Conflicting Heuristics for Low-Cost Launch Vehicle Architectures

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Abstract

Architects for low-cost launch systems use different and often conflicting heuristics when making architecture decisions. The primary decisions involve funding sources, reusability, prototyping, manned systems, staging, propellant choice, take-off and landing modes, and engine development. Heuristics are described for each choice. Case studies of recent launch vehicle developments are described with the heuristics chosen for each.

Introduction

One of the most challenging subjects in space systems engineering is the design of low-cost launch vehicles. Currently placing a satellite in orbit costs thousands of dollars per pound. Satellite designers are driven to extraordinary measures to find ways to shave ounces off the weight of their systems. Once satellites are in orbit, it is normally impossible to perform any refueling, maintenance, or repairs, so they must be engineered for many years of continuous operation. Those factors make satellites so expensive that they are produced in small lots, eliminating economies of scale. The holy grail of launch vehicle designers is to make access to space so cheap that satellite designers could design for minimum cost instead of minimum weight, and that repair missions would become practical and routine. Many analysts predict that once costs were dramatically reduced new uses for space would become practical, expanding the market for the low-cost launch vehicles.[1]

A broad variety of architectures have been proposed for low cost launch vehicles. Some concepts have been advocated for decades, some are only a few years old. Investors have poured millions of dollars into systems with diametrically opposite technical approaches. Architects may find that their approaches are constrained by the wishes of their investors, government policy, or the changes in market predictions.

Launch system architects do work with a set of heuristics, but any two architects rarely have the same set. Most of the heuristics described by Rechtin[2] apply to these architectures as much as any other complex system, but the mission-specific heuristics are not yet fully defined. Different factions of the community have heuristics that they advocate, sometimes to the point of religious terminology being introduced to describe their beliefs. Detailed technical analyses are performed to show the merits of one heuristic over the other, but usually depend on assumptions that have not yet been tested in the real world—the response of the market to price cuts, the practicality of untested technologies, the proper trade-off between affordability and reliability. Architects working to the same set of heuristics will produce similar designs, but the number of decisions to be made are large enough that any two systems being developed will be noticeably different.

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[1] London, 1994, Ch. 8, Gaubatz, 1995.

[2] Rechtin, 1991.

This survey will look at the top-level heuristics that are contested in the launch vehicle community. Similar disputes occur on lower level issues (series vs. parallel staging, for example) but the are outside the scope of this paper. Other writers have discussed the issues covered here but focused their discussion on their preferred architecture[3]. This is not a complete list but should provide a starting point for understanding launch vehicle architectures and contemplating future architectures.

Any architect intending to provide a dramatic improvement in cost over existing systems must have some innovation to base the design on, either a new technology or a novel way of using existing components. Both suffer the hazards of systems that may encounter unexpected behavior when operating with unproven components or in an unknown environment. Attempted system developments to date have used aerospike engines, rocket-powered vertical landings, supersonic combustion engines, and aerial propellant transfer. Proposals without development funding have included "biamese" vehicles with identical parallel stages, using ground-based lasers to heat reaction mass on board the booster, and magnetic catapults for initial velocity boost. All of these have attractive performance benefits if they can be made to work. X-vehicles (pure technology demonstrators) have been built to demonstrate the practicality of some of these options, such as the DCX showing successful rocket-powered landings. While an X-vehicle can show the technical feasibility of an option, it can not settle the performance trade-offs for using, and most innovative ideas are only usable for specific types of architectures. Partisans of each concept have developed analyses and heuristics to show their benefits but this level of detail is outside the scope of this paper.

This analysis also excludes new boosters that only aim for modest (10% - 50%) reductions in launch costs. New systems such as Sea Launch, EELV, and Delta 3, and Athena have been developed but use the same architectures, and sometimes the same vehicles or engines, as the previous generation of boosters. They do not illustrate the heuristics under discussion here as they are focused on minimal investment to provide savings rather than maximizing savings through innovation.

Conflicting Heuristics

Decision 1: Government or Commercial Funding

The biggest factor affecting an architect's decisions is the nature of the system's sponsor and the expected mission or market model (i.e., how many launches the system can sell). Government-funded programs usually have significant constraints placed on their architecture by the sponsoring agency (NASA often has specific technology research to be incorporated, military agencies are focused on the launch needs of specific programs). Commercial funding requires convincing investors that the project will have acceptable risk (which constrains technology) and a financial return great enough to justify that risk

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[3] Kaplan, 1998. London, 1994, Ch. 6.

(i.e., large market capture).

Projecting the market for satellite launches is difficult. Many more satellites are proposed than flown, and even high priority government programs are subject to delay or cancellation due to technical problems or Congressional whim. Commercial geostationary communications satellites have been the most stable portion of the market, but even that segment has had fluctuations in response to the economic crisis in Asia and other events. A historical curve is relatively flat, and there is little hard evidence to support projections for major increases. In that environment there is minimal incentive for commercial investors to place their bets on anything more aggressive than an upgrade of existing ELVs (such as Delta 3 or Sea Launch).[4]
Heuristic 1a: **In a Stable Launch Market Only the Government Can Fund Brand-New Launch Systems.**

Many new launch systems pin their hopes on new markets. The LEO commsat constellations were projected to be a large enough market to justify new system developments, but the failure of Iridium and its competitors has ruined the hopes of the companies founded to pursue this market. Other markets requiring launches into orbit have been projected—tourism, manufacturing facilities, power generation—but are so impractical under current costs that not even test projects can be done to find out the launch cost at which they would become profitable.[5] Advocates of those markets are confident that a dramatic lowering of launch costs would allow new markets to come into existence, but can’t prove that the new markets would be large enough to make up for the loss of revenue from the old ones, or that the markets would grow fast enough to prevent the bankruptcy of the company which made the cost breakthrough.
Heuristic 1b: **A Dramatic Lowering of Launch Costs will Make New Markets Viable, and Commercial Investors will Support that Leap.**

Decision 2: Expendable vs. Reusable Vehicles

The reusability decision is one of the earliest to be made in the process. Components will have to be either high-reliability, long-life, or low-cost one-use. Making the system reusable will require additional subsystems for reentry, components designed for long life under stressful conditions, and high margins to ensure the reliability of the system. An acceptable failure for an expendable system could destroy the viability of a reusable one.

A reusable launch vehicle (RLV) requires a high number of flights to justify the high costs of developing sturdy, reliable components. If it is commercially funded, the flights must come early enough in the program history to provide a high rate of return to investors (revenue earned more than 7-10 years after investment has little impact on the rate of return).[6] A RLV ideally has its cost per flight dominated by the marginal operations costs (i.e., the cost of material and activities needed to add one more flight to

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[4] Asker, 1994.
[5] Gaubatz, 1995.
[6] Stine, 1996, Ch. 21.

the schedule). This requires a very high flight rate—Pioneer's Pathfinder forecast a 350-flight mission and still found the cost per flight was dominated by development costs. For an ideal RLV an additional launch can be added to the flight schedule for only the cost of propellants and perhaps some crew overtime. This gives RLVs must more capacity to respond to an expansion of the launch market.
Heuristic 2a: **RLVs have a Lower Cost for Additional Launches**

One of the advantages of RLVs is that higher reliability can be achieved through investment in higher-quality design and test flights of hardware. Many flaws in an ELV can only be detected by launching, with the consequent loss of vehicle and payload if it fails. An RLV built for safe aborts when problems occur can have such flaws found and corrected before a payload is placed on board.[7]
Heuristic 2b: **Achieving High Reliability Requires a Reusable Vehicle (Sturdy, Reliable Components and Flight History on Vehicle).**

The alternate approach to achieving high reliability is to have extensive inspection of all components before launch—this is currently used for the Shuttle and many ELVs, but drives launch costs and delays.[8]
Heuristic 2c: **Reliability Comes From Thorough Inspection**

Expendable launch vehicles (ELVs) have the majority of their costs in the manufacturing and operation of the vehicle. The development costs are much lower as there is much less need for detailed analysis, reliable components, or extensive testing of the initial product. The flight rate is limited by the capacity of the production line and operations crews. Adding flights to the mission model after a certain point requires adding additional factories, launch pads, and trained personnel, which cannot be done quickly. Up to that limit the marginal cost of another launch is equal to the nominal cost, above it the marginal cost has to cover the cost of all the additional infrastructure.[9] A vehicle can be made reusable and still not be lower-cost. The Space Shuttle incurs massive costs per flight, mostly in post-flight refurbishment, and has a very limited flight rate (less than monthly).
Heuristic 2d: **Expendable Vehicles have Lower Up-Front Costs.**

A multi-stage vehicle can compromise on this decision by making one stage (usually the first) reusable while having an expendable upper stage. This is common to many reusable launch vehicle designs as sending a payload beyond low Earth orbit requires an additional stage. RLVs that can't make orbit by themselves will cover this failing by adding an expendable stage to provide the necessary extra performance. This can be used as a stepping stone design between an unaffordable high-performance RLV and an ELV with limited potential for further improvements.

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[7] Stine, 1996, Ch. 26.
[8] London, 1994, Ch. 4.
[9] Sackheim and Dergarabedian, 1995, Wertz, 2000.

Decision 3: Develop Operational Vehicle Immediately or Prototypes/X-Vehicles First.

Up to the X-33 program all NASA launch vehicle efforts were aimed directly at the development of an operational system. NASA has a strong bias toward immediate development of the operational vehicle. The Apollo program schedule did not allow for another design/build/test cycle before the planned Moon landing so the Saturn and Apollo vehicles were developed and tested in their operational form, with full success. The Space Shuttle also has been operationally successful with its single design iteration.
Heuristic 3a: **Don't Waste Money Building Vehicles that Can't Do the Mission**

Other groups tend to favor prototypes or X-vehicles when a significant change in technology or operations is being introduced. The most dramatic example is Rotary Rocket's plan for four no-payload X-vehicles to precede their operational Roton (each testing a different innovation—rotor landing, composite structure, thermal protection system, and rotary engine).[10] The SDIO SSTO program planned on two X-vehicles prior to its operational one, the suborbital reusability demonstrator and a zero-payload SSTO capability demonstrator.[11] For systems with smaller technology jumps a subsystem demonstration may fill the need. Pioneer Rocketplane planned this type of demonstration for their aerial LOX tanking.
Heuristic 3b: **Building a Test Vehicle and Then Designing a Good Operational Vehicle is Cheaper than Designing a Bad Operational Vehicle.**

To be useful, a demonstration, prototype, or X-vehicle must be tested early enough that the data can be applied to the design of the next vehicle. If it is delayed past that point there's no useful benefit to be gained as the new vehicle is already being fabricated with the design margins needed to cover the unknowns. The LASRE aerospike flight demonstration was cancelled when it slipped past the CDR for the X-33 vehicle.

Decision 4: Manned or Unmanned system.

A manned system requires additional mass, volume, and power to provide life-support to the people on board, on top of the mass of the crew itself.[12] Every pound of those systems is a pound taken away from the payload capacity of the booster. Even for systems that have personnel transport as part of their mission (Space Station support, tourism) a permanent operator position detracts from the performance when doing cargo-only missions—the VentureStar has the capability for control from the personnel pod but can also operate unmanned.
Heuristic 4a: **People On Board Reduce Performance.**

For cargo systems the decision depends on whether a crew is needed to provide essential control functions or redundancy to automated or remote controls. Some agencies

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[10] Hudson, 1998.
[11] Stine, 1996, Ch. 9.
[12] London, 1994, Ch. 6.

(NASA, USAF) have a preference for manned systems because of the background of key decision makers as astronauts or fighter pilots (commercial entities are not immune to this). Commercial systems facing the need to gain FAA licensing have also been driven toward crew-controlled systems as the FAA has significant doubts about the maximum reliability of automated systems. Systems relying on aerial tanking or helicopter autorotation landings are designed with pilots as automated systems are not up to doing those tasks reliably.[13]
Heuristic 4b: **People Can Do Things Computers Can't (Including Keeping the FAA Happy).**

Decision 5: Number of Stages

Reaching orbit with a single vehicle that drops no components on the way is an unsolved problem. Numerous solutions have been proposed but none successfully implemented. A single-stage-to-orbit (SSTO) vehicle would be able to operate more cheaply by avoiding the time and manpower required for mating large, complex structures. This is most attractive to architects designing for a high-flight-rate system. Development costs may also be lower for an SSTO than a two-stage system as costs tend to scale more with parts count than the dry weight of the system. For RLVs the SSTO capability could be a benefit if can be done affordably. A high flight rate vehicle needs to spend a minimal amount of time being turned around between flights which is much easier with a aircraft-style preflight and refueling than if the vehicle needs to be physically integrated with another of comparable size.[14]
Heuristic 5a: **SSTO Reduces Cost and Turn-Around Time**

The downside of SSTO is that the performance needed may not be technically achievable or affordable if possible. A multi-stage system (normally only 2 or 3 stages) would have much higher design margins for the same level of technology. This would reduce the development and manufacturing costs for the system significantly. Since those costs dominate for expendable vehicles all ELVs have been multiple-stage.
Heuristic 5b: **Staging Reduces Performance Requirements**

New technologies have been advocated to provide SSTO capabilities—scramjets, slush hydrogen, tripropellant engines, etc.—but are generally far enough from deployment that basing an architecture on them means creating a research and development program rather than constructing a vehicle. This matches the interests of some sponsors such as NASA's Marshal and Langley Centers.[15]
Heuristic 5c: **SSTO Requires New Technology Development**

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[13] Sarigul-Klijn, et al, 1999.
[14] Stine, 1996, Ch. 4.
[15] London, 1994, Ch. 3.

Decision 6: Propellant Choice

The choice of propellants for a system, while on the surface easily decided by technical issues, can become noticeably emotional. The author triggered a ten-minute rant from the head of TRW's propulsion center by inquiring of the merits of hydrogen peroxide, while a start-up company was building hardware using it only 100 miles away. A large variety of materials have been investigated as candidates for rocket engine propellants[16] but only a few combinations are actively considered for new developments:

Liquid Oxygen (LOX) and Liquid Hydrogen (LH)
LOX and Kerosene
Hydrogen Peroxide (HP) and Kerosene
Solid Propellants

LOX/LH has the highest specific impulse of any combination and thus allows the highest mass fraction in a vehicle with a given performance, but has a number of penalties. Hydrogen's low density forces the vehicle to have very large fuel tanks with resulting increases in structural mass and atmospheric drag. Keeping hydrogen liquid requires low temperatures which severely limit the materials that can be chosen and the lifetime of components. Cooling systems can add more weight penalty to the vehicle.[17]
Heuristic 6a: **Hydrogen provides the highest performance.**

Hydrogen Peroxide and Kerosene have a lower specific impulse than the other liquid propellants discussed here but make up for it with the highest density. This allows the vehicle to have smaller fuel tanks and therefore a lighter structure. The reduced vehicle size can also reduce losses due to drag, which is significant for horizontal take-off designs.[18] HP has an operational advantage over LOX and other oxidizers by being non-cryogenic. Not only are cryogens difficult and hazardous to handle, but water vapor freezing onto LOX valves has caused several launch failures. Pure peroxide avoids the cryogen hazards but has its own difficulties, as it will energetically decompose in the presence of many substances (including wool and other types of clothing). Only limited work had been done with peroxide before the mid-1990s, so almost no experienced personnel were available to support new developments using it. Peroxide is superior to solids and other non-cryogenic propellants such as hydrazine/tetroxide by being non-toxic and environmentally friendly. Peroxide is being using in an Orbital Sciences Corp. upper stage development as well as in the NASA/Boeing X-37 test vehicle.
Heuristic 6b: **Dense propellants improve mass fraction.**

The default propellant combination for most launch vehicle designers has been LOX and kerosene (RP-1). Cheap, denser than hydrogen, and widely used, it's a combination that will work. It has the greatest selection of engines available using it (particularly Russian designs, which are superior to American LOX/kerosene engines). The availability of off the shelf engines and experienced personnel can be more attractive than the relative specific impulse or density benefits for the vehicle technical design.

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[16] Clark, 1971.
[17] Clark, 1971.
[18] Burnside Clapp, 1994

Heuristic 6c: **LOX/kerosene has good performance and is easier to use.**

The cheapest development option for any system is to use solid motors and avoid the costs of liquid-fuel engines. This has been selected for most of the recent ELV developments (Pegasus, Taurus, Athena) but no RLV design has solid motors. Solids are difficult to scale up for large systems and each new motor can only be used once, which makes it impossible to detect flaws with test firings or flights. Cracks or other flaws can cause the motor to explode or produce excessive thrust, and as the motor cannot be shut down in flight this would destroy the entire vehicle.[19]
Heuristic 6d: **Solids are lowest cost.**

Decision 7: Take-Off and Landing Modes

A vehicle's take-off and landing modes define its physical layout. Landing modes are only an issue for RLVs and all ELVs (except Pegasus) use vertical take-off, so this discussion will focus on RLV impacts. The only practical combinations are vehicles that take off and land vertically (VTVL), do so horizontally (HTHL), or take off vertically and then land horizontally as the Space Shuttle does (VTHL). The drivers of the decision are:

1. The performance impact in terms of the vehicle dry weight needed to support a particular landing option
2. The operations delay in taking a just landed vehicle and readying it for the next flight
3. The reliability impact of not being able to abort during some parts of the ascent trajectory

A vehicle landing horizontally needs additional structure to provide aerodynamic lift, either as wings or in the less-efficient layout of a lifting body. If high reliability is wanted some propulsion capability for landing may be needed, as glide landings are intolerant of error. Even though the Shuttle has managed over a hundred successful landings it still has no capability to go around in the event of a problem on approach. Horizontal landing is the best analyzed option as we have a huge experience base for it and vehicle design can be done without needing to build an X-vehicle to test the landing technique.
Heuristic 7a: **Horizontal landing is safest due to the experience base**

Vertical landing vehicles use a ballistic entry to decelerate to terminal velocity and then use rocket thrust to reach a soft touchdown. This was the landing mode demonstrated by the DCX. Alternate methods include helicopter blades (Roton) and parachutes (Kistler K-1). The rocket landing mode can reduce structural mass by eliminating the landing structures but will require additional fuel for landing which will detract from payload weight. The other options also require additional structural weight, which may not necessarily be a savings over wings.[20]

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[19] London, 1994, Ch. 6.
[20] Stine, 1996, Ch. 12.

Heuristic 7b: **Vertical landing can save vehicle structural weight.**

Turn-around operations can be greatly eased by allowing the vehicle to land at the launch site in a state similar to how it launches. HTHL vehicles can turn around just as an airplane does by landing on its take-off runway and being merely refueled before the next flight. VTVL vehicles can have similar efficiencies, and both options benefit from being able to abort to a landing during any part of the ascent trajectory.[21] VTHL systems are harder to operate, as they must be erected on the pad as part of turnaround—a delicate procedure with very large vehicles—and during the early part of the ascent trajectory it will be unable to land if an anomaly demands an abort. Picking HTHL or VTVL does not guarantee an easy turn-around. The Kistler stages land by parachute some distance from the pad and must then be picked up, readied, and stacked on the pad, a much more tedious operation than desired by most VTVL advocates.
Heuristic 7c: **Matching landing and take-off modes can streamline operations.**

For a horizontal landing vehicle to also take off horizontally requires more lift structure than a vertical takeoff but allows the thrust to be lower. This is a significant net increase in dry weight for most vehicle designs, as the weight of a full propellant load is a much heavier burden on the wings than the weight of the vehicle landing with empty tanks. HTHL designs are generally two-stage (requiring less performance at take-off) or use techniques such as towing, tanking, or carrier aircraft to reduce the load on the vehicle.
Heuristic 7d: **Vertical take-off reduces structural weight.**

Decision 8: New or Off-The-Shelf Engines

Engine development programs usually require extensive testing to ensure the engine will behave safely and meet its performance requirements. Freezing the rest of the system design before the engine has been completed is risky, as an engine design change can require redoing extensive work on the rest of the system. However, taking advantage of new technology can be a significant performance increase for the system. Scramjets, aerospikes, and rotary-pump engines have all been seen as essential to make a new system viable.[22]
Heuristic 8a: **New engines increase system performance.**

Numerous off the shelf engines are available. Aerojet Corp. has dozens of Russian NK-33 engines that they are ready to deliver to the first buyer with cash in hand. Numerous other engines are still in production or could be produced again on short notice. Designing a system is made much easier by having precise values for that key component, but the most significant benefit could be eliminating the schedule delay and risk for the new engine development.[23] Drawn out schedules can lead to loss of government funding or failure of commercial projects.
Heuristic 8b: **Off-the-shelf engines reduce program risk and schedule.**

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[21] Stine, 1996, Ch. 21.
[22] Hudson, 1998.
[23] Gallagher, 1999.

Case Studies

Case Study 1: National AeroSpace Plane (NASP)

One of many proposed NASP designs.

The NASP was a government-led program focused on achieving SSTO with advanced airbreathing propulsion. There was no lead architect on the program, multiple government agencies and contractors collaborated on decisions. The stated flight date was not achievable with the technology available and most work on the program consisted of pure research and development into supporting technologies.[24]

To achieve the desired cost savings the architects believed a radical departure from the Space Shuttle was needed. The design was focused on increasing performance through advanced technology to produce an SSTO vehicle (Heuristic 2a: **RLVs have a Lower Cost for Additional Launches,** Heuristic 5c: **SSTO Requires New Technology Development**). The parameter to be improved was the specific impulse, which required developing an airbreathing scramjet engine (Heuristic 8a: **New engines increase system performance**). Slush hydrogen was planned for the fuel (Heuristic 6a: **Hydrogen provides the highest performance**). This initial decision drove the rest of the architecture, as the system had to fly a horizontal take-off trajectory to provide air for the engine while accelerating to orbital speed.

The NASP program intended to produce an X-vehicle (X-30) that would fly directly to orbit. Trying to develop an SSTO with an unproven type of engine was very difficult, but program managers felt that to compromise the SSTO goal would endanger the funding for the program (Heuristic 3a: **Don't Waste Money Building Vehicles that Can't Do the Mission**). The projected date for deciding to build the vehicle kept slipping as technologies failed to be ready in time. Lower-level efforts were focused on technology development and were not considering the needs of the overall vehicle. Some areas, such

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[24] London, 1994, Ch. 3.

as hypersonic aerodynamics, were so unready for the NASP mission that more effort went into developing new analysis tools than into vehicle analysis. The design never became mature enough to have confidence that a flight vehicle would have SSTO capability and the program was downscoped to an engine test program (Hyper-X).

Case Study 2: Delta Clipper

Delta Clipper SSTO

DCX Test Vehicle

The Delta Clipper team, led by William Gaubatz, was focused on creating a vehicle that would ultimately serve new commercial markets. The program began as a proposal for the Strategic Defense Initiative Organization, which wanted low-cost launch capability to support its plans for massive defenses in space (Heuristic 2a: **RLVs have a Lower Cost for Additional Launches,** Heuristic 2b: **Achieving High Reliability Requires a Reusable Vehicle (Sturdy, Reliable Components and Flight History on Vehicle)**).[25] The initial competition led to the flight test of the Delta Clipper-Experimental (DCX), a low-performance reusable rocket which proved a number of aerodynamic and operations assumptions about the Delta Clipper design (Heuristic 3b: **Building a Test Vehicle and Then Designing a Good Operational Vehicle is Cheaper than Designing a Bad Operational Vehicle.**).

The architects focused on low-cost operations and using as much off-the-shelf technology as possible. SSTO was chosen for its operational simplicity, as was VTVL (Heuristic 5a: **SSTO Reduces Cost and Turn-Around Time,** Heuristic 7c: **Matching landing and take-off modes can streamline operations.**). The landing technique was to decelerate aerodynamically and then land on rocket thrust, an unprecedented combination (landing

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[25] Stine, 1996, Ch. 9-20.

on rocket power had only previously been done on the Moon) (Heuristic 7b: **Vertical landing can save vehicle structural weight**). Since the delta-V requirements of the Delta Clipper were so high (including not just ascent to orbit but also landing fuel) hydrogen was chosen for its high specific impulse (Heuristic 6a: **Hydrogen provides the highest performance**). Other off the shelf technology was used including composite structures and aircraft avionics (tested on the DCX). The engines were to be modifications of the SSME or RL-10.

The goal of the program was to create a government-funded RLV that would lower launch costs enough to allow new commercial markets to spring up (Heuristic 1a: **In a Stable Launch Market Only the Government Can Fund Brand-New Launch Systems**). Delta Clippers would then be operated by commercial companies serving both the government and commerce. After McDonnell Douglas lost the X-33 competition and was bought out by Boeing the Delta Clipper architects left to form their own company, Universal Space Lines, under the leadership of the late Pete Conrad.

Case Study 3: VentureStar

The VentureStar SSTO

Long-time Lockheed SkunkWorks engineer David Urie was the architect for the VentureStar RLV. This was an unconventional vehicle in the SkunkWorks tradition which used several new techniques to produce a higher-performance vehicle than they believed otherwise possible (Heuristic 5c: **SSTO Requires New Technology Development**). A hydrogen-burning linear aerospike engine was combined with a lifting body shape to produce a well-integrated design (Heuristic 6a: **Hydrogen provides the highest performance,** Heuristic 8a: **New engines increase system performance**). New structural technology (multilobe composites) was developed to allow the tankage to use the vehicle volume efficiently.[26]

Lockheed had not entered the SDIO competition for the DCX demonstrator but reentered the RLV competition when NASA took it over from BMDO (the renamed—and reduced—SDIO). The VentureStar design was focused on NASA's key missions for Space Station support and as a lower-cost Space Shuttle replacement (Heuristic 2a:

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[26] Dornheim, 1996.

RLVs have a Lower Cost for Additional Launches, Heuristic 5a: **SSTO Reduces Cost and Turn-Around Time**). The VTHL operations would have the least change to NASA's daily routine (Heuristic 7d: **Vertical take-off reduces structural weight,** Heuristic 7a: **Horizontal landing is safest due to the experience base**). The one break from the Shuttle was the provision for unmanned operation, though personnel capsules could be carried in the payload bay with connections to the control system (Heuristic 4a: **People On Board Reduce Performance**). LockheedMartin stated that the VentureStar could be funded commercially but the vehicle's Shuttle-equivalent payload was oversized for most commercial missions. They have lobbied for Federal loan guarantees to reduce the cost of borrowing development funds from investors (Heuristic 1a: **In a Stable Launch Market Only the Government Can Fund Brand-New Launch Systems**).

Lockheed (by then Lockheed-Martin) claimed it could produce an operational VentureStar given sufficient funding but NASA only had enough for the X-33 demonstrator.[27] The X-33 would have proven out the engine and tank technologies and shown how flight operations would work, but progress to date has been disappointing. Architect David Urie retired before the project got fully underway and responsibilities were scattered to facilities across the country losing the "SkunkWorks" advantage. The vehicle layout was frozen before all aerodynamic analysis was completed, and changes to the outer shell increased weight and left unused volume as the designs for interior components has already been set. With additional troubles such as a failure of the composite tanks the X-33 is several years behind its planned first flight. The prospect of a full-scale VentureStar being built is equally gloomy for right now. Lockheed-Martin is not planning to fund construction and NASA's only support is the opportunity to compete for additional funds to finish X-33.

Case Study 4: Black Horse/Pioneer Rocketplane Pathfinder

Black Horse SSTO

Pathfinder First Stage RLV

The architect of this system was Mitchell Burnside Clapp, first as an Air Force officer then as company founder. The initial concept was the Black Horse military space plane.

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[27] Asker, 1994.

When it became apparent that the Air Force would not fund actual development the architect took the concept to the private sector, and the architecture changed to reflect its new environment. Both architectures used the concept of "Aerial Propellant Transfer" (APT), a launch vehicle taking off horizontally from a runway with empty oxidizer tanks and filling them from a tanker aircraft at altitude (Heuristic 7a: **Horizontal landing is safest due to the experience base,** Heuristic 7c: **Matching landing and take-off modes can streamline operations)**. This reduced the loads on the vehicle at take-off and therefore the wing and engine weight needed. A pilot was needed to fly the vehicle through the tanking maneuvers as no automated systems capable of that type of formation flying have been developed (Heuristic 4b: **People Can Do Things Computers Can't)**.

Black Horse was a "military space plane"—a single stage to orbit, rapid turnaround, small payload vehicle. It was optimized to do satellite launch, reconnaissance, on-orbit servicing, and other missions of military interest.[28] It was purely rocket powered and used peroxide/JP-5 (high density kerosene) to minimize its structural mass (Heuristic 6b: **Dense propellants improve mass fraction)**. The Black Horse would take off with just enough peroxide to conduct the APT tanking maneuver and load the rest of the peroxide from the tanker, then ascend to orbit. The 1000 lb. payload could serve a variety of missions while not demanding the development costs of a larger vehicle. The Air Force Forecast 2020 study envisioned a squadron of Black Horse SSTs exercising "space control" with their rapid response capability (Heuristic 2b: **Achieving High Reliability Requires a Reusable Vehicle (Sturdy, Reliable Components and Flight History on Vehicle),** Heuristic 5a: **SSTO Reduces Cost and Turn-Around Time)**. To reduce the development risks studies suggested a pair of preliminary X-vehicles (Heuristic 3b: **Building a Test Vehicle and Then Designing a Good Operational Vehicle is Cheaper than Designing a Bad Operational Vehicle)**. The Black Foal would demonstrate peroxide tanking and flight control while having the vehicle more than double its weight. The Black Colt was a stepping stone to provide some Black Horse capabilities while waiting for a peroxide/kerosene engine to be developed—it would take on LOX and boost a solid upper stage out of the atmosphere where it could deliver satellites to orbit. A long development program was acceptable to the military if it could produce a useful system and the risk reduction provided by the Black Foal and Black Colt could make it easier to justify the large appropriations for the SSTO engine and vehicle programs (Heuristic 1a: **In a Stable Launch Market Only the Government Can Fund Brand-New Launch Systems)**. However, as the post-Cold War drawdown continued the Air Force diverted its funds to support its aircraft elements and didn't support advanced spacecraft such as Black Horse.

The architect turned down promotion to major and left the Air Force in 1995, not just frustrated at the lack of progress by the military but also drawn by the opening of a new commercial market that could support development of his system (Heuristic 1b: **A Dramatic Lowering of Launch Costs will Make New Markets Viable, and Commercial Investors will Support that Leap)**. This was during the heyday of Iridium and Teledesic with dozens of other systems following in their path, and more than half a

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[28] Daehnick, 1995.

dozen launch vehicle companies were founded to service those systems. Mitchell Burnside Clapp partnered with famed scientist Robert Zubrin and founded Pioneer Rocketplane. Their launch vehicle was dubbed "Pathfinder" and the architecture was reconsidered.

The new system would have to be focused on the commercial launch market and sized for the satellites planned by Teledesic and others while underpricing other launch providers (Heuristic 2a: **RLVs have a Lower Cost for Additional Launches)**. The development cost would have to be kept affordable by private investors. To provide the rate of return demanded by the capital markets operations would have to begin three to four years after the program is fully funded. To assure investors that the system could be developed without major risks the company planned to subcontract development and manufacturing to a major aerospace company. These constraints forced significant changes from the Black Horse to the Pathfinder architectures.

The new architecture went directly to the operational Pathfinder with no test vehicles (Heuristic 3a: **Don't Waste Money Building Vehicles that Can't Do the Mission)**. No time or funds were available for development of a new engine so the off-the-shelf LOX/kerosene RD-120 engine was baselined (Heuristic 6c: **LOX/kerosene has good performance and is easier to use,** Heuristic 8b: **Off-the-shelf engines reduce program risk and schedule)**. These changes made aiming for SSTO performance impractical so the two-stage Black Colt concept was used for the basis of the Pathfinder design (Heuristic 5b: **Staging Reduces Performance Requirements)**. A liquid-fuel upper stage had to be substituted for the original solid upper stage to meet the performance required by Teledesic and planned Iridium follow-ons. The system kept the original operations concept with a pilot controlling horizontal take-off and landing.[29]

A small architecture team went to work on optimizing the design and found a configuration that could meet the requirements. Funding for full development and construction was never obtained, and with the decline in the LEO commsat market the system most likely will never be built.

Case Study 5: Rotary Rocket Roton

The architects of the Roton have a long history of involvement in privately-funded launch vehicles. Gary Hudson built the Percheron ELV (built but failed before flight) and designed the Phoenix tourist-carrying RLV (never funded). Bevin McKinney was chief designer for the American Rocket Company, whose hybrid-motor booster was safer than solids (so safe that the payload was recovered intact after it failed on the pad). They began their collaboration on McKinney's idea of using centrifugal force to pump propellants into an engine rather than elaborate turbomachinery. This grew into the Roton vehicle, a design that took all the aggressive choices available in a double-or-nothing attempt to create a profitable private-enterprise SSTO.

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[29] Gallagher, 1999.

The original Roton architecture placed the rocket engines at the end of helicopter blades containing pipes for LOX and kerosene. At full spin rate the propellants would be delivered at extremely high pressure, supporting SSTO-level performance by the engines.[30] While an elegant design—gaining lift from the rotor blades as well as thrust—it could not scale up to support the payload size the market appeared to demand.


Roton SSTO


ATV Prototype

The new architecture had a radically different engine—a spinning wagon wheel, mounted horizontally on the base of the cone-shaped vehicle, with engines on the rim and propellants delivered along the spokes (Heuristic 8a: **New engines increase system performance)**. An independent set of helicopter blades were mounted on the top of the vehicle to be used for landing only (Heuristic 7b: **Vertical landing can save vehicle structural weight)**. Pilots were required on board to handle the landing and were used to support all flight operations, which complied with the proposed FAA regulations for space launch vehicles (Heuristic 4b: **People Can Do Things Computers Can't (Including Keeping FAA Happy)**). An all-composite structure was designed, including unlined composite LOX tanks (Heuristic 6c: **LOX/kerosene has good performance and is easier to use**). The engines were cooled with LOX and the vehicle base with water transpiration. This whole package of innovations—each a significant performance boost if it worked—was to be implemented by a start-up company with a brand-new team and facilities. This was a deliberate attempt to capture the "skunk-work" efficiencies of a low-overhead operation focused on a single goal.

Design decisions focused on keeping costs per flight down by reducing the turnaround time between flights (Heuristic 2b: **Achieving High Reliability Requires a Reusable Vehicle (Sturdy, Reliable Components and Flight History on Vehicle),** Heuristic 5a: **SSTO Reduces Cost and Turn-Around Time,** Heuristic 7c: **Matching landing and take-off modes can streamline operations)**. The controlled vertical landing approach,

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[30] Hudson, 1996.

making the new engine sturdy and low maintenance, and insisting on SSTO performance were all aimed at that.[31] Even if the vehicle fell short of SSTO, having a small assist strap-on or upper stage would be a much smaller operations hassle than integrating two vehicles with equivalent delta-V capabilities.

A series of four demonstration and prototype vehicles were planned, one for each of the major design innovations planned (Heuristic 3b: **Building a Test Vehicle and Then Designing a Good Operational Vehicle is Cheaper than Designing a Bad Operational Vehicle**). The first, only testing the rotor landing technique, was built and flown, though it didn't complete the planned flight series before the company ran out of money. The demonstration vehicles were not just to test the technical concepts but also to hone the skills of the team by taking them through multiple design-build cycles before tackling the SSTO and to impress potential investors with the capability of the company to use their money effectively.[32]

The architects and investors were focused on the goal of a cheaply built, cheaply operated, high performance vehicle which would out-compete all existing rockets in its weight class and enable new markets to spring into existence (Heuristic 1b: **A Dramatic Lowering of Launch Costs will Make New Markets Viable, and Commercial Investors will Support that Leap,** Heuristic 2a: **RLVs have a Lower Cost for Additional Launches**). If successful, the Roton would have changed the world, and that vision drove the whole team forward. Support from the government was avoided so the design could be focused on the architect's vision, not that of a sponsoring agency. Rotary supported active lobbying of the FAA to ensure that safety regulations would not constrain the design. Work that had to be subcontracted went to outfits such as Scaled Composites that has a similar outside-the-establishment ethic.

Rotary Rocket did make more progress than any of the launch vehicle startups. The first of their X-vehicle demonstrators was built and demonstrated the rotor landing concept, and a LOX cooled rocket engine—dozens of which would populate the spinning disk of the vehicle—was successfully fired. Unfortunately Rotary's slipping schedule had them still performing these preliminary tasks when the LEO commsat market started to collapse. The early revenue from those missions were essential to make the system attractive to investors and as the business case weakened the investments stopped.

Case Study 6: Kistler Aerospace—Two Architectures

Walt Kistler and Bob Citron founded a company to develop a private-enterprise SSTO as the first of the many start-ups chasing the LEO commsat market. They pulled in more investment financing then all the other launch start-up companies put together (Heuristic 1b: **A Dramatic Lowering of Launch Costs will Make New Markets Viable, and Commercial Investors will Support that Leap**). Their original concept was radically

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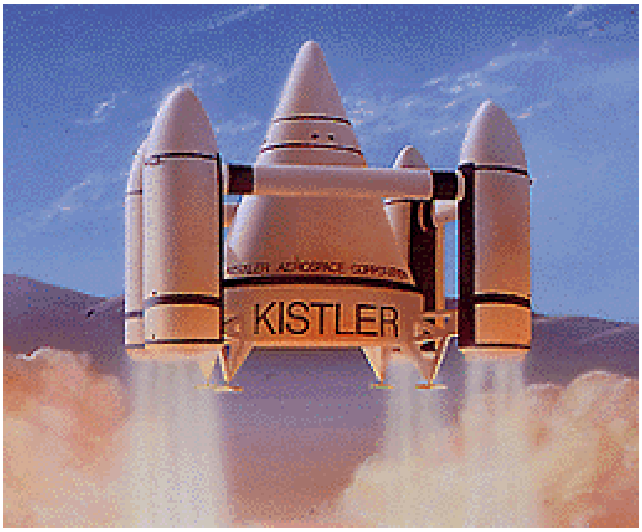
[31] Sarigul-Klijn, et al, 1999.
[32] Hudson, 1998.

changed when the company brought in a new architecture team with a NASA background. While the environment of the system stayed the same, two different system architecture teams went in almost opposite directions.

The original Kistler team planned to produce an SSTO as their “K-3” design, with a K-0 X-vehicle providing proof of concept and the K-1 and K-2 prototypes being increasingly high performance vehicles making it to orbit with the help of a reusable first stage or “launch assist platform”.[33] The orbital vehicles were cone-shaped with Apollo-capsule like proportions to ease the deceleration to a vertical landing. Landing would be on rocket power, with the K-1 saving the weight of landing gear by lowering itself into a large steel cable net. The feasibility of that option was to be tested by the K-0 demonstrator, to the relief of many of those briefed on the concept (Heuristic 3b: **Building a Test Vehicle and Then Designing a Good Operational Vehicle is Cheaper than Designing a Bad Operational Vehicle**). The orbiters and launch assist platforms were to have safe abort capability during their entire flight profile to ensure the system would be safe and reliable (Heuristic 2b: **Achieving High Reliability Requires a Reusable Vehicle (Sturdy, Reliable Components and Flight History on Vehicle)**).



Original Kistler Architecture—K1 and LAP

Final Kistler Architecture

Kistler’s original vision was to push existing technology to the limit and use rapid prototyping cycles to improve the performance of the vehicle (Heuristic 5a: **SSTO Reduces Cost and Turn-Around Time**). Off-the-shelf RL-10 engines were specified to avoid new engine development while maintaining a high specific impulse (Heuristic 6a: **Hydrogen provides the highest performance,** Heuristic 8b: **Off-the-shelf engines reduce program risk and schedule**). A “skunk works” style approach was planned to have an efficient, low-cost development effort. The prime principle was to accept risk to reduce costs in the hope of a hugely profitable payoff down the line. The first two versions (two two-stage systems, one suborbital, one orbital) were to be developed and flown on a budget of $250 million.

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[33] Weber, 1994.

Unfortunately for Kistler's original plan his investors were more risk-adverse than he was and they brought in a new architect for the system. Dr. George Mueller was NASA Associate Administrator for Manned Space Flight during the Apollo program and replaced the original Kistler technical team with NASA veterans[34] [Stine, 183]. The focus became risk reduction and the investors signed up for a more expensive vehicle than originally planned.

The current Kistler K-1 configuration is a two stage vehicle looking almost like a modern expendable launch vehicle (Heuristic 5b: **Staging Reduces Performance Requirements**).[35] The hydrogen-burning RL-10 engines were replaced with rugged Russian NK-33 engines using kerosene (Heuristic 6c: **LOX/kerosene has good performance and is easier to use,** Heuristic 8b: **Off-the-shelf engines reduce program risk and schedule**). The controlled landing became an unguided one using parachutes and airbags to land the stages. Rather than develop a lean production team in-house the detail design and manufacturing work was subcontracted to established aerospace companies such as Lockheed Martin (tanks) and Northrop Grumman (structure). The possible flight rate for the system was cut considerably—rather than a single vehicle that would arrive ready to be processed for the next flight, the stages would have to be retrieved and hauled hundreds of miles back to the launch site then painstakingly integrated together to prepare for the next flight. The planned demonstration and prototype vehicles were cut back to a practice drop of a stage under parachutes (Heuristic 3a: **Don't Waste Money Building Vehicles that Can't Do the Mission**).

The new architecture eliminated technical risk at the cost of increased operational risk (uncontrolled landings) and financial risk (a much more expensive development plant). The financial risk decided the fate of the company as Kistler has spent about $450 million and has only components for a flight vehicle built. Needing an additional $400 million to assemble and launch the vehicle Kistler does not seem likely to make orbit. The low-risk approach used twice as much money as the high-risk one without success.

Case Study 7: Beal Aerospace BA-2

Andrew Beal took the reverse approach of the other launch vehicle startups. They were some engineers who came up with a design and then started looking for funding. Beal was a banker who began studying rockets as a hobby, picked a design and then found some engineers to build it for him. With a steady $100 million a year available Beal was willing to support a long term development program if it would give him a system that would outcompete all the existing ones. The company eventually decided to focus on the geostationary commsat market that they considered (correctly) to be the more reliable market (Heuristic 1b: **A Dramatic Lowering of Launch Costs will Make New**

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[34] Stine, 1996, p183.
[35] Ianotta, 1998.

Markets Viable, and Commercial Investors will Support that Leap). The original BA-1 design aimed at the LEO market was discarded and effort was focused on the larger BA-2 (Heuristic 3a: **Don't Waste Money Building Vehicles that Can't Do the Mission**).


Beal BA-2 ELV


2nd Stage Engine Test Firing

Beal's team settled on a three-stage expendable rocket using kerosene and hydrogen peroxide (Heuristic 2c: **Expendable Vehicles have Lower Up-Front Costs,** Heuristic 5b: **Staging Reduces Performance Requirements,** Heuristic 6b: **Dense propellants improve mass fraction**).[36] The propellants were pressure-fed to reduce the complexity of the engine development program. No appropriate engines were available so the team began developing four new engines—a subscale prototype and engines sized for each of the three stages (Heuristic 8a: **New engines increase system performance**). The engine program made considerable progress before Andy Beal shut the program down due to technical problems and the fear of government competition.

Case Study 8: Microcosm Scorpius

Microcosm Corp. has pursued the development of its Scorpius expendable launch vehicle design through a series of government study contracts, mostly with the US Air Force (Heuristic 1a: **In a Stable Launch Market Only the Government Can Fund Brand-New Launch Systems**). Scorpius development is explicitly focused on low-cost development and manufacturing (Heuristic 2c: **Expendable Vehicles have Lower Up-Front Costs**).[37] The only new technology is in the low-cost ablatively-cooled engines, which are intended to underprice solid rocket motors (Heuristic 8a: **New engines increase system performance**). The Scorpius family ranges from pure proof-of-concept prototypes to multi-ton payload vehicles (Heuristic 3b: **Building a Test Vehicle and Then Designing a Good Operational Vehicle is Cheaper than Designing a Bad**

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[36] Beal website.
[37] Wertz and Keith, 1995.

Operational Vehicle). So far only the smallest suborbital version has flown and the government is continuing funding at a low level of effort.

Scorpius family from sounding rockets to 7 tons to LEO boosters.

The Scorpius concept uses extreme simplicity to minimize costs. The engines and tanks are made from composite materials. The engine is pressure-fed and ablatively cooled, produced by new manufacturing techniques sponsored by the Air Force Phillips Lab. LOX/Kerosene were used as propellants (Heuristic 6c: **LOX/kerosene has good performance and is easier to use**). Identical units are bundled together in parallel stages to make larger versions of the vehicle (Heuristic 5b: **Staging Reduces Performance Requirements**). This approach keeps the costs within the government's threshold of pain and does not require large markets to pay off the initial investment.

Conclusions

Launch system architects need to decide on the approach their system will take early in design process. Sponsors will often put constraints on the decisions through specific technologies to use or avoid, or by having preferences for rapid or drawn-out schedules. Identifying which decisions need to be made up front, and using heuristics to consciously make the decisions rather than proceeding with a default assumption, is key to creating a usable architecture.

Most of the conflicts discussed above cannot be resolved without building operational systems using each of the conflicting heuristics and allowing them to compete. X-vehicles can answer some questions about the technical viability of options but can't prove they will provide the dramatic cost savings or performance improvements desired. An X-vehicles that fails may be seen as a failure of the implementation or development team rather than the concept itself. Still, the knowledge gained from actually building and flying a new device can be a substantial advantage in making the operational design a success.

At this writing there is little immediate prospect of a new launch vehicle with radically lower costs being developed. The need is still there and many engineering teams are working on approaches to the problem. When the next opportunity comes they'll be ready.

References

Asker, James R., "Lockheed Details RLV Plans", Aviation Week, December 5th, 1994.

Beal Aerospace, http://www.bealaerospace.com.

Burnside Clapp, Mitchell, "Peroxide Fuels", presentation at Making Orbit '94 conference, Jan. 14, 1994.

Clark, John D., Ignition—An Informal History of Liquid Rocket Propulsion, John Wiley & Sons, 1971. (Currently out of print but available through UMI repro services.)

Daehnick, Maj. Chris, "SPACE LIFT: Suborbital, Earth to Orbit, and on Orbit", Spacecast 2020 White Paper, Air Power Journal, Summer 1995.

Dornheim, Michael A, "Follow-on Plan Key to X-33 Win", Aviation Week, July 9th, 1996.

Gallagher, Karl, "Optimization of ascent trajectory and related design issues for an aerial propellant transfer rocketplane", AAS 99-129, 9th AAS/AIAA Space Flight Mechanics Meeting.

Gaubatz, Dr. William A., "Space is a Place", McDonnell Douglas Aerospace document, September 1995.

Hudson, Gary C., "Insanely Great? Or Just Plain Insane?", Wired Magazine, May 1996.

Hudson, Gary C, "Roton Development and Flight Test Program", AIAA Paper 98-5258

Iannotta, Ben, "Small Startups Vie for Big Business", Aerospace America, August 1998.

Kaplan, Marshall, "Laws of RLV Design", International Space Industry Report, November 23rd, 1998.

London, Lt Col John R. III, LEO On The Cheap, Air University Press, Maxwell AFB, Alabama, 1994

Rechtin, Eberhardt, Systems Architecting, Prentice Hall, Englewood Cliffs, NJ, 1991

Sackheim, R. L., and P. Dergarabedian, "Reducing the Cost of Space Transportation", TRW Space & Electronics Group internal document, March 1995.

Sarigul-Klijn, Dr. Marti, Brian Binnie, Richard V. Stockmans, and David P. Gump. "Safety and the Roton Development Program", IEEE Paper 99-063.

Stine, G. Harry, Halfway to Anywhere, M. Evans & Co, New York, 1996.

Weber, Steve, "Company Vows to Build SSTO for $250 Million", Space News, October 3, 1994.

Wertz, James R., and Edward L. Keith, "The Scorpius Low Cost Launch System", 9th Annual AIAA/USU Conference on Small Satellites, September 20th, 1995.

Wertz, James R. "Economic Model of Reusable vs. Expendable Launch Vehicles." Presented at IAF Congress, October 2nd, 2000.