2.0 Launch Vehicle Technologies

2.1 Introduction

The future launch requirements for the Air Force and the nation and the technologies needed to meet these requirements have been studied extensively in the recent past. Virtually every study over the past twenty years has highlighted the need to lower the cost of access to space. Launch costs of existing expendable launch vehicles—most of which in the US are based on designs originally produced as ballistic missiles—are a major factor in space systems affordability and have historically been an inhibiting influence on the nation's approach to exploiting space. Despite the early cost-reduction projections of NASA's "reusable" Space Transportation System (STS), little progress has been made over the past two decades in significantly lowering the cost of access to space. All of the world's existing market economy launchers (from small expendable rockets to the STS) place payloads in low earth orbit (LEO) for between $8,000 and $16,000 per pound. The cost of placing satellites in geostationary orbit (GEO) is even more daunting: approximately $30,000 per pound. The high cost of launch is pervasive in its effect. Within the national security space community, launch costs have contributed to a paradigm that embodies several dilemmas:

- Satellites have tended to become heavier in order to perform their intended function and survive in the harsh space environment for as long as possible.
- Long-lived satellites mean fewer launches, so economies of scale are elusive and satellites become technologically antiquated early in their mission life.
- Big, long-lived, complex satellites are enormously expensive, typically costing $40,000 per pound (or more) to produce.
- The cost of launch failure with such expensive satellites is almost prohibitive, resulting in a strongly risk-averse mentality.
- Existing launch systems all have high reliability (0.92 - 0.99) because reliability and performance have historically had a greater emphasis than cost.
- Until lower cost launchers demonstrate equally high reliability, satellite program offices will not entrust their payloads to new launchers.
- Without sufficient assurance of payload customers, it is difficult to secure the capital required to commercially develop launchers and to demonstrate the needed reliabilities.

These statements describe the strong cause-and-effect relationship between the spacelift function and on-orbit capability. The current environment has an impact not just in the development and operational communities, but in the technology community as well. Technologies that violate this paradigm, but offer other advantages, have not always been well received. Several factors have emerged over the past several years that are prompting changes in the environment:

- Foreign competition, offering lower-cost systems, has captured more than half the free world's annual commercial launch market.

- The US federal budget is under severe pressure to reduce chronic deficits.
- Decision makers realize that exploiting the full potential of space will require less expensive ways of achieving orbit.
- Technologies are emerging that allow much smaller satellites to be produced, while still meeting mission needs.

Over the past ten years, the Air Force has embarked on several attempts to develop a new space launch system, some of them in cooperation with NASA. Each attempt has failed because of a lack of consensus on the requirements, and because the cost of a new launcher development (estimated at $10B or more) was assessed to deliver marginal return, in both cost and performance, over current capabilities. While NASA has historically shared an interest in acquiring affordable access to space to support its programs in space exploration, permanent human presence in earth orbit, and continuous earth observation, NASA has differed from the Air Force on the need for a manned system. NASA's requirement in this area is especially time-sensitive since the Shuttle system will soon be 20 years old, and nearing the end of its 30-year design life (in 2010).

Most government and private sector studies have concluded that even by applying advanced technology, the cost of spacelift using expendable chemical propulsion rocket systems cannot be reduced by more than 50% over current costs. These same launch studies have concluded that only reusable launch systems offer the potential for truly revolutionary reductions in the cost of access to space. However, reusable launch systems also have significant challenges:

- There is widespread skepticism over the technology risk associated with producing a fully reusable single-stage-to-orbit (SSTO) launch system with adequate payload lift capacity. (The risk is not as pronounced with two-stage to orbit systems, although these systems have other disadvantages.)
- Development costs for reusable launch vehicles (RLVs) are relatively high, and the cost risk is assessed to be very high.
- Small shortfalls in the dry weight goals for an RLV system or the specific impulse (I_{sp}) of its engines result in little or no useable payload to orbit.

As a result, both Congress and government agencies have been reluctant to pursue the development of a fully reusable launch system, and have instead focused on programs to better understand cost, risk, and performance factors before committing to a full scale development program. These so-called "X" programs are an essential step enroute to an operational RLV and will be reviewed later in this chapter.

2.2 Background

The Air Force has expended a considerable effort in planning the modernization of its space launch capability. In the past decade, space launch has been one of the most thoroughly studied technology areas within the DoD.

2.2.1 Previous Launch Studies

The years 1992, 1993 and 1994 were marked by several studies on the issue of space launch, with affordability being the prime focus. Most recently, Congress (in the FY 94 Defense Authorization Act) directed DoD to accomplish yet another space launch study. This study, known as the *Moorman Study,* was able to achieve consensus among NASA, the DoD, the intelligence community, and the commercial sector on the preferred direction for space launch. The Moorman Study was the basis for President Clinton's August 1994 Space Transportation Policy, which gives NASA overall responsibility for reusable launch vehicles and the Air Force the lead for expendable launch vehicles. Importantly, on the topic of spacelift technology funding, the Moorman Study found that the current DoD enabling core technology program for spacelift is "significantly underfunded and lacks long term commitment and stability." The study recommended that the spacelift core technology program within DoD be increased from its current level (approximately $45M per year) to $120M per year by FY 96. A summary of the core technologies with the associated funding profile is presented in Figure 2-1. Note that the figure shows significant unfunded requirements in the outyears.

	Propulsion	**Vehicle**	**Operations**
Expendable Unique	Low Cost Engine Storable Propellants Storable Propellants Clean Solid Propellants Hybrid Propulsion	Low Cost Booster	
Common	Upper Stage- Propulsion Russian Engine Test Simple Pumps Chamber/lnjectors Test Beds High Energy Fuels	Adaptive GN&C AI/LI Structures Composites Low Cost Mfg Man Tech	Automated Processes Heath management Non Destructive Inspection Leek Free Joints Fault isolation
Reusable Unique	Linear Aerospike Advanced Propulsion Preburner Turbopumps Tripropellants	Primary Structure Insulation Reliable Sensors CryoTanks Aerothermo	Recovery/Refurbishment

Total FYDP Unfunded Core Technology Investment $384M (CY94$)

94	**95**	**96**	**97**	**98**	**99**
$0M	**$45M**	**$89M**	**$86M**	**$83M**	**$81M**

Figure 2-1. Air Force funding for core spacelift technologies

2.2.2 Requirements and Air Force Planning

In 1992, the Air Force implemented a 25-year modernization planning process known as Mission Area Planning (MAP) to help guide planning, technology, and associated investment decisions. Air Force Space Command developed the following five top-level tasks for its Space Launch MAP:

- *Launch satellites in accordance with the national mission model*
- Operate the launch and range facilities
- *Perform transpace operations*
- *Recover space assets*
- Identify the launch requirements of the other sectors (commercial, civil, intelligence)

The highlighted tasks have significant technology implications. The results of the Mission Needs Analysis for these spacelift tasks identified deficiencies in the following areas:

- Affordability (the most pervasive deficiency)
- Schedule dependability (i.e., responsiveness, supportablity, and maintainablity)
- Launch rate and reliability
- Object recovery and return

2.2.3 Current Investment in Spacelift Technology

The current and planned US technology funding for spacelift consists of the following:

- Approximately $100M in FY 95, including $65M of Congressionally added funds not requested by the Administration
- Annual programmed funding of approximately $40-45M per year for FY 96-01
- NASA spacelift technology investment of approximately $70M per year 96-01
- NASA X-33 and X-34 program funding of approximately $800-900M for FY 97-00

A major portion of the Air Force effort falls under the Evolved Expendable Launch Vehicle (EELV) program. The EELV program will acquire a single family of expendable vehicles to launch the national mission model in the medium launch vehicle (MLV) and heavy launch vehicle (HLV) classes, which are currently serviced by Titan II, Delta, Atlas, and Titan IV. The commercial sector is likely to take the lead in small (less than 4500 lbs to LEO) launch vehicles in the near future. The Air Force can adapt the technologies that are developed commercially in this area and concentrate its technology investments in developing heavier-lift vehicles. EELV's objective is to reduce costs, maintain mission assurance, and improve reliability and operability within program cost constraints. First launch of the MLV class of EELV is set for 2001, with first launch of the HLV version planned for 2005. EELV is aimed at a 20-50% reduction in spacelift costs, with smaller improvements in responsiveness and reliability.

The major US RLV projects at this time are NASA's X-33 and X-34 programs. The X-33 is a sub-scale advanced technology demonstrator designed to support commercial and government decisions in 1996 and later regarding reusable launch vehicles, with the objective of leapfrogging future competition for space launch. The X-33 technologies are currently under development by Lockheed Martin, McDonnell Douglas Aerospace, and Rockwell International Corporation. The X-34, which is planned to fly in 1998, is a cooperative effort between NASA and Orbital Sciences Corporation for a smaller advanced launcher. The X-34 is intended to demonstrate technologies applicable to future reusable launch systems and to stimulate industry/government funded development of a reusable small launch vehicle with commercial applications.

2.3 Air Force Requirements for Launch Vehicles

Although expendable launch vehicles do not harbor the possibility of revolutionary (order-of-magnitude) reduction in the cost of access to space, they will be the likely mode for Air Force spacelift in the near term. A revolutionary reduction in launch costs (required to enable advanced missions) will, however, require investment in reusable launch vehicle technologies. The current work in progress at the component and system levels in both the EELV and NASA X-33 and X-34 programs will figure prominently in the development of new advanced launch concepts using chemical propulsion systems. However, it is unlikely that Air Force and NASA objectives for RLVs will be completely congruent. In particular, the Air Force has needs for rapid reaction and rapid turnaround (akin to aircraft operations) that will have no NASA counterpart in the foreseeable future.

The Air Force has also been interested in so-called transatmospheric vehicles (TAVs) that could augment generic RLVs. Military RLVs and TAVs are intended to be *operated and maintained like Air Combat Command aircraft*. The military needs a rapid-reaction (launch within a few hours of a decision), quick-turnaround (sortie-like operations), low-cost vehicle with minimal requirements for unique space launch ground infrastructure. It should be a space vehicle with operations costs and operability characteristics more akin to aircraft than today's spacelift systems. In most concepts, it has relatively small payload to orbit; it derives its utility not from simply space transportation, but, particularly for TAVs, as a multi-mission platform for such applications as quick-reaction reconnaissance, on-orbit inspection of friendly and potentially hostile satellites, and perhaps weapons delivery.

While existing national policy gives NASA the lead in developing RLV concepts and technology, it also provides for continued Air Force/NASA cooperation and collaboration. When applied to technology development, this division of responsibility is somewhat blurry because many of the reusable and expendable launch vehicle goals are similar (e.g., lower cost, simpler operations, high reliability). In particular, the USAF brings core competencies in operations, testing, and support activities from its aircraft operations legacy that are directly applicable to RLVs. A number of Air Force-led technology programs aimed at expendable launch vehicles directly support NASA's reusable launch vehicle program as well. The Air Force should participate in the X-33 program to provide technical support and to provide input for future vehicle development decisions. A sustained launch technology program will be necessary to make RLV/TAV systems a reality. The Air Force should continue developing and demonstrating technologies that fall into the following areas:

- Rocket propulsion

- Vehicle structures
- Launch processing and operations

2.4 Rocket Propulsion

Rocket propulsion capability is the most important technology necessary to enable many of the RLV applications envisioned for the future. Small increases in rocket engine specific impulse (I_{sp}), for example, translate into much more capable launch systems. Advanced lightweight, high-thrust-to-weight propulsion will only be achieved, however, through a combination of technology initiatives.

2.4.1 The State of the Art in Rocket Propulsion

Russian rocket engines represent the current state of the art in rocket propulsion. Russian rocket propulsion technology is advanced compared to US systems, particularly with respect to liquid oxygen/hydrocarbon engine development, tri-propellant engines, and operations. In particular, Russian engines are very robust, routinely use staged combustion cycles, and operate at higher chamber pressure than their US counterparts. Russian engines are being considered for use in several of the competing designs for EELV. The Space Shuttle Main Engine (which was the last large rocket engine developed in the US) is the only US staged-combustion-cycle engine, and it suffers from high manufacturing cost, lower than desired thrust-to-weight, and a lack of necessary robustness for RLV applications.

2.4.2 Technologies for Evolutionary Change in Rocket Propulsion

The Integrated High-Payoff Rocket Propulsion Technology (IHPRPT) effort is a national (government/industry) strategic planning process (patterned after a similar long-standing aircraft propulsion program) with the goal of improving rocket engine against several specific metrics. IHPRPT will be performed in three phases with specific goals for each phase, as shown in Table 2-1. These goals were chosen to be challenging but achievable to encourage the development of new technology. The goals will be demonstrated to full scale in integrated demonstrators at the end of each phase. For an example, the Integrated Power Demonstrator will demonstrate simplified, high reliability low-cost turbomachinery and thrust chamber component technology in an integrated engine demonstration at the 250,000 lb thrust level. The Upperstage Engine Demonstrator program will demonstrate a 50,000 lb thrust liquid oxygen/liquid hydrogen (LOX/LH_2) upperstage engine technology for use on the upgrades of the EELV and the next generation launch vehicles. Industry will thus be able to insert the technologies promptly and realize a return on investments before the end of the 15 year program.

Although the cost goals show a reduction in hardware and support costs of only 35% by 2010, the impact of achieving all of the goals simultaneously will provide the technology to reduce the cost to orbit by 80% of what today's technology can provide. The additional cost benefits are obtained from substantial payload increases (gained from I_{sp} and engine thrust-to-weight improvements) and reduced costs of failure.

The IHPRPT program is jointly run by both the government (DoD and NASA) and industry (both liquid and solid propulsion houses) with all participants fully endorsing the program goals. Government-sponsored and industry-IR&D-funded efforts are fully coordinated in the area of rocket propulsion. With coordination from all groups, the IHPRPT process will naturally eliminate duplication of effort and insure the maximum return on investment of research and development funding. The program goals in rocket propulsion are technically feasible but are constrained by funding, which is currently a very limited. Increased, sustained funding will be needed to achieve these goals.

Table 2-1 Goals of the IHPRPT program

BOOST & ORBIT TRANSFER	2000	2005	2010
Reduce Stage Failure Rate	25%	50%	76%
Improve I_{sp} (sec)	14	21	26
Reduce Hardware and Support Costs	15%	25%	35%
Improve Thrust to Weight	30%	60%	100%
SPACECRAFT	**2000**	**2005**	**2010**
Improve Mass Fraction	15%	25%	35%
Improve I_{sp} (sec)	10%	15%	20%

Upper stage engines, used for transfers from LEO to higher orbits, benefit from many of the same technological advancements as booster engines. For upper stage applications, however, additional technologies are feasible. The Air Force is currently funding research in solar-thermal propulsion. The I_{sp} range for this type of engine is between 800 and 1200 seconds depending on the parameters of the particular design. Thrust is approximately 9 Newtons. Concentrated (10,000 suns equivalent) solar energy comes from two 7 meter x 9 meter off-axis paraboloidal thin film concentrators. Trip time from LEO to GEO ranges from 10 to 60 days depending on the thrust, payload, thruster type, and concentrator.

2.4.3 Technologies for Revolutionary Change in Rocket Propulsion

The highest-leverage technology area impacting launch vehicles is the development of high-energy-density materials (HEDM) for use as propellants, which offer the promise of significantly reducing both booster and upper stage weight and hence lowering launch costs per pound of payload delivered. While the existing USAF program of this name is oriented primarily towards rather modest near term improvements in I_{sp}, (in the range of 7-20 seconds), much more effort should be devoted to revolutionary advances in this field. If I_{sp} could be increased from today’s limit of about 450 seconds to nearer the theoretical limit of 1500 seconds, payload mass fractions would increase (all other things being equal) by a factor of approximately four to six. While it is still not clear how this might be done with propellants capable of being contained in a reasonable structure, such an achievement would fundamentally change the nature of spacelift.

HEDM is already examining one advanced concept to use metals as fuel additives. Metal atoms or small molecules stored in liquid hydrogen, for example, could yield I_{sp} gains of 50 or 100 seconds, resulting in a 25% increase in performance in a system such as the STS. The long-term goal for energetic propellants should be an I_{sp} increase of much greater than 100 seconds. Material systems such as metallic hydrogen would produce such increases in I_{sp}. The use of computational chemistry techniques to enable the design of even more energetic propellants needs to receive increased emphasis, because such technologies could enable missions thought to be impossible by today's standards. The potential benefit of HEDM technology justifies a significant investment by the Air Force.

Another high leverage technology area within launch concerns materials that could withstand extremely high heat loadings (such as those generated in rocket engines) without failing. Engine specific impulse (which scales as the square root of the maximum temperature allowed in the combustion chamber) and thus engine thrust-to-weight ratios could dramatically increase if materials that could withstand extremely high heat loadings were available. Besides increasing maximum specific impulse, these materials would enable critical portions of the engine to be operated without the added complexity and mass of an active cooling system. Such dramatic improvements may enable such revolutionary concepts as the scramjet engine to become a reality; a scramjet would have the distinct advantage of taking its oxidizer from the atmosphere rather than carrying it along and hence could allow more of the vehicle mass to be devoted to payload. The potential benefits of the development of such materials justify substantial sustained development.

2.5 Vehicle Structures

Dry structural weight of an RLV comprises a significant portion of the vehicle mass fraction (propellant mass divided by total vehicle mass) and must be minimized if RLVs are to become a reality.

2.5.1 The State of the Art in Vehicle Structures

Today's vehicle structures are primarily aluminum, with some use of composites. All current vehicles capable of placing a payload in orbit consist of multiple stages. Based on the current level of technology, with the specific impulses available in today's engines, a single-stage-to-orbit vehicle is not capable of achieving positive payload to LEO. Advanced compounds like aluminum-lithium (Al/Li) would offer substantial weight savings, but are not yet widely available.

2.5.2 Technologies for Evolutionary Change in Vehicle Structures

The NASA report on the Access to Space study concluded that advances in technology areas such as composite cryogenic tanks and thermal protection systems are critical to making a fully reusable launch vehicle feasible. Ongoing cryogenic tank efforts address metal-lined tanks (relying on the liner to contain the propellant) because, to date, all unlined tanks have leaked at the penetrations and at the composite laminates. A new program, looking at unlined tanks, is planned to begin in FY 95, with the goal of decreasing tank cost and weight. Research is being done to find new composite structural materials that are impact-resistant and resist cracks and delaminations when exposed to extreme and cyclic conditions. Payoffs to the Air Force include reduced cost of manufacturing fuel tanks that are light and reliable while increasing the load carrying capabilities and reducing life cycle costs. Composite structures and tankage offer a potential of replacing traditional metallic launch vehicle structures due to their high strength-to weight ratio, flexibility in design, custom tailoring of desired properties, and the ability to exist in different environments. According to one study, the use of composite materials could reduce tooling, part count, manufacturing lead time, cost, and structural weight by as much as 40%. The Air Force should continue to invest in concepts to reduce vehicle dry mass while maintaining the required structural stiffness, integrity, and robustness to enable low life cycle cost.

Similarly, considerable effort is being focused in the area of thermal protection systems. The rigid tiles currently used on the Shuttle require extensive, expensive, manual inspection and maintenance after each flight. Current programs are pursuing more damage-resistant, less brittle, lighter-weight tile concepts. Further efforts are planned to look at better approaches for attaching thermal protection systems to the vehicle structure, or even to the propellant tanks themselves, to further reduce weight, reduce cost and increase reliability.

2.5.3 Technologies for Revolutionary Change in Vehicle Structures

In addition to the need in rocket engines, high temperature materials that do not require active cooling are a vital area of technology investment for advanced thermal protection systems. Such materials will be essential for military TAV's and RLVs. Advanced thermal protection systems will become particularly important if air-breathing (e.g., Scramjet) propulsion concepts are used for a large portion of the TAV flight profile within the atmosphere. For advanced vehicle concepts, material systems capable of 4000K on one surface and cryogenic temperatures of 4K on the other side will be required for use in engines and structures.

Vehicles may be designed with the cryogenic tanks integrated for vehicle load structure, such as wing elements, while still requiring a thermal protection surface. For RLV's, the high temperature materials used for the thermal protection system will also have a requirement to be operable and more importantly, field-repairable. Integrated structures combining reusable cryogenic storage with a thermal protection system would reduce the overall dry weight of the vehicle. In addition, the integrated structure would include self-diagnosing sensors, enabling the vehicle to report on its condition, a critical capability if short turnaround time is to be achieved. Thus lightweight integrated structures combining reusable cryogenic storage, thermal protection, and self diagnostics to enable a *responsive* reusable launch capability are revolutionary technologies in which the Air Force must make a sustained investment.

2.6 Launch Vehicle Processing and Operations

Advances in launch vehicle operations are as critical as the design of the vehicle itself to ensuring the responsiveness necessary for Air Force spacelift in the 21st century.

2.6.1 The State of the Art in Launch Vehicle Processing and Operations

Today's US launch systems are widely criticized as being non-responsive in terms of the time it takes from a decision that a launch is needed to the actual launch. Many factors are responsible for the current situation, including management philosophies, but the response time for the current systems varies from approximately 30 days to more than 270 days. Today's process includes substantial amounts of on-pad integration, checkout, test, and verification that is personnel-intensive and thus contributes to the high cost of launch. The US launch infrastructure, concentrated for the most part in its two coastal launch locations at Cape Canaveral AFS and Vandenberg AFB, is also not conducive to rapid pad turnaround and relaunch.

2.6.2 Technologies for Evolutionary Change in Launch Vehicle Processing and Operations

The EELV/RLV will incorporate improvements in launch processing and operations to reduce costs. The improvements will come from design changes and incorporation of technologies that have been under development, but have not yet been utilized in US launch vehicles. Design changes will allow more of the processing and checkout operations to be accomplished off-pad, resulting in more efficient utilization of the launch facility. Improvements in propellant handling and loading, as well as improvements in the availability and reliability of downrange systems for safety and tracking are currently being realized as systems are being automated and generally modernized. In addition, integrated health monitoring technologies will expedite the verification and checkout of the vehicle and pad systems. Some of these improvements may come from incorporation of Russian automated launch operations techniques. Finally, X-33 and X-34 demonstrations will serve as an "operations laboratory" that will allow the Air Force and NASA to learn how to operate rockets and space hardware with manpower, maintenance, and support characteristics akin to conventional aircraft. The Air Force should closely monitor improvements in launch vehicle operations that are driven by the commercial sector. A number of commercial interests are proposing constellations of many tens to hundreds of satellites for global communications systems. For these systems to be commercially viable, the cost of access to space must be reduced. The commercial sector has aggressively pursued efficiencies in operating satellites and is likely to do the same when launching them.

2.7 Recommendations for Investments in Launch Vehicle Technologies

The Air Force should follow a carefully targeted plan of investments in launch vehicle technologies, investing for both revolutionary and evolutionary improvements in launch vehicle systems.

2.7.1 Revolutionary Launch Vehicle Technologies in Which the Air Force Must Invest

Several key launch vehicle technologies offer the possibility of a substantial increase in the exploitation of space by the Air Force, the potential impact of which is so great that the Air Force must invest now. These technologies are:

- High energy density chemical propellants to enable spacelift with high payload mass fractions; specific impulses of 1000 seconds or greater (in high-thrust systems) should be the goal of this effort
- Lightweight integrated structures combining reusable cryogenic storage, thermal protection, and self diagnostics to enable a *responsive* reusable launch capability
- High temperature materials for engines and rugged thermal protection systems

2.7.2 Evolutionary Launch Vehicle Technologies in Which the Air Force Should Invest

The Air Force should invest for evolutionary improvements in performance or reduced life-cycle costs to its systems. The technologies that offer such benefits in the area of launch vehicles are:

- Engine technologies (e.g., turbomachinery)
- Upper stages (Alternate propulsion concepts will be addressed in the payloads chapter of this report.)
- Lightweight vehicle structures (e.g., aluminum-lithium (Al/Li) or advanced composite tankage)

2.7.3 Commercially Led Launch Vehicle Technologies

Another set of technologies that will allow for evolutionary change in launch vehicle technologies will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should invest as necessary to adapt these technologies to its needs. These technologies are:

- Small launch vehicles (less than 4500 lbs to low earth orbit)
- Technologies for vehicle operations

Finally, the Air Force should reexamine the overall level of funding devoted to spacelift technology. While spacelift investment should be fully coordinated and integrated with the long term technology program within NASA and industry for the next generation RLV, it is important to realize that that some launch requirements are unique to the DoD. With the exception of the Space Shuttle work in the 1970s and the some SDIO technology spending in the late 1980s, launch vehicle technology funding (and associated laboratory manpower) within the Air Force has been on a relatively steady decline since the early 1960s. This trend must be reversed if the Air Force is serious about space control and exploitation as core missions. The current relative level of technology funding is inconsistent with Air Force aspirations to develop space as one of its core competencies.