the launch assist has numerous synergistic effects in addition to added ΔV, to include a landing gear sized for landing weight in lieu of much higher takeoff weight, a much smaller wing platform, and a 25-30 percent increase in engine performance at vehicle rotation; 3) very simple design: and 4) very low vehicle dry weight and small vehicle footprint. Serious drawbacks include a very aggressive inert mass fraction, very tight design and performance margins (inherent with all single-stage-to-orbit vehicles), and the loss of operational flexibility assumed through the use of ground launch assist. It must be noted, however, that unrealistically low inert mass fractions plague all launch vehicle designs. Hence, the best hedge against low inert mass fractions is the design and performance margin inherent with the design itself. These two examples illustrate how single-stage-to-orbit vehicles such as Argus typically lack margin, demanding a very high degree of confidence in subsystem performance gained through demonstration before a vehicle is built. Alternatively, a two-stage-to-orbit system such as FASST has sufficient inherent margin to permit some maneuvering room within the design space and provide higher confidence that the objective system can meet its overall system performance specification.

"NATIONAL" SYSTEM ATTRIBUTES

There is a two-part question that can now be answered: How can R^2ISA be achieved, and is a national solution possible? A brief synopsis of the findings and intermediate conclusions presented thus far will frame the answer.

First, a quantifiable definition of R^2ISA is necessary. The next (second) generation launch system should demonstrate a sustainable launch recycle time of 100 hours or less, a mission reliability rate of 99.9 percent or greater, and a cost per pound to low-earth orbit of $1000 or less. The rationale behind these numbers is grounded in supporting analysis as well as moderated by current technological limitations and practical considerations. Next, the linkages between R^2ISA and the overall vehicle design as well as its relationship with an overarching space transportation architecture make it clear that R^2ISA must be considered in a very broad contextual framework. Emphasis on a system-of-systems perspective that optimizes the performance trade-offs between the earth-to-orbit and space segments keeps all elements of the architecture in proper balance and the senior decision-maker focused.

The second set of issues surround the apparent conflict between civil, military, and commercial mission requirements. A 20,000 lb payload mass to low-earth orbit is a reasonable compromise reached between the civil and military communities and valuable to the commercial sector as well. The military's preference for a launch-on-demand system with short launch and recycle times is not a priority for civil missions. It is, however, a necessary precursor to lower costs. Hence amelioration through aggressive movement toward the military requirement is appropriate. Reliability of 99.9 percent or greater also exhibits an acceptable degree of convergence between the civil and military communities for a second-generation vehicle. Although the civil requirement includes man-rated systems, this objective exceeds demonstrated shuttle reliability by more than a factor of ten. Higher reliability coupled with lower launch costs and sharply reduced cycle times is sufficient to induce substantial growth within the commercial sector. Clearly, however, the commercial market is the most sensitive to any demonstrated reliability less than those currently enjoyed by today's airline/package delivery operations.

Lessons learned are abundant and provide invaluable insight into what won't work. First, there is the realization that R^2ISA is not really necessary to continue the very expensive, moderate to high risk, low launch rate (about thirty annually) environment that perpetuates the status quo. Between the Shuttle, Titan, Delta, Atlas, and other foreign expendable launch vehicles, the current payload manifest can be easily met. Second, "incrementalism" has permeated U.S. space policy for more than three decades. The bureaucratic debate over government policy, requirements, technology, and resources has derailed any coherent long-term strategy. A close look at the shuttle program illustrates how up-front design compromises intended to lower developmental costs later manifested themselves in astronomically high operations and maintenance overhead. Third, the X-30 and X-33 programs clearly illustrated that a neither an airbreathing or rocket-based single-stage-to-orbit system is currently feasible. The recent Space Launch Initiative restructure confirms that a rocket-based two-stage-to-orbit solution conforming to rigid NASA requirements and programmatic constraints is unaffordable. NASA subsequently chose to defer a second-generation reusable launch vehicle development decision to no earlier than 2009. This decision removes any possibility of R^2*ISA* until 2020 or beyond without external intervention.

Valuable technical/programmatic lessons learned, to include technology, risk, requirements, cost/schedule estimates, and organization, punctuate the need for major change. Environmental lessons learned to include credible and compelling need, recognition of competing interests, realistic expectations, national commitment, parallel approaches, small steps versus giant leaps, and focused leadership cannot be ignored. These experiences in aggregate strongly suggest that a successful reusable launch vehicle development program hinges on an evolutionary, capabilities-based approach. It also suggests that success rests as much upon a national commitment to a politically sensitive, realistic, focused, evolutionary solution as it does to making the appropriate design choices that are responsive to a clear requirement/market.

Chapter 3 introduced the technical and economic nature of the barriers to R^2*ISA*. An understanding of the fundamental metrics commonly used within the space launch arena provide a powerful tool to compare expendable versus reusable launch vehicles as well as quantifying the impact of technological progress. Four main technology areas—propulsion, advanced materials, vehicle integration, and thermal protection—represent the major requisite technologies for R^2*ISA*. These topics, in turn, explain the challenges with single-stage to-orbit and why it cannot currently deliver R^2*ISA* as well as explaining why two-stage-to-orbit vehicles can. This difference can be summed up on a single concept—design margin—two-stage-to orbit designs have it, single-stage-to-orbit designs currently do not. The economic side of the equation is dominated by a market failure in space transportation and makes it clear that it is unreasonable for the government to expect or demand a large commercial cash commitment until *R^2ISA* is demonstrated. The swiftest and most certain solution demands a disciplined and well-conceived government policy backed up by decisive action.

The economic discussion continues with the arguments explaining why expendable launch vehicles can never achieve *R^2ISA*. A further examination of direct launch costs shows a four to five order of magnitude difference in labor intensity between aircraft and launch vehicles (expendable and reusable alike). This is a chasm that must be bridged if space launch operations ever hope to approach routine space flight operations akin to what we enjoy today in the terrestrial domain. A close examination of shuttle operations not only reinforces this observation, but also explains how $3.2 billion is spent to support four shuttle launches in 2002. A functional breakdown of shuttle costs using NASA definitions of direct, indirect, and support comprise 10, 20, and 70 percent of the total shuttle budget respectively. The latter is comprised of very labor-intensive activities across all of the NASA Centers to get the shuttle prepared for its next launch.

Chapter 4 centers around technical solutions to the space launch impasse surrounding *R^2ISA*. A close examination of reusable rocket technology indicates that additional maturation is required before a pure rocket-based solution to *R^2ISA* is viable. A much closer examination of the air-breathing hypersonic status shows that despite the great promise these technologies afford, the uncoordinated allocation of far too few resources has brought inevitably slow progress to date. However, recent advances in supersonic and hypersonic air-breathing propulsion indicate that near-term solutions to *R^2ISA* may be possible.

A summary of major conclusions are that 1) *R^2ISA* will never be achieved with expendable launch vehicle technology while reusable launch vehicles are the only economically and operationally viable path toward achieving *R^2ISA*; 2) current technology limitations make pursuit of a single-stage-to-orbit solution imprudent at this time while a two-stage-to-orbit reusable launch vehicle is the logical next step towards *R^2ISA*; 3) despite conflicting requirements, a common "national" solution for civil, military, and commercial application is both possible and desirable. One possible national solution to *R^2ISA* is now presented. There are undoubtedly others.

ONE VISION OF SUCCESS

There are a number of vital prerequisites to *R^2ISA* to secure the road to success. First is the commitment to an evolutionary, capabilities-based approach. The space shuttle's first flight as a prototype was also the first flight of the objective system. The design compromises during development created shuttle's unforeseen yet overwhelming ground support infrastructure and high labor intensity that could not be reasonably exorcised from the system. A robust X-vehicle and Y-prototype development approach is essential for both cost and risk management. Dr. Terry Bahill surveyed 20 projects of widely varying complexity and reported his results in the book *Metrics and Case Studies for Evaluating Engineering Designs*. He observes that breakthrough design approaches may cost three times what a continuous improvement model does for the same performance. He further concludes that projects with "high political risk" should be designed with "stable intermediate forms."[238] A second vital characteristic of *R^2ISA* is the utilization of X-vehicles that are part of a technology maturation program focused on ***risk reduction***. Y-prototypes are built to demonstrate ***performance***, ***operability***, and ***maintainability*** as well as ***scalability*** and ***traceability*** to an objective system design. Y-prototypes should also have sufficient "residual" capability to capture enough missions to justify a reasonably high sortie rate over the short term (3-5 years). Once a Y-prototype has served its purpose, it is scavenged for parts and sent to the museum. Third, ad-hoc oversight as well as cooperative agreements between agencies for the purpose of technology maturation is a recipe for mediocrity and inefficiency. A stable, well-funded, joint system program office pursuing the design and development of an objective system that serves federal agency stakeholders (such as DOD and NASA) that is at the same time accountable to a higher authority is key. These three elements should be considered a prerequisite for any serious effort toward *R^2ISA*. A scenario follows.

A joint DOD/NASA/DARPA program office should be immediately established to develop an overarching space transportation architecture designed to satisfy military, civil, and commercial space requirements. A reusable two-stage-to-orbit earth-to-orbit launch vehicle capable of delivering a minimum of 20,000 lbs to low-earth orbit and satisfying second-generation *R^2ISA* criteria should be its top priority. Currently, about two-thirds of all commercial payloads are satellites between 1-10,000 pounds launched directly into geostationary orbits at 22,500-mile altitudes.[239] Direct insertion of these payloads via a space launch vehicle is a very inefficient and expensive practice. A much more economical approach is to boost the satellite into low-earth orbit and then use a much higher efficiency and flexibly responsive reusable orbital transfer to finish the job. This permits much smaller launch vehicles due to the significantly reduced payload requirements, particularly for geostationary transfer orbit (the upper stage(s) are no longer required).

The objective system first stage is Mach 6-10 horizontal take-off horizontal land waverider powered by either a turbine-based or rocket-based combined-cycle engine. A precursor Y-prototype with a 10,000 lb to low-earth-orbit capability uses separate hydrocarbon turbine or air-turboramjet propulsion system to accelerate to Mach 4-6 before engaging a rocket-based second stage for sub-orbital or orbital missions. The airbreathing first stage can accomplish a powered return to the launch site. Separate DOD and NASA upper-stages are tailored to their specific unique mission requirements. The DOD can develop any combination of a separate Space Maneuver Vehicles for space control and earth/space reconnaissance, a Modular Insertion Stage for affordable space access, or a Common Aero Vehicle to enable prompt global strike. Additional military first-stage utility can be explored through tests as a strategic reconnaissance and global strike platform capable of reaching any point on the earth within two hours and returning to its launch location. A commercial variant will be the most inexpensive means for low-earth-orbit satellite insertion. The commercial variant could also demonstrate the ability for global two to three hour package delivery and act as a testbed for a potential passenger vehicle. NASA requirements will focus on a second stage that maximizes payload delivery to the international space station.

The benefits of such a system are numerous. First, it provides a flexible space transportation solution for DOD, NASA, and commercial customers. Second, the core first stage has significant military (reconnaissance/strike) and commercial (package delivery/passenger) potential. Third, the core first stage vehicle can experience the high flight rates necessary for R^2*ISA*. Fourth, a horizontal take off and land system with fly-back capability provides a wide array of basing/landing options. The use of hydrocarbon fuels keeps vehicle size and dry-weight low (relative to rockets and hydrogen-fueled reusables) enabling a vehicle to approach aircraft-like operations. Finally, a sub-scale Y-prototype powered by turbine/air-turboramjet engines and rockets could be built using existing technology. This vehicle would provide the system experience necessary to build a highly maintainable and operationally efficient objective system, possess residual space launch capability, and act as a testbed for sorely needed hypersonic research. The supporting X-vehicle development program would validate the combined cycle engine concepts that merit use on the objective system. As rocket and hypersonic propulsion technology continued to mature, one would likely prove superior for incorporation into third-generation single-stage-to-orbit launch systems. The knowledge and experience gained through the approach outlined above would prove integral to its success.

The linkages between vehicle design and R^2ISA are now well established. However, discussion of the relationship between R^2ISA and the role it plays within the larger space transportation architecture must also be addressed. Figure 23 illustrates this architecture and the role of R^2ISA within it.

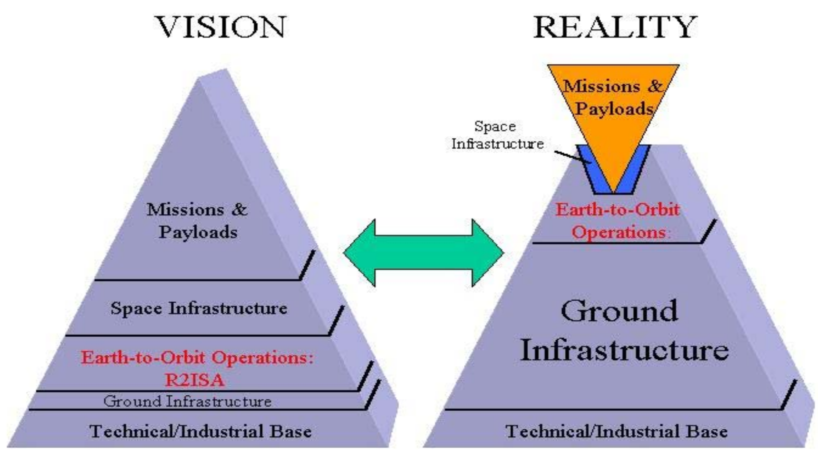


Figure 23. R^2ISA and the Space Transportation Architecture: Vision versus Reality

The U.S. space transportation architecture is built to support the varied civil, military and commercial space missions and their payloads. In a mature architecture, one would expect a top-down flow of requirements and few limiting constraints preventing self-optimization of the elements of the architecture. This creates an environment for the proliferation of diverse and inexpensive (likely smaller) payloads responsive to changing mission requirements through easy upgrade/replacement as the situation dictates. The space infrastructure would grow to accommodate easy access and replacement of these payloads as well as other scientific and commercial endeavors. Orbital transfer vehicles could economically ferry systems to and from their mission orbits, and sufficient space-based infrastructure would be built to support this activity. *R^2ISA* permits the fluid movement of personnel, payloads and equipment from earth to orbit. Dedicated ground support infrastructure is minimized, leveraging heavily upon the existing military/commercial air transportation infrastructure and existing spaceports. A robust space industrial and technical base is free to focus its resources on new products and services rather than the care and feeding of the space transportation architecture itself. However, space, the "dormant frontier" as some have called it, today endures a very different reality. Earth-to-orbit operations are unpredictable, risky, and expensive. Beyond the heavily subsidized civil space program, only the most critical defense payloads or economically compelling commercial missions are pursued. To reduce the risk of on-orbit failure and the probability of re-launch, many payload systems are made doubly or triply redundant, increasing the cost and weight of the satellites. If launch costs can be reduced significantly, it may no longer be necessary to design to such high levels of redundancy. Further, a large, inefficient, labor-intensive ground support infrastructure is required for both the orbital payloads as well as the launch vehicles themselves. This situation limits the opportunities afforded the industrial/technical base, stunting its growth, limiting its economic viability as a commercial profit center, and even threatening its existence.

Furthermore, there are subtle interactions between payload and launch costs. As launch costs increase, so do payload costs. It may be possible to recover payloads in orbit, and if payloads were designed modularly, they could be quickly repaired on-orbit. Such payloads could cost considerably less than existing satellites. Such a capability may enable a new era of low-cost access to space."[240]

R^2ISA is the enabling infrastructure element that can overcome the current impasse, but maximum benefit can only be realized if the other architecture elements can evolve with it. For example, the current annual commercial space launch market demand is about thirty launches. Most of

these involve large systems requiring insertion into a geostationary transfer orbit, unserviceable by a 20,000 lb to low-earth-orbit payload capability. However, these same satellites could be delivered to low-earth orbit where an on station orbital transfer vehicle could economically insert these satellites into their mission orbits. Although the incentive to build large, redundant satellites will quickly erode once R^2*ISA* is demonstrated, it makes better economic sense to have these smaller payloads ready from the outset. The space infrastructure would quickly grow to accommodate this change, which could include the servicing of orbital transfer vehicles as well as certain high value payloads once it made good economic sense.

The complexity and scope of the issues discussed suggest that a new centralized management authority is appropriate. A National Aerospace Transportation Agency responsible for developing an overarching space transportation architecture, accountable to the President, and responsive to military, civil, and commercial needs could provide that authority. This agency would not be designed to compete with NASA, but rather take responsibility for the development and early operation of a complete space transportation architecture focused on securing long term economic viability, compatibility and interoperability between architecture elements, and the optimum allocation of limited resources. Ultimately, it would spin off all major elements of the space architecture back to NASA, DOD, other government agencies (i.e. FAA) and commercial industry before dissolving itself. Or alternatively, become a National Aerospace Transportation Authority responsible for the efficient operation of the space transportation infrastructure it creates. During the build-out of this architecture, the Agency must have the authority to "coercively" integrate and ameliorate disparate Civil, DOD, and commercial requirements into a single joint space transportation architecture. The Joint Program Office responsible for second generation space launch system development would be comprised of DOD, NASA, and DARPA personnel and take these adjudicated requirements to design, develop, and test the joint space launch system designed to deliver R^2*ISA*.

The agency would require its own budget, but initial budget authority as well as programs would be extracted from the relevant developmental activities ongoing within DOD, NASA, and DARPA. This includes the existing remnants of NASA's Space Launch Initiative, the proposed National Aerospace Initiative effort, the coalescing National Hypersonics Strategy, X-Vehicle programs to include X-37 and X-43-like programs. The total budget authority as well as the oversight and management of the space shuttle and International Space Station would also fall under the new agency within two years. This should free NASA to pursue its original charter in lieu of managing burdensome cash strapped programs. Current plans to develop an Orbital Space Plane should be accelerated in conjunction with either man-rating the Evolved-Expendable Launch System or a developing companion crew escape system for the space plane. Once both are in place and crew transfer to and from the international space station is validated, shuttle operations should cease immediately. The fleet should then be "mothballed" or partially dismantled, and all planned shuttle life-extension upgrades cancelled. All unused budget authority reverts to the Agency. Ideally, Agency funding should come under the oversight of only one authorization and appropriation subcommittee in each house of Congress. Some may consider the methods described above draconian or politically unwieldy. While one may concede either, thirty years of failure highlight the need for systemic change.

V. Conclusions and Recommendations

If a sufficient number of management layers are superimposed on each other, it can be assured that disaster is not left to chance.

—Augustine's Law Number XXVI

By the time the people asking the questions are ready for the answers, the people doing the work have lost track of the questions.

—Augustine's Law Number XXX

What is R2ISA and why is it important?

Robust, Reliable, and Inexpensive access to space (*R^2ISA*) is the cornerstone of continued U.S. civil, military, and commercial leadership in space. Existing expendable and reusable launch systems fail to demonstrate *R^2ISA* by a wide quantifiable margin and artificially constrain U.S. space exploitation. A second generation reusable launch vehicle capable of a 100 hour launch re-cycle time, no higher than a 1/1000 probability of loss of vehicle, at a cost of less than $1000 per pound to low-earth orbit has the potential to unleash an increasing non-linear demand for civil, military, and commercial space activity.

R^2ISA must be developed as an element of a larger space transportation architecture

R^2ISA is a key component of a larger space transportation architecture that includes missions and payloads, space infrastructure, earth-to-orbit operations, ground infrastructure, and a technical/industrial base. Virtually all existing satellites are 20,000 pounds or less, defining a quantitative upper limit to low-earth-orbit payload delivery capability. Space launch vehicles are a very inefficient way to drive payloads to mission orbits/velocities once a minimum threshold orbital velocity is achieved. By leveraging a robust set of highly efficient orbital maneuvering vehicles and a 20,000 pound upper payload limit, much

smaller and operationally efficient reusable space launch capability that delivers R^2*ISA* is enabled. Fully matured R^2*ISA* will make smaller and lighter satellites more attractive. Smaller payloads, coupled with suitable technology, can result in even smaller and supportable third-generation launch systems, drastically reducing the size and scope of a costly, labor-intensive ground support infrastructure. This in turn permits the reallocation of a limited technical/industrial base toward the development of new products and services in lieu of servicing and adding cost to an already bloated space transportation architecture. Opening up the entire space transportation "trade-space" is an essential prerequisite to achieving R^2*ISA*.

Economic Reality Discourages Investment in R^2*ISA*

Economic factors play a pivotal role in enabling R^2*ISA*. The commercial space launch market is characterized by a market failure similar to that experienced by past commercial rail, automobile, and air transport systems. Market elasticity (a one percent drop in price results in a greater than one percent increase in demand) enters the commercial launch market at around $1000 per pound to low-earth orbit. Current prices between $2000 per pound for Russian/Chinese systems and $5000 per pound for Western systems that result in an inelastic market (a one percent drop in price produces no more than a one percent increase in demand), combined with relatively poor reliability and robustness, undermine any economic incentive for commercial enterprise to invest and improve launch vehicle performance. Hence, it is unreasonable for the government to expect any voluntary large-scale commercial participation in a space launch system until R^2*ISA* is demonstrated. A closer examination of space launch vehicle direct launch costs shows a four to five order of magnitude difference in labor intensity between aircraft systems and launch vehicles for both expendable and reusable systems. The underlying root causes for this gap must be eliminated to permit R^2*ISA*. Finally, economic constraints combine with fundamental technology limitations to prevent expendable launch vehicles from achieving R^2*ISA*.

Technology Investment is a Key Enabler for ***R^2ISA***

Demonstrated ability to harness technology to overcome the fundamental physical challenges of accelerating payloads to orbital velocity remains an *R^2ISA* limiting factor. Two-stage-to-orbit solutions are necessary for second-generation reusable space launch, while more operationally and economically efficient single-stage-to-orbit vehicles are possible for third and fourth-generation reusable launch systems. Existing technology demands single-stage-to-orbit inert (structural) mass fractions below 10 percent of overall vehicle mass. Although this has been demonstrated for expendable launch systems, it is currently unrealistic to build single-stage-to-orbit reusable vehicles with structural mass fractions less than 20 to 30 percent of total vehicle mass. Current technology provides insufficient design and performance margin to support the development of a single-stage-to-orbit vehicle capable of *R^2ISA*. However, sufficient margin exists to support a two-stage-to-orbit *R^2ISA* that simultaneously demonstrates future key enabling single-stage-to-orbit technologies. Four main enabling technology areas include propulsion, advanced materials, thermal protection, and vehicle integration. Additional technology maturation is required before a purely reusable rocket-based *R^2ISA* solution is viable. However, government investment in both rocket and combined-cycle hypersonic engine technologies is orders of magnitude below what is necessary to enable *R^2ISA*. Recent advances in supersonic and hypersonic air-breathing propulsion indicate that a near-term two-stage-to-orbit solution is possible, specifically for lower Mach number first stage applications.

Mission Requirement Adjudication

Seemingly divergent civil/military/commercial requirements are reconcilable, implying that a "national" space launch solution is possible. A 20,000-pound payload mass to low-earth orbit, supplemented with a robust space infrastructure to include orbital transfer vehicles, can satisfy all civil and military requirements and is valuable to the commercial sector as well. The military's need for a launch-on-demand system with short flight-recycle times is not a fundamental priority for civil missions, but it is a necessary precursor to lower costs. Reliability of 99.9 percent (1/1000 probability of loss of vehicle) or greater exhibits an acceptable degree of convergence between the civil and military reliability requirements in the near term. The combined impact of higher reliability coupled with lower launch costs and sharply reduced recycle times of second-generation *R^2ISA* is sufficient to induce substantial growth within the commercial sector.

Lessons Learned

Today’s space launch environment is laden with an inertia making progress difficult. *R^2ISA* is not necessary to meet today’s low global space launch demand that perpetuates the status quo characterized by an inelastic market providing expensive, risk laden and inflexible launch services. Existing capacity for launch services far outstrips demand, removing the incentive for even modest incremental improvements in existing systems until absolutely necessary, as well as completely undermining new commercial ventures intending to enter the market. The space shuttle program was originally intended to deliver revolutionary capability at revolutionary prices ($385 per pound to low earth orbit in 1971) that that today exceeds $10,000 per pound. The shuttle’s first flight as a prototype was also the first flight of the objective system. Hence, design compromises in development that created shuttle’s unforeseen yet overwhelming ground support infrastructure and high labor intensity could not be reasonably exorcised from the system. Further, an order of magnitude shortfall in annual flight rate (from forty to four) artificially ballooned the program overhead, dwarfing incurred marginal individual mission costs. A functional breakdown of shuttle costs using NASA definitions of direct, indirect, and support comprise 10, 20, and 70 percent of the total $3.2 billion FY02 shuttle budget respectively. The latter is comprised of very labor-intensive activities across all of the NASA Centers to get the shuttle prepared for the next launch. A solution to the shuttle conundrum has to be found that does not compromise commitments to the international space station and manned space flight, while freeing sufficient resources to develop a space launch system that delivers *R^2ISA*.

The aborted X-30 and X-33 programs make it clear that neither an airbreathing nor rocket based single-stage-to-orbit system is ready for development and production. The recent Space Launch Initiative restructure indicates that a rocket based two-stage-to-orbit solution conforming to NASA requirements and programmatic constraints is clearly unaffordable. However, these lessons do not imply that pursuit of R^2*ISA* is unachievable or ill advised. On the contrary, it merely demands a national commitment to an evolutionary, capabilities based spiral development approach in lieu of a technology leveraged, high risk, performance driven point design solution. R^2*ISA* demands leveraging technology to infuse system reliability, robustness, and margin rather than an over-fixation on maximizing performance.

Breakthrough design approaches may cost three times what a continuous improvement model does for the same performance, and projects with "high political risk" should be designed with stable intermediate forms. Continuity provides a symbiotic maturation of the vehicle design with the supporting ground infrastructure that can only be gained through operational experience. Prudent use of X-vehicles for technology maturation and Y-prototype development for risk reduction can fill the void that lies between a computer aided design and the production system. Many X-vehicles designed and flight-tested to demonstrate high-risk technology solutions have been very successful. However, no X-vehicle intended to fly as a prototype for a follow-on production system has ever flown. The X-30 and X-33 clearly illustrate this point. A Y-prototype is most useful in demonstrating successful system integration and is invaluable tool for controlling cost and risk for moderate to high-risk system development. Y-prototypes must clearly demonstrate scalability and traceability to an objective system design as well as possess sufficient "residual" capability to capture enough missions to justify a reasonably high sortie rate over its relatively short "operational" life (3-5 years). Residual capability ensures a sufficient sortie rate that in turn provides the operational experience necessary to learn the tough lessons that come only with flying and operating the vehicle. This is the best way to gain sufficient insight to infuse operability and maintainability into the objective system. Thirty years of failure should make it clear that taking shortcuts will only lead to more failure. R^2*ISA* is enabled by continuity in system development, not through a discontinuous, revolutionary vehicle design approach.

Vital Reform

Ad-hoc oversight or unenforceable cooperative agreements between agencies as an enabler for R^2*ISA* is also highly suspect. There is an array of promising space technology programs funded across the federal government that are part of "technology roadmaps" that lead to nowhere. Nowhere is there a link to an objective launch system that might enable some rational prioritization of scarce resources. Today it is currently done at best by cooperative, well-intentioned "enlightened" intuition, and at worst by political or personal agendas. Further, the lack of an objective system removes the imperative for any sorely needed increases in budgets or accelerations to programs. The solution demands a stable, well-funded joint system program office serving all federal agency stakeholders (including DOD and NASA) chartered to deliver R^2ISA and held accountable to a higher authority. A joint DOD/NASA/DARPA program office should be immediately established to develop an overarching space transportation architecture designed to satisfy military, civil, and commercial space requirements. A reusable two-stage-to-orbit earth-to-orbit launch vehicle capable of delivering a minimum of 20,000 lbs to low-earth orbit and satisfying second-generation R^2ISA criteria should be its top priority.

R^2ISA is the key element and current limiting factor to the development of a robust space transportation architecture. The complexity and scope of circumstances that have resulted in a 30-year impasse with no foreseeable solution demands the establishment of a National Aerospace Transportation Agency (NATA) responsible for the development of an overarching space transportation architecture responsive to civil/military/commercial mission needs. The agency would be led by a Presidential appointee guided by an Executive Steering Committee comprised of NASA administrator; Deputy Secretary of Defense; Director, Defense Developmental Research and Engineering; Undersecretary of the Air Force for Space; and designated representatives from industry to serve in an advisory capacity. This agency would complement rather than compete with NASA by taking direct control of the development, early operation, and successful maturation of a complete space transportation architecture focused on securing long term economic viability, compatibility and interoperability between architecture elements as well as determining the optimum allocation of limited resources. Eventually, it would spin off all major elements of the space architecture back to NASA, DOD, other government agencies (i.e. FAA) and commercial industry before ultimately dissolving itself. Alternatively, if deemed appropriate, the agency could divest itself of all developmental activities and become the National Aerospace Transportation Authority.

The Agency must have the authority to fully integrate and ameliorate disparate Civil, DOD, and Commercial requirements into a single joint space transportation architecture. The Joint Program Office would take responsibility for the research, development, test and evaluation of any X-vehicle and Y-prototype systems and be comprised of DOD, NASA, and DARPA personnel. The using organizations (i.e. NASA, USAF, NRO, etc.) would fund operations and maintenance of the prototype systems that were supporting their missions. Where "voluntary" utilization may not be forthcoming, it may need to be mandated. All ongoing DOD, NASA, and DARPA programs deemed relevant to R^2*ISA* architecture development would be transferred to the Agency. Recent historical precedent for such action can be found with the Presidential actions surrounding the transitioning of the Ballistic Missile Defense Office into the Missile Defense Agency.

NATA would require its own budget with initial budget authority as well as programs transferred to the agency from DOD, NASA, and DARPA. This includes the remnants of NASA's Space Launch Initiative, DOD's proposed National Aerospace Initiative, any coalescing programs within the National Hypersonics Strategy, and the X-37 and X-43 programs. The oversight, management, and budget authority of the space shuttle and International Space Station would also fall under the new agency within two years. This action would free NASA to pursue its original charter in lieu of managing burdensome cash strapped programs. Current plans to develop an Orbital Space Plane should be accelerated in conjunction with man-rating the Evolved-Expendable Launch System. Once both are in place and crew transfer to and from the International Space Station is validated, shuttle operations should cease soon thereafter. Ideally, agency funding should come under the oversight of only one authorization and appropriation subcommittee in each house of Congress.

A Proposed Solution

A two-stage-to-orbit space-launch system using a first stage waverider design leveraging combined cycle engine technology is the best and fastest route to R^2*ISA*. First, it provides a flexible space transportation solution for DOD, NASA, and commercial customers. Second, the core first stage has significant military (reconnaissance/strike) and commercial (package delivery/passenger) potential. Third, the core first stage vehicle can experience the high flight rates necessary for *R^2ISA*. Fourth, a horizontal takeoff and land system with fly-back capability provides a wide array of basing/landing options. The use of hydrocarbon fuels keeps vehicle size and dry-weight low (relative to rockets and hydrogen-fueled reusables) enabling a vehicle to approach aircraft-like operations. Finally, supporting X-vehicle program can validate combined cycle engine concepts that merit use on the objective system while a sub-scale Y-prototype first stage could be built today using existing propulsion technology (either rockets, advanced turbines, or pulse detonation) until a turbine combined cycle engine was ready. This vehicle would provide the system experience necessary to build a highly maintainable and operationally efficient objective system, possess residual space launch capability, and act as a test bed for sorely needed hypersonic research.

The two-stage-to-orbit objective system would deliver up to 20,000 pounds to low earth-orbit (100 nm, 28.5 deg inclination) using a Mach 4-6 horizontal take-off / horizontal land waverider powered by hydrocarbon-fueled Revolutionary Turbine Accelerator derived turbine-combined-cycle-engine with the capacity to return to its launch site. The second stage would ideally be an airbreathing waverider using a rocket-based combined cycle engine, but could implement a simpler wing/fuselage rocket design as an alternative if sufficient second stage performance can be demonstrated. Separate DOD and NASA upper-stages could be developed and tailored to accommodate their unique mission requirements.

The DOD could develop any combination of a separate Space Maneuver Vehicle for space control and earth/space reconnaissance, a Modular Insertion Stage for affordable space access, or a Common Aero Vehicle to enable prompt global strike. Additional military first stage utility can be explored through tests as a strategic reconnaissance and global strike platform capable of reaching any point on the earth within three hours and returning to its launch location. A commercial first stage variant will enable inexpensive low-earth-orbit satellite insertion, demonstrate global two to three hour package delivery, and serve as a test bed for a potential future passenger vehicle. NASA requirements will likely focus on a second stage maximizing payload delivery to the International Space Station. As rocket and hypersonic propulsion technology continues to mature, one will likely prove superior for incorporation into third-generation single-stage-to-orbit launch systems.

The knowledge and experience gained through the approach outlined above would prove integral to its future success.

In the Final Analysis…

R^2ISA as part of an integrated space transportation infrastructure is the key to unlocking the limitless civil, military, and commercial potential of space. This paper has introduced one potential path to achieving it that if fully implemented, can ***guarantee*** ultimate success. The United States with the close cooperation of NASA, DOD, industry, and academia must lead the way to muster and organize the means to build a sufficiently robust, reliable, and inexpensive reusable launch system to evolve space exploration and exploitation beyond the realm of limited government and commercial enterprise into the public domain. Mark Twain wrote more than a century ago, "Twenty years from now you will be more disappointed by the things that you didn't do than by the ones you did do. So throw off the bowlines. Sail away from the safe harbor. Catch the trade winds in your sails. Explore. Dream. Discover." These words were meant to inspire the individual. Today they hold new meaning for the Nation. It is time to roll up our sleeves and get on with building *R^2ISA*. To do so will free countless individuals of future generations to "Explore, Dream, and Discover." America and the world will be better for it.

Notes

[1] This was the U.S. Air Force motivation behind "assured access" that ended USAF reliance on a single launch system after the near simultaneous loss of Challenger and other expendable launch vehicle failures in the 1986-1987 timeframe. Assured access included maintaining the viability of two separate and distinct launch vehicle vendors within the Evolved Expendable Launch Vehicle program. Hence high costs do not necessarily impede established high-value missions such as the insertion of a lucrative commercial communication or sensitive military payloads into geostationary orbit.

[2] "Commercial Space Transportation Study," NASA Langley Research Center, Hampton, VA, 1994.

[3] Commercial Space Transportation Study, Section 1.1.

[4] Commercial Space Transportation Study, Section 4.1.3.

[5] Inflating $600 and $1000 from FY94 dollars, based upon the U.S. Consumer Price Index (CPI) to 2002 yields $723 and $1211 respectively. The $800 average between the two FY94 values inflates to $969 in CY 2002 dollars. This value is conservatively rounded to $1000. "What is a Dollar Worth?" *Federal Reserve Bank of Minneapolis*, on line, Internet, 30 November 2002, available from http://minneapolisfed.org/research/data/us/calc.

[6] The National Aeronautics and Space Administration uses the first, second, and third-generation nomenclature in its Integrated Space Transportation Plan describing the space shuttle as a first-generation reusable launch vehicle. Subsequent systems are described as second and third-generation systems respectively.

[7] Commercial Space Transportation Study, Section 4.1.3.

[8] William R. Claybaugh, *Economics of Space Transportation*, AIAA Professional Development Short Course, (Washington, DC: American Institute of Aeronautics and Astronautics, 2002), 148. Percent probabilities quoted are at 95% confidence.

[9] Claybaugh, 155-159.

[10] "A Review of Space Shuttle Data: Replaced Items – LRUs per Flight," *National Aeronautics and Space Administration*, on-line, Internet, 30 November 2002, available from

Notes

http://science.ksc.nasa.gov/shuttle/nexgen/Nexgen_Downloads/A_Review_of_Space_Shuttle_LRU_Data.doc.

[11] Claybaugh, 161-162.

[12] National Aeronautics and Space Administration, *Introduction to NASA's Integrated Space Transportation Plan and Space Launch Initiative*, (May 17,2001), 3.

[13] Robert Wall, "Pentagon Accidents, Fatalities Rise," *Aviation Week and Space Technology*, October 7, 2002, 31. DOD Class A tri-service accidents per 100,000 flight hours typically range between 1 and 1.5.

[14] "Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000," *Futron Corporation*, Bethesda, MD, 6 September 2002, 2-3.

[15] Orbit inclination ranges from zero to 180 degrees. A zero inclined orbit travels over the equator in a west to east (prograde) direction. Rotating this orbit ninety degrees results in a polar (90 degree inclined) orbit, while rotating it a full 180 degrees results in an equatorial orbit traveling in a westerly (retrograde) direction. A due east launch from Cape Canaveral (at 28.5 latitude) defaults into a 28.5 degree inclined orbit and maximizes the benefit of the earth's rotational velocity to achieve orbit.

[16] As quoted by AIA President Don Fuqua, *Military Space* (12 December 1994), 1.

[17] Frank Morring, Jr., "NASA to Leave ISS Crew Size Issue Open," *Aviation Week and Space Technology*, 18 November 2002, 45.

[18] Paul Dergarabedian, *Comments on National Space Transportation*, position paper, The Aerospace Corporation, El Segundo, CA, 1988, 2-3.

[19] Steven J. Isakowitz, Joseph P. Hopkins, and Joshua B. Hopkins, *International Reference Guide to Space Launch Systems, Third Edition*, (Washington D.C.: American Institute of Aeronautics and Astronautics, 1999), 415. The shuttle was estimated to cost $10.5 million and designed to deliver up to 65,000 pounds to low earth orbit.

[20] Joan Johnson-Freese and Roger Handberg, *Space the Dormant Frontier: Changing the Paradigm for the 21st Century* (Westport, CT: Greenwood Publishing Group, 1997), 89.

[21] "Legislative Update," *Aerospace America*, November 2002, 12. FY03 NASA appropriations bill provided $3.2B for four space shuttle

Notes

launches supporting the International Space Station. This translates into $800M per launch, or approximately $16,000 per pound to LEO.

[22] Scott Pace, "U.S. Space Transportation Policy," *Space Policy*, November 1988, 321.

[23] John R. London, *LEO in the Cheap: Methods for Achieving Drastic Reductions in Space Launch Costs*, Air University Research Report No. AU-ARI-93-8 (Maxwell AFB, AL: Air University Press, 1994), 10-11.

[24] Jeffery M. Lenorovitz, "Congress Cancels NLS Launcher Family," *Aviation Week and Space Technology*, 12 October 1992, 20.

[25] Johnson-Freese, 24.

[26] Johnson-Freese, 23.

[27] The National Commission of Space, *Pioneering the Space Frontier* (New York: Bantam Books, 1985), 12.

[28] Matt Bille, Tony Williams, Vic Villhard, and Lisa Reed, "Dreams to Reality: The Path to the RLV," *AIAA, IEEE, and AAS Core Technologies for Space Systems Conference Proceedings*, November 2002, 4.

[29] Paul Hoversten, "U.S. Air Force Won't Fund X-33, X-37 Space Planes," *AviationNow.com*, 6 September 2001, on-line, Internet, 18 December, 2002, available from http://www.aviationnow.com/avnow/news/channel_space.jsp?view=story &id=news/smil090601.html

[30] Bille, 5-6.

[31] "Boeing's Phantom Works gets $301M X-37 contract," *St Louis Business Journal*, 25 November 2002, n.p., on-line, Internet, 18 April 2003, available from http://stlouisbizjournals .com/stlouis/stories/2002/11/25/daily23.html.

[32] The Space Launch Initiative is a direct descendant of the NASA Space Transportation Architecture Study that concluded that $5B of government investment would be needed to enable commercial RLV development. Refer to http://www.hq.nasa.gov/office/codea/codeae/ stas_results.html.

[33] National Aeronautics and Space Administration, *Introduction to NASA's Integrated Space Transportation Plan and Space Launch Initiative*, 17 May 2001, 4.

Notes

[34] "The Administration/NASA Integrated Space Transportation Plan," *National Aeronautics and Space Administration,* n.p., on-line, Internet, 25 October, 2002, available from http://www. aerospace.nasa.gov/home&home/glenn/invasp/tsld004.htm.

[35] Stephen Trimble, "NASA Whittles SLI Concepts to 15," *AviationNow.com*, 30 April 2002, on-line, Internet, 18 December 2002, available from http://www.avaiationnow.com/ avnow/news/channel_space.jsp?view=story&id=news/ssli043002.html.

[36] "NASA Postpones Review of SLI Program," *AviationNow.com*, 22 Oct 2002, on-line, Internet, 18 Dec 2002, available from http://www.aviationnow.com/avnow/news/channel_ space.jsp?id=news/csli102202.html.

[37] Jefferson Morris, "NASA Budget Amendment Delays Next-Gen RLV, Cuts SLI By $2.323 Billion," *AviationNow.com*, 13 November 2002, on-line, Internet, 18 December, 2002, available from http://www.avaiationnow.com/avnow/news/channel_space.jsp?view=story &id =news/snextgen121302.html.

[38] Robert K. Steele and Peter L. Portanova, "EELV: New Acquisition Strategy for a New Launcher," *Aerospace America* (July 1996), 38.

[39] Johnson-Freese, 90.

[40] Glenn W. Goodman, Jr., "Assured Access to Space," *Armed Forces Journal International*, July 2002. As of 26 August, 2002, the Air Force has awarded 21 launch contracts to Boeing worth $1.5B and seven to Lockheed-Martin worth $500M.

[41] Sidney Kimhan, Janet Grondin, et.al., "EELV Program – An Acquisition Reform Success Story," *Program Manager*, vol. 28 no. 3 (May-June, 1999): 87-88.

[42] "Military EELV Launches Could Save $10B," *Aviation Week and Space Technology*, 26 August 2002, 23.

[43] Charles E. Lindbloom, "The Science of Muddling Through," Public Administration Review, no. 19 (1959), 79-88.

[44] "NASA Readies 2nd Generation RLV Project for the Chop," *SpaceDaily*, 22 Oct 2002, n.p., on-line, Internet, 25 October 2002, available from http://www.spacedaily.com/news/ rocketscience-02zh.html.

[45] The Crew Return Vehicle (CRV) will initially fly to the International Space Station (ISS) unmanned using a heavy-lift configured

Notes

EELV to serve as a lifeboat to return astronauts in the event of an emergency aboard ISS. This configuration may eventually be crew rated, eliminating the requirement to use the Space Shuttle for ISS mission crew transport.

[46] "Reassessing Space Shuttle Upgrades Strategy," *SpaceRef.com*, 3 April 2002, n.p., on-line, Internet, 28 February 2003, available from http://www.spaceref.com/news/ viewers.html?pid=5124.

[47] "Legislative Update," *Aerospace America*, November 2002, 12.

[48] Jess Sponable, "Military Spaceplane S&T Demonstrator: Two Stage Hypersonic Testbed," Air Vehicles Directorate, Air Force Research Laboratory, Wright Patterson Air Force Base, OH, 1 July 2002, 3.

[49] "Air Force Space Command Strategic Master Plan," Headquarters USAF Space Command, 9 January 2000, on-line, Internet, 18 April 2003, available from http://www.spacecom.af.mil/hqafspc/library/AFSPCPAOffice/chapterone.htm. Definitions include Space Force Enhancement: operations conducted from space to support forces; e.g., navigation, communications, reconnaissance, surveillance, ballistic missile early warning, and environmental sensing. Space Forces Support: sustain, surge, or reconstitute elements of military space systems or capabilities (includes spacelift and satellite command and control). Space Control: ensuring friendly use of space while denying its use to the enemy. To accomplish this, space forces must survey the space environment, protect our ability to use space, prevent adversaries from interfering with that use, and negate the ability of adversaries to exploit their own forces. Space Force Application: attacks against terrestrial, airborne, or space targets carried out by weapons operating in or through space.

[50] *Strategic Master Plan FY04 and Beyond*, United States Air Force Space Command, 1-21, on-line, Internet, 5 November 2002, available from http://www.spacecom.af.mil/hqafspc.

[51] Daniel Gonzales, Mel Eisman, et al., *Proceedings of the Rand Project AIR FORCE Workshop on Transatmospheric Vehicles*, RAND, MR-890-AF, 1997, xiv.

[52] Gonzales, xiv.

[53] Gonzales, xv.

[54] Gonzales, 16.

Notes

[55] Gonzales, 17.

[56] "NASA-USAF Reusable Space Launch Development: 120 Day Study Overview," presented to the National Aerospace Initiative Steering Group, 5-7 March 2002, 4.

[57] John Hawley, "Red Team Observations and Recommendations on 120-Day NASA/USAF RLV Study," 2002, 4.

[58] Paul Branch, "30 Day Launch Forecast," HQ USAF/XOO, the Pentagon, 16 January 2003. The Soyuz-U launch vehicle delivers the Progress spacecraft (unmanned Russian space station resupply ferry) to low-earth orbit. Progress weighs 16,095 pounds, carries 3,970 pounds of consumables in the cargo compartment and 2,072 pounds of fuel (for orbit insertion and de-orbit) in the service module.

[59] "120 Day Study Overview," 25.

[60] "120 Day Study Overview," 16.

[61] "120 Day Study Overview," 25.

[62] Hawley, 5.

[63] "2003 Aerospace Source Book," *Aviation Week and Space Technology*, 13 January 2003, 160-164.

[64] "2003 Aerospace Source Book," 151-152.

[65] Commercial Space Transportation Study, Section 2.0.

[66] Commercial Space Transportation Study, Appendix A, Figure 1-1.

[67] Consolidated Space Transportation Study, Section 3.5.1.

[68] Stephen J. Isakowitz, *International Reference Guide to Space Launch Systems* (Washington D.C.: American Institute of Aeronautics and Astronautics, 1991), 246-246.

[69] Isakowitz, 1991, 247-248.

[70] Carey M. McCleskey and Edgar Zapata, "Designing for Annual Spacelift Performance," *International Astronautical Federation,* IAF-98-U.2.05, 1998, 6.

[71] McCleskey, 7.

[72] McCleskey, 9.

[73] McCleskey, 7.

[74] McCleskey, 7.

[75] McCleskey, 6.

[76] Gonzales, xii.

[77] Gonzales, xii.

Notes

[78] Gonxales, 37.
[79] Gonzales, xii.
[80] Gonzales, 37.
[81] Gonzales, 33.
[82] S. Dornheim, "Follow-on Plan Key to X-33 Win," *Aviation Week and Space Technology*, 8 July 1996, p.20.
[83] Gonzales, 42-44.
[84] Gonzales, 25.
[85] Gonzales, 25.
[86] Gonzales, 26.
[87] Gonzales, 26.
[88] S*tatus of the X-33 Reusable Launch Vehicle Program*, United States Government Accounting Office (GAO/NSIAD-99-176), August 1999, 2.
[89] Frank Mooring, "NASA Kills X-33, X-34, Trims Space Station," *Aviation Week and Space Technology*, 17 June 2001, n.p., on-line, Internet, 18 December 2002, available from http:// Aviationnow.com/avnow/content/publication/awst/20010305/nasa.htm.
[90] Dennis Bushnell, Chief Scientist, Langley Research Center, email memo with Dr. Ron Sega, Director USD/DDR&E, "NASA Gen 3/Airbreathing to Orbit Evaluation," 20 March 2002.
[91] Matt Bille, Tony Williams, Vic Villhard, and Lisa Reed, "Dreams to Reality: The Path to the RLV," AIAA, IEEE, and AAS Core Technologies for Space Systems Conference Proceedings, November 2002.
[92] Including the X-20, X-30, X-33, X-37, Space Shuttle, Soviet, and commercial RLVs.
[93] Including the X-15, U-2, SR-71, F-117, B-2, and Apollo programs.
[94] *Department of Defense Space Technology Guide FY2000-01*, United States Department of Defense, Ch 4-11.
[95] Loomis, 220.
[96] The reader is encouraged to visit http://members.aol.com/luthben/ unit.html for a very helpful discussion on English to Metric conversion, particularly the relationship between pound-force, pound-mass, slug, and kilogram.

Notes

[97] William H Heiser and David T. Pratt, *Hypersonic Airbreathing Propulsion* (Washington D.C.: American Institute of Aeronautics and Astronautics, 1994), 128.

[98] Humble, Table 1.2, 11.

[99] "SSME Specifications," *Andrews Space and Technology*, n.p., on-line, Internet, 20 January 2003, available from http://spacetech.com/spacedata/engines/ssme_specs.shtml.

[100] "RS-68 Engine," *Boeing*, n.p., on-line, Internet, 20 January 2003, available from http://www.boeing.con/defense-space/space/propul/RS68.html.

[101] "RS-27A Propulsion System," *Boeing*, n.p., on-line, Internet, 20 January 2003, available from http://www.boeing.com/defense-space/space/propul/delta.html.

[102] "2003 Aerospace Source Book," 122. 260,800 lbs maximum thrust at seal level, 9,670 lbs dry weight; specific fuel consumption 0.334 lb/hr/lb; Avweek 2003 Source Book, 122.

[103] "2003 Aerospace Source Book," 132. 23,770 lbs maximum thrust at sea level; 3,265 lbs dry weight; specific fuel consumption of 2.1 lb/hr/lb.

[104] Uwe Hueter and Charles McClinton, "NASA's Advanced Space Transportation Hypersonic Program," *American Institute of Aeronautics and Astronautics*, 11th AIAA/AAAF International Conference on Space Planes and Hypersonic Systems, (AIAA-2002-5175), September 2002, 2.

[105] Hueter, 2.

[106] "X-15 First Flight: X-15 Concept Evolution," *NASA*, Figure 3, on-line, Internet, 20 January 2003, available from http://www.hq.nasa.gov/office/pao/History/x15conf/concept.html. The X-15 had a launch weight of 33,000 pounds and a re-entry weight of 14,600 pounds. A total of 308 pounds was allocated to avionics with another 300 pounds allocated to the pilot and associated life support equipment. Hence an approximated payload mass of 600 pounds was used for this calculation.

[107] "2003 Aerospace Source Book," 40.

[108] "2003 Aerospace Source Book," 70.

[109] Humble, 66.

[110] Humble, figure C.1, 716.

Notes

[111] Humble, figure 2.11, 64.

[112] Whitehair, et al, "Operational Design Factors for Advanced Space Transportation Vehicles," *International Aeronautical Federation*, IAF-92-0879, 1992.

[113] A structure designed to successfully withstand the maximum anticipated stresses experienced within its performance envelope possess a safety factor of 1.0. FAA Regulations Part 31 requires a minimum safety factor 1.5, and higher safety factors by exception.

[114] Humble, Appendix B.

[115] Gonzales, 63.

[116] Gonzales, 64.

[117] Gonzales, 67.

[118] Gonzales, xviii.

[119] Gonzales, xx.

[120] "Titanium aluminides such as $TiAl$ and Ti_3Al developed for NASP offer the advantages of a high maximum operating temperature (800°C) compared to other titanium compounds (500-700°C), improved oxidation and creep resistance, and relatively low density to the aluminum content. They are however, presently more brittle than common titanium compounds at room temperature. Nickel based alloys such as Inconel 617 have significantly higher maximum operating temperatures (e.g., 1100°C for Inconel 617), allowing use on lower fuselage surfaces and other high-temperature areas. They are creep and oxidation resistant, but have significantly higher density than aluminum alloys." Gonzales, 72-73.

[121] Gonzales, xx.

[122] Gonzales, 67.

[123] Gonzales, 69.

[124] Low lift to drag (L/D) ratios at subsonic speeds and moderate to high L/D at supersonic speeds have stability concerns during landing.

[125] Jay P. Penn, *SSTO vs. TSTO Design Considerations – An Assessment of the Overall Performance, Design Considerations, Technologies, Costs, and Sensitivities of SSTO and TSTO Designs Using Modern Technologies*, The Aerospace Corporation, Space Technology & Applications International Forum (STAIF-96), 7-11 January 1996, Albuquerque, NM.

Notes

[126] Gonzales, 42.

[127] S. Dornheim, "Follow-on Plan Key to X-33 Win," *Aviation Week & Space Technology*, July 8, 1996, 20.

[128] "NASA Nears X-33 Pick," *Aviation Week and Space Technology*, 17 June 1996, 29.

[129] Gonzales, 48-49.

[130] Gonzales, xix.

[131] Rocket engine thrust is at a maximum when exhaust exit pressure is equal to ambient pressure, hence performance is maximized by a variable exit nozzle configuration that permits exit pressure modulation during vehicle ascent. The linear-aerospike engine not only permits such modulation, it operates at much lower chamber pressures (the most important design parameter impacting rocket engine complexity).

[132] London, 100.

[133] Gonzales, 34.

[134] Gonzales, 34.

[135] London, 99.

[136] Claybaugh, 87.

[137] Claybaugh, 92-94. Two "arguably" private investments in space transportation have occurred: Pegasus and Athena. On the basis of return-on-investment, no purely private investment in new space transportation assets has been successful. Based upon FY99$, the estimated investment and estimated ten year ROI for Pegasus and Arthena was $73.8M/(-39.1%) and $145.2M/(-61.9%). A ten-year treasury rate is used for discounting purposes, assumes 30% of launch revenue is returned (highly unlikely), and does not consider costs associated with correcting launch failures.

[138] Carol Loomis, "Mr Buffet on the Stock Market," *Fortune*, 22 November 1999, 218-220. Regarding the automobile: "All told there appear to be 2,000 car makes, in an industry that had an incredible impact upon people's lives. If you had foreseen in the early days of cars how the industry would develop, you would have said, "here is the road to riches." So what did we progress to by the 1990's? After corporate carnage that never let up, we came down to three corporate car companies—themselves no lollapaloozas for investors. So here is an industry that had an

Notes

enormous impact on America—and also an enormous impact, though not the anticipated one, on investors."

[139] Loomis, 220.

[140] Claybaugh, 98.

[141] Claybaugh, 99.

[142] Claybaugh, 90.

[143] Walter J Boyne, "The Man Who Built the Missiles," *Air Force Magazine*, October 2000, 84-86.

[144] Under Secretary of Defense for Acquisition and Technology, *Space Launch Modernization Plan*, Office of Science and Technology Policy, 1995.

[145] Data for delivery of propellants to NASA Kennedy Space Center in January 2000 included Kerosene (RP-1), Liquid Hydrogen, and Liquid Oxygen at $0.278, $1.300, and $0.064 per pound respectively. Claybaugh, 24.

[146] E. Zapata and Dr. A. Torres, "Space Transportation Cost Modeling and the Architectural Assessment Tool – Enhanced," *International Astronautical Federation*, IAF-99-IAA1.1.01, 1999, 3.

[147] Claybaugh, 28 except as noted. Pegasus, Atlas IIAS, Delta II, and Titan IV: Isakowitz, 1991.

[148] "Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000," Futron Corporation, Bethesda, MD, 6 September 2002, 2-3 except as noted. Titan IV, Isakowitz, 1991, p. 268.

[149] Futron, 2-3 except as noted. Titan IV, Isakowitz, 1991, p. 268 ($154 Million in FY1990 inflated to $203 million in $FY00).

[150] Ted Nicholas and Rita Rossi, "U.S. Space Data Book," Data Search Associates, Fountain Valley, CA, February 1996, page 11-11 except as noted. All values inflated from FY 95 values. Delta II: $3440M; Atlas II: $6991M. Claybaugh, page 27 for Space Shuttle, X-15, X-33, and X-34. Also noted B-777 at $25,000/lb FY2002.

[151] Claybaugh, 29.

[152] Claybaugh, 18.

[153] London, 49.

[154] An F-16CJ Block 50 has the following approximate characteristics: 21,000 lb dry weight, 7,200 lb internal fuel, and a 37,500 lb gross takeoff weight, implying a maximum useful "payload" of 9300 lb.

Notes

[155] The "sonic" trendline is independently verifiable in Air University Air Force 2025 Study, Vol. 2 Ch 5, "Spacelift 2025: The Supporting Pillar," 1996.

[156] Claybaugh, 18.

[157] Based upon previously discussed space shuttle data, the lower labor intensity may be surprising. However, when one considers that the shuttle is a 4.5 million pound vehicle at launch, its lower labor intensity per pound can be mostly attributed to its enormous size (weight).

[158] Claybaugh, 18.

[159] Claybaugh, 26.

[160] Claybaugh, 27.

[161] Claybaugh, 6-31. More sophisticated cost estimating relationships applying linear regression techniques on data sets are commonly used in both government and industry.

[162] Claybaugh, 23.

[163] Claybaugh, 32-33.

[164] Claybaugh, 35.

[165] John C. Mankins, "Lower Costs for Highly Reusable Launch Vehicles," *Aeropsace America*, March 1998, 36-37.

[166] C.M. McCleskey, "Identifying STS Cost and Cycle Time Design Root Causes," SLI Architecture Working Group Meeting, NASA John F. Kennedy Space Center, Florida, 21 August 2002, Package 1, 24.

[167] McCleskey, Package 1, 23.

[168] McCleskey, Package 1, 17. A 7-8 flight per year launch rate between 1996 and 1997 was demonstrated. The orbiter landed at Kennedy Space Center on 26 September 1996. Orbital Processor Facility turnaround occurred between 26 September and 5 December 1996. Vehicle Assembly and Integration began on 5 December 1996 culminating in a 12 January 1997 launch.

[169] McCleskey, Package 1, 12.

[170] London, 1.

[171] G.W. Elverum, Jr., "Boosters" (Transcript of a talk presented at the Aerospace Productivity Conference), The Aerospace Corporation, El Segundo, CA, 1987.

[172] London, 14.

[173] Gonzales, xxii.

Notes

[174] London, 100-101.

[175] HEDM: DARPA has funded HEDM research at AFRL for more than 20 years. AFRL has successfully synthesized the octanitrocubane and the N5+ cation. Octanitrocubane is "hammer" stable and 30% more energetic than HMX. Availability of N5+ cation implies potential synthesis of N8. N8 can potentially be designed into a cubane structure that may offer a very high Isp and high energy density propellant.

[176] James R. Wertz, "Economic Model of Reusable vs. Expendable Launch Vehicles," *International Astronautics Federation Congress*, Rio de Janeiro, Brazil, 2-6 October 2000, 11.

[177] Wertz, "Economic Model of Reusable vs. Expendable Launch Vehicles," 14.

[178] Wertz, "Economic Model of Reusable vs. Expendable Launch Vehicles," 11.

[179] Dennis Bushnell, Chief Scientist, NASA Langley Research Center, private email communication, "Questions on RLVs," 21 November 2002.

[180] Hueter, 2.

[181] Steve Cook, "Next Generation Launch Technology Program," Presentation to the USAF Research Laboratory, Wright-Patterson AFB, Ohio, 18 December 2002, 28.

[182] Cook, 28.

[183] Dennis Bushnell, Chief Scientist, NASA Langley Research Center, email to Dr. Paul Dimotakis, California Institute of Technology, "Revolutionary Rocket Technology," 16 July 2002.

[184] Dennis Bushnell, Chief Scientist, Langley Research Center, email memo with Dr. Ron Sega, Director, OUSD/DDR&E, "NASA Gen 3/Airbreathing to Orbit Evaluation," 20 March 2002.

[185] Bushnell, "NASA Gen 3/Airbreathing to Orbit Evaluation."

[186] "Space Shuttle Main Engine," *Boeing*, n.p., on-line, Internet, 20 January 2003, available from http://www.boeing.com/defense-space/space/propul/SSME.html. The maximum equivalent horsepower developed by the Space Shuttle Main Engine is just over 37 million horsepower, and the energy release from a single engine is equivalent to the output of nearly eight Hoover Dams. Although not much larger than an automobile engine, the SSME high-pressure fuel turbopump generates 100 horsepower for each pound of its weight,

Notes

while an automobile engine generates about one-half horsepower for each pound of its weight.

[187] "RLV Propulsion," Boeing Rocketdyne presentation to Col Gardner, U.S. Air Force Space and Missile Center, 5 April 2002, 41.

[188] "RLV Propulsion," 22-23.

[189] "RLV Propulsion," 13.

[190] Ramon Chase and Ming Tang, "The Quest for Single-Stage-to-Orbit: TAV, NASP, DC-X and X-33 Accomplishments, Deficiencies, and Why The Did Not Fly," 11th AIAA/AAAF International Conference on Space Planes and Hypersonic Systems Technologies, (AIAA-2002-5143), September 2002, 3.

[191] Gonzales, xi.

[192] Gonzales, xxi.

[193] Gonzales, 51.

[194] Gonzales, 22.

[195] Gonzales, xviii.

[196] Cook, 26.

[197] Jack L. Kerrebrock, *Hypersonic Technology for Military Application*, (Washington D.C.: National Academy Press, 1989), 11.

[198] Kerrebrock, 11.

[199] Kerrebrock, 11-12. Note that molecular oxygen and nitrogen dissociate at 2000 and 4000 degrees Fahrenheit respectively. Nitric Oxide (NO) forms at 4000 degrees Fahrenheit, and both oxygen and nitrogen ionize at 9000 degrees Fahrenheit.

[200] Stagnation temperature is the total temperature reached by high velocity air that is slowed to zero velocity (stagnation). The kinetic energy of the flow is being converted into heat, manifesting itself as higher temperatures.

[201] A. Richard Seebass, et al., *Review and Evaluation of the Air Force Hypersonic Technology Program*, (Washington D.C.: National Academy Press, 1998), 6.

[202] Seebass, 1.

[203] The temperature of chemical combustion no longer exceeds the temperature of the combustion medium.

[204] Cook, 29.

Notes

[205] "The Heart of the SR-71 Blackbird, the J-58 Engine," n.p., on-line, Internet, 20 January 2003, available from http://aerostories.free.fr/technique/J58/J58_01/page8.html.

[206] Craig Covault, "Hypersonics Strategy Sets Stage for 'Next Great Step'," *Aviation Week and Space Technology*, 26 March 2001.

[207] Cook, 31-36.

[208] Gray Creech, "X-43 Soars on Scramjet Power," n.p., on-line, Internet, 27 March 2004, available from http://www.nasa.gov/missions/research/x43_soars_feature.html.

[209] Couvalt, "Hypersonics Strategy Sets Stage for 'Next Great Step.'"

[210] Cook, 35.

[211] Cook, 33.

[212] Cook, 33.

[213] Covault, "Hypersonics Strategy Sets Stage for 'Next Great Step.'"

[214] HyTech funding between FY 96 to FY 01 has never exceeded $20 million annually. A. Richard Seebass, et al., *Review and Evaluation of the Air Force Hypersonic Technology Program*, (Washington D.C.: National Academy Press, 1998), 49.

[215] Stanley W. Kandebo, "Landmark Tests Boost Scramjet's Future," *Aviation Week and Space Technology*, 26 March 2001, 58-59. Editor's note: As of January 2004, Pratt & Whitney successfully completed ground testing of GDE-1 had been selected for a follow-on effort that is scheduled to result in flight tests in the 2007-2008 timeframe. See, "Air Force Selects Pratt & Whitney and Boeing Team For the Scramjet Flight Demonstrator Program," on-line, Internet, 14 May 2004, available from http://www.pratt-whitney.com/pr_011304.asp.

[216] Cook, 33.

[217] Within a dual combustion ramjet, supersonic air is ingested into one inlet and slowed to subsonic speeds, mixed with a conventional hydrocarbon fuel in a fuel-rich environment, and ignited as in a ramjet. To break through the ramjet's operating speed limitations, the expanding combustion products are then mixed with supersonic air entering through a second inlet and are more completely burned in a supersonic combustor. The dual combustion ramjet has an operating threshold of Mach 3 and a maximum operating speed of Mach 6.

Notes

[218] Stanley W. Kandebo, "New Powerplant Key to Missile Demonstrator," *Aviation Week and Space Technology,* 2 September 2002, 56-58.

[219] Couvalt, "Hypersonics Strategy Sets Stage for 'Next Great Step.'"

[220] "Hypersonic Waveriders," Summary, 1, n.p., on-line, Internet, 18 Jan 2003, available from http://www.aerospaceweb.org/design/waverider/ main.shtml.

[221] "Hypersonic Waveriders," Examples, 1.

[222] "Hypersonic Waveriders," Summary, 1-2.

[223] "Hypersonic Waveriders," Optimized Waveriders, 2.

[224] "Hypersonic Waveriders," Optimized Waveriders, 5-6.

[225] "Flexible Aerospace System Solution for Transformation," *Boeing*, n.p., on-line, Internet, 8 February 2002, available from http://www.boeing.com/phantom/fasst.html.

[226] Marty K. Bradley, Kevin G. Bowcutt, et.al., "Revolutionary Turbine Accelerator (RTA) Two-Stage-To-Orbit (TSTO) Vehicle Study," *American Institute of Aeronautics and Astronautics*, 38th Joint Propulsion Conference (AIAA-2002-3902), July 2002, 2.

[227] "Flexible Aerospace System Solution for Transformation," 1.

[228] Kevin G. Bowcutt, Mark Gonda, et al., "Performance, Operational and Economic Drivers of Reusable Launch Vehicles," *American Institute of Aeronautics and Astronautics*, 38th Joint Propulsion Conference (AIAA-2002-3901), July 2002, 6.

[229] "Flexible Aerospace System Solution for Transformation," 1.

[230] The 1994 Commercial Space Transportation Study established Mach 4 capability as the threshold for viable worldwide package delivery operation.

[231] Bradley, 9.

[232] "Flexible Aerospace System Solution for Transformation," 1.

[233] Mankins, 37.

[234] Mankins, 39-41.

[235] J. R. Olds, P.X. Bellini, "Argus, a Highly Reusable SSTO Rocket-Based Combined Cycle Launch Vehicle with Maglifter Launch Assist," *American Institute of Aeronautics and Astronautics*, 8th International Space Planes and Hypersonic Systems and Technologies Conference (AIAA-98-1557), April 1998, 3.

Notes

[236] Olds, 4-6.
[237] Olds, 5.
[238] J.A. Moody, A.T. Bahill, et al., *Metrics and Case Studies for Evaluating Engineering Designs*, (New York: Prentice Hall Publishers, 1997).
[239] "2003 Aerospace Source Book," 155-160.
[240] Gonzales, 78-79.