January 2003 (Revised September 2003) AIAA 2003-0909

Flight Mechanics of Manned Sub-Orbital Reusable Launch Vehicles with Recommendations for Launch and Recovery

Marti Sarigul-Klijn, Ph.D. and Nesrin Sarigul-Klijn*, Ph.D.
Mechanical and Aeronautical Engineering Department, University of California, Davis, CA 95616-5294

An overview of every significant method of launch and recovery for manned sub-orbital Reusable Launch Vehicles (RLV) is presented here. We have categorized launch methods as vertical takeoff, horizontal takeoff, and air launch. Recovery methods are categorized as wings, aerodynamic decelerators, rockets, and rotors. We conclude that both vertical takeoff and some air launch methods are viable means of attaining sub-orbital altitudes and wings and aerodynamic decelerators are viable methods for recovery. These conclusions are based on statistical methods using historical data coupled with time-stepped integration of the trajectory equations of motion. Based on the additional factors of safety, customer acceptance, and affordability, we also conclude that the preferred architecture for a commercially successful manned sub-orbital RLV is Vertical Takeoff using hybrid rocket motor propulsion and winged un-powered Horizontal Landing onto a runway (VTHL).

NOMENCLATURE

BC = Ballistic Coefficient
g = Earth's gravitational acceleration
g_o = Gravitational constant
h = Peak trajectory altitude
I_{sp} = Specific Impulse
LEO = Low Earth Orbit
M = Mach number
MR = Propellant mass ratio, W_o/W_f
t_b = Engine burn time
T/W = Thrust to weight ratio
T = Thrust
W_f = Burnout weight
W_o = Takeoff weight
W_p = Propellant weight
ΔV = Change in velocity (delta V)
δ_p = Propellant mass fraction

INTRODUCTION

Space tourism is predicted to be a multibillion-dollar industry when a safe and economical space vehicle is built.[1] With the exception of NASA's Space Shuttle and the Russian Soyuz, there are no other manned vehicles that can leave the Earth's atmosphere and return safely. The shuttle is expensive and current US law prevents tourists from buying a ride, even if they could afford to. A tourist seat is currently available on the Russian Soyuz every 6 months, but at a cost of $20 million.

The St. Louis based X-Prize Foundation is offering a $10 million prize to the first team that launches a privately financed vehicle capable of carrying three people to a 100 kilometer (328,000 feet) sub-orbital altitude and repeat the flight within two weeks. Only one person and equivalent ballast substituted for the other two persons are actually required to make the flights. Also no more than 10% of the vehicle's first flight non-propellant mass may be replaced between flights. The X-Prize is being offered to help speed the development of concepts that will reduce the cost of manned space flight.[2]

However, there exists considerable disagreement on the correct architecture for a safe and economical space vehicle. Fundamentally, teams must decide on a takeoff mode and on a landing mode.

There are three basic takeoff modes available; vertical, horizontal, and air launch. Early success in manned space flight was achieved with vertical takeoff using rocket power with such vehicles as the Russian Vostok and American Mercury-Redstone rockets. Sub-orbital manned space flight was achieved using air launch takeoff with the American rocket powered X-15. So far no sub-orbital or orbital flights have been achieved with either rocket powered horizontal takeoff aircraft such as the German Me-163 (peak altitude of 42,000 ft or 12,800 m) or combined rocket and jet powered horizontal takeoff aircraft such as the Lockheed NF-104 (peak altitude of 120,800 ft or 36,800 m) and the British Saunders-Roe SR-53 (peak altitude of 67,000 ft or 20,400 m).

---

*Associate Fellow AIAA, nsarigulklijn@ucdavis.edu

In terms of landing mode, there are 4 major recovery methods available: wings, aerodynamic decelerators (such as parachutes), rockets, and rotors. Wings and parafoils (a rectangular ram-air lifting parachute) are considered horizontal landing. The rest are considered vertical landing.

Horizontal landing with wings and wheeled landing gear has been successful for manned piloted vehicles, although one Space Shuttle was lost due to failure of its wing thermal protection system. Other examples include the X-1 and X-15.

Vertical landing using parachutes into the water has also been successfully demonstrated in the Mercury, Gemini, and Apollo programs, although one astronaut did almost drown during the second manned Mercury landing. The Russians have had success with parachute landings using a retrorocket to soften the landing. However, there was one cosmonaut fatality during the first manned Soyuz due to a failure of its parachute system.

Other landing methods have not been used for manned earth return missions, although some tests have been conducted. These include vertical landing using rockets only (such as the McDonnell DC-X), vertical landing using a rotor (Rotary Rocket Company's Roton), vertical landing with parachutes using airbags to soften the landing (Kistler K-1), and horizontal landing using a parafoil parachute (NASA's X-38). Manned vertical landing using rockets has been successfully demonstrated on the Moon during the Apollo program.

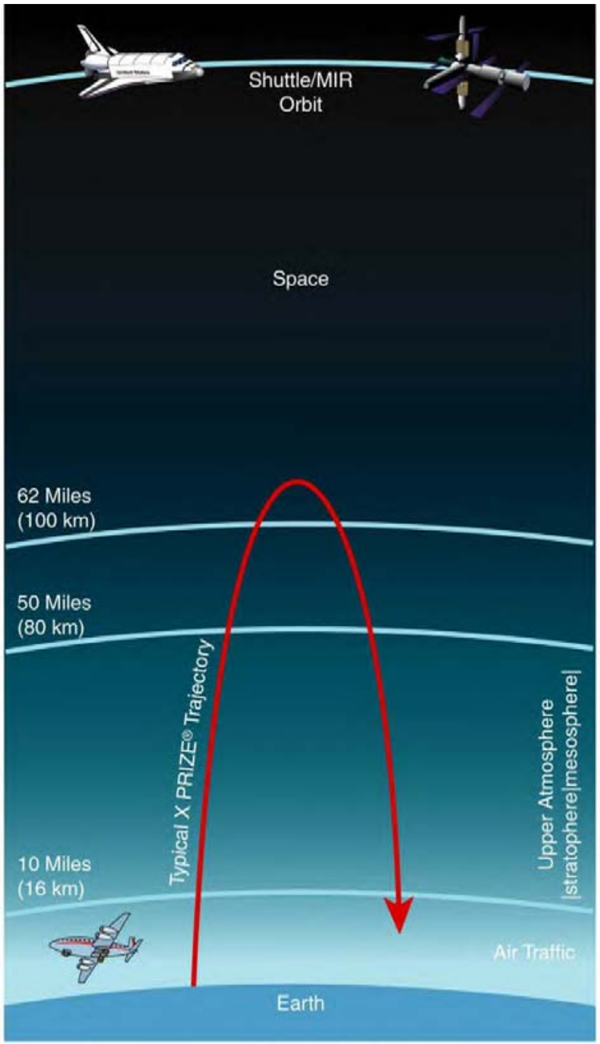
The 3 takeoff modes and 4 landing modes result in 12 possible architectures for a sub-orbital RLV. As this paper will show, only 4 of these 12 architectures are viable candidates for the X-Prize.

ASCENT FLIGHT MECHANICS

The adjacent figure presents the typical trajectory of a X-Prize vehicle, a trajectory that is also considered typical for vehicles planned for the sub-orbital tourist market. A substantial portion of the trajectory is above the atmosphere. The only propulsion system that can work in the vacuum above the atmosphere is a rocket engine.

Specific Impulse and the Rocket Equation

A quantity called specific impulse and abbreviated by "I_{sp}" provides a convenient measure of a rocket engine's intrinsic efficiency. The specific impulse or I_{sp} of a rocket and propellant combination is analogous to "miles per gallon" for an automobile. The I_{sp} of a rocket-propellant combination is defined *as the number of seconds a pound (lb) of propellant will produce a lb of thrust*. For example, an I_{sp} of 200 seconds means that a rocket engine would consume 1 lb (or kilogram) of propellant when producing 1 lb (or kilogram force) of thrust for 200 seconds. Generally speaking, designers strive for the highest I_{sp} they can achieve.



Typical X-Prize® Trajectory[2]

Realistic sea level I_{sp} for a space tourist vehicle's engine is in the order of 200 to 275 seconds based on today's technology (we are assuming that liquid hydrogen will not be used as a fuel). Many X-Prize concept designs are erroneously based on much higher I_{sp}. Rocket engine books and reference sources provide convenient tables of I_{sp} for various propellant combinations. These tables often give data for the theoretical operation of rocket engines using a combustion chamber pressure of 1000 pounds per square inch (psi or 68 bar) operating in a vacuum. Rocket engines have lower I_{sp} when operating in the atmosphere or at lower combustion chamber pressures. For example, the theoretical performance of a kerosene and liquid oxygen (LOX) engine is about 350 seconds when operating in a vacuum. In contrast the demonstrated I_{sp} at sea level for the Saturn V's F-1 engine is 265 seconds, the Delta's RS-27 is 262 seconds, and the Atlas's MA-5 is 259 seconds. Tourist vehicles will likely have engines that operate at much lower combustion chamber pressures than these engines since most will be pressure fed instead of turbo pump fed. This means the sea level I_{sp} will be even lower.

Once I_{sp} is known, then the ideal rocket equation, which is also called Tsiolkovsky's equation in honor of the Russian schoolteacher who first derived it over 70 years ago, indicates the maximum velocity that can be obtained from a load of propellant. It is given by the following equation:

$$\Delta V = I_{sp} \cdot g_o \cdot \ln (W_o / W_f) \qquad (1)$$

It says that the change in velocity (called delta V and symbolized by ΔV) is directly proportional to the specific impulse, I_{sp} , multiplied by the gravitational constant, g_o (equals 32.174 ft/sec^2 or 9.806 m/sec^2), and multiplied by the natural logarithm of the ratio of the weight of the rocket at takeoff, W_o , and the weight of the rocket at burnout, W_f. This ratio of takeoff weight to burnout weight, W_o/W_f , is called the propellant mass ratio and is sometimes written as *MR*. It has a value always greater than 1.

When comparing design concepts, it is much easier to use propellant mass fraction, δ_p , which is related to propellant mass ratio, *MR*, by:

$$MR = 1 / (1 - \delta_p) \qquad (2)$$

Propellant mass fraction, δ_p , is defined *as the amount of propellant relative to the takeoff weight*. For example, if the mass of a rocket at takeoff is 50% propellant, then its propellant mass fraction, δ_p , is 0.50. In this example the propellant mass ratio, *MR*, would be 2 since the takeoff weight is twice the burnout weight.

Hence if we know the propellant mass fraction, δ_p , and specific impulse, I_{sp} , we can then determine a rocket's delta V, ΔV.

Delta V Budget for Sub-Orbital Flight

The next question that we need to answer is "How much delta V is needed to reach a sub-orbital height of 100 kilometers?" The smallest delta V to reach 100 km (328,000 ft) would be achieved by firing the launch vehicle out of a large cannon vertically. In the absence of an atmosphere, the cannon would have to accelerate the launch vehicle to about 4,600 feet per second (fps or 1,400 m/s) to reach 100 km above the earth's surface. Placing this hypothetical cannon at 25,000 ft (7,600 m) altitude to represent an air launch would reduce the ideal delta V somewhat to about 4,400 fps (1,340 m/s). Of course neither of these methods is practical due to the high acceleration imposed on the crew, but these numbers are easy to calculate and they set the lower limit on the delta V required. The delta V that a launch vehicle's rocket motor must actually provide is greater than these amounts because of several losses.

The first loss is known as the gravity loss. Gravity loss arises because part of the rocket engine's energy is wasted holding the vehicle against the pull of Earth's gravity (g). Gravity losses depend on the takeoff thrust to weight (T/W) ratio. A T/W ratio of 1.0 means that the rocket engine's thrust just equals the vehicle's weight. The T/W ratio obviously needs to be greater than unity in order to climb. For launch vehicles designed to launch payloads into low earth orbit (LEO), initial T/W has been in the order of 1.2 to 1.5 for liquid rockets and somewhat higher for solid rockets. Gravity losses can be expected to be in the order of 2,000 to 4,000 fps (600 to 1,200 m/s) for a vertical trajectory to 100 km (328,000 ft).

Drag is another loss and is caused by friction between the launch vehicle and the atmosphere. Drag losses are in the order of about 500 fps (150 m/s) for medium sized launch vehicles such as the Delta or Atlas rockets for an earth to orbit trajectory. A long slender cylinder with a pointed nose is a favored shape to reduce drag losses since over three-quarter of drag losses are caused by supersonic drag. Also drag losses are subjected to the "cubed-squared" law. As an object's external dimensions increase, the surface area increases with the square of the dimension while the volume increases with the cube. Since drag is a function of surface area and not volume, then increasing the launch vehicle size will reduce drag losses. For example, the huge Saturn V moon rocket had drag losses of only 130 fps (40 m/s). The cubed-squared law is one of the reasons why the shortest launch vehicle to reach LEO was 43 feet long (the British Black Arrow). Otherwise drag losses are simply too high.

Vehicles that are air launched potentially can have the lowest drag losses since they are launched above much of the atmosphere. On the other hand, horizontal takeoff vehicles have the highest drag loss. Not only does their trajectory spend the most time in the atmosphere, but their wings also produce additional drag due to generating lift. This drag is called induced drag.

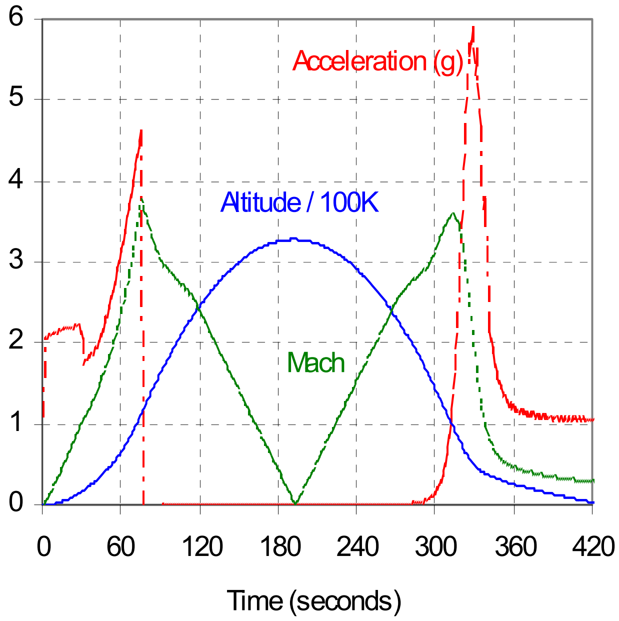
Steering loss is the last major loss and is caused by the need to steer the launch vehicle. It arises because the instantaneous thrust vector is not always parallel to the current velocity vector. This mismatch is necessary; otherwise, it would be impossible to steer a launch vehicle. Of course a vehicle can use aerodynamic control surfaces to steer. Such surfaces would reduce steering loss, but would increase drag losses, as well as add additional inert weight. In order to get an appreciation for steering losses, the Delta II rocket has only 110 fps (34 m/s) of steering losses as compared to the Space Shuttle's 1,200 fps (365 m/s), both for a low earth orbit trajectory.[3] Vertical takeoff vehicles should have least amount of steering losses since there is no need to pitch their trajectory upward 90 degrees to the vertical.

Notice that a compromise flight profile must be chosen to minimize losses. A high thrust to weight (*T/W*) ratio would reduce gravity losses but it would increase drag losses since the vehicle would be traveling very fast while low in the atmosphere. On the other hand, a low *T/W* ratio would reduce drag losses but greatly increase gravity losses.

Flight trajectory simulation computer programs, such as NASA's POST (Program to Optimize Simulated Trajectories) are needed to numerically integrate the equations of motion and to find the best trajectory. These equations typically do not have a closed-form solution because of the complex nature of the drag and steering losses. The amount of input and output data for various flight simulation programs can range from the simple to vast; for example, the POST program requires over a thousand inputs.

Fortunately, the amount of delta V required to reach 100 km for a vertical takeoff vehicle can be easily calculated. The actual value will depend on thrust to weight (T/W) ratio and on the vehicle's drag, but an approximate delta V to reach 100 km should be between 7,000 to 8,000 fps (2,100 to 2,400 m/s). The next figure presents the results from a trajectory program for a vertical launch from sea level. The blue solid line is the altitude in feet divided by 100,000, the red dashed line is acceleration in g's, and the green dotted line is Mach number. Peak aerodynamic pressure for this particular trajectory during both ascent and reentry is 750 pounds per square foot (psf), equal to 470 knots equivalent airspeed (KEAS).

The delta V for an air launch is more difficult to calculate since it depends on the altitude of the air launch and on the airspeed and pitch attitude at release. Also, how the pull-up is flown is a factor. In general, an air launch will require less delta V as compared to a vertical takeoff. In contrast, the horizontal takeoff takes the most delta V, since the vehicle first must accelerate horizontally and then pitch up into the vertical direction.



Estimation of Propellant Mass Fractions

As shown by the rocket equation (equation 1), propellant mass fraction and delta V are directly related. A launch trajectory that requires a higher delta V will require a higher propellant mass fraction. In general, an air launch trajectory will require the least propellant mass fraction, while a horizontal takeoff trajectory will require the most.

As an example of propellant mass fractions, the trajectory program that prepared the above figure also showed a propellant mass fraction of 0.63 was required for a vertical launch from the ground for a vehicle that was over 50 ft (15 m) long, assuming an average specific impulse, I_{sp} , of 225 seconds for motor operation from sea level to vacuum.

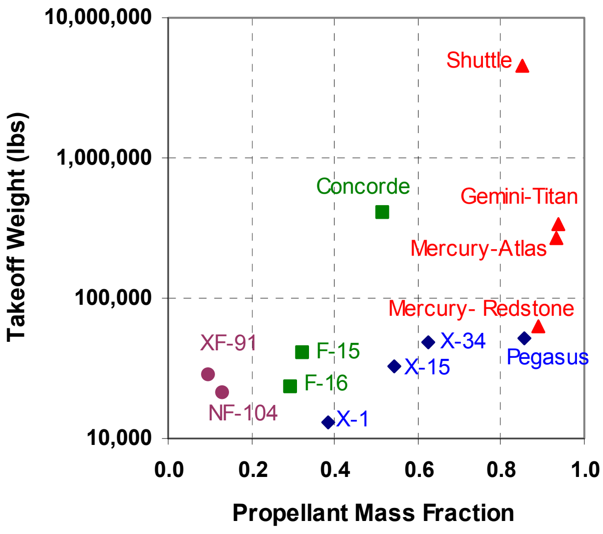
In addition to the propellant that is burnt by the rocket engines, all launch vehicles carry residual and reserve propellants. Residual propellant is propellant that is trapped in the propellant tanks or lines. Reserve propellant is extra propellant loaded onboard the vehicle to ensure that enough is available to complete the mission. Combined residual and reserve propellant mass fraction can be as little as 0.01 for a turbo pump fed liquid fueled engine with a mixture control system to as much as 0.07 for a simple pressure fed liquid rocket or for some solid or hybrid rocket motors.

Residual and reserve propellant must be added to the propellant determined by a trajectory program to get the propellant mass that must be actually carried by the launch vehicle. Hence total propellant mass fraction, δ_p , can be as much as 0.70 for a vertical takeoff vehicle in order to reach 100 km (328,000 ft).

In the case of an air launch, the propellant mass fraction should be less, in the order of 0.5 to 0.6, since the delta V required to reach 100 km is less. In the case of a horizontal takeoff, the propellant mass fraction can exceed 0.7.

Vehicle Mass Fractions

The takeoff mass of a vehicle is the sum of the crew and payload mass, the propellant mass, and the empty mass of the vehicle itself. These can be expressed as a percentage or a fraction of the takeoff mass. Historically, all vehicle designers were highly motivated to decrease empty mass fraction as much as possible, since doing so increases both the propellant and crew / payload mass fractions. Aerospace vehicle design has reached a point in which mass estimation is evolutionary rather than revolutionary; that is, a new vehicle design's mass fractions are usually an evolutionary change from previously existing designs. Hence they can be estimated statistically from historical trends.



This figure presents the propellant mass fractions, δ_p, for various types of vehicles. Vertical takeoff rockets are represented with red triangles. These are multistage expendable vehicles and only a portion is safely returned to earth. Air launched rocket powered vehicles are shown as blue diamonds and, except for Orbital Science's Pegasus, the entire vehicle returns to earth in one piece. Supersonic jets are shown for reference as green squares. Finally, combined rocket and jet powered planes are shown as purple circles.

Notice that the type of vehicle has a strong effect, with horizontal takeoff using combined jet and rocket power having the lowest mass fraction (0.09 to 0.13) available for the rocket propellant, and vertical takeoff rockets having the highest (0.85 to 0.94). Also notice that propellant mass fractions increase with increasing takeoff weight. The trends for each type of vehicle fall along approximately straight lines. Finally, reusable vehicles have a lower propellant mass fraction as compared to vehicles that have expendable parts.

Note that the horizontal takeoff vehicle has a trajectory that requires the largest delta V and hence requires the largest propellant mass fraction, yet historically it is capable of carrying the smallest propellant mass fraction.

TAKEOFF MODE TRADE

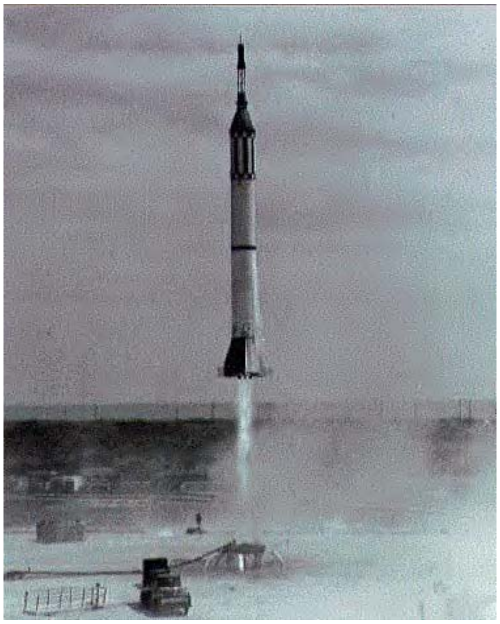
Vertical Takeoff

The Mercury-Redstone that carried American astronauts on their first sub-orbital flights is an example of a vertical takeoff vehicle. A vertical takeoff rocket easily has the necessary propellant mass fraction required to reach 100 km (328,000 ft). Vertical takeoff vehicles also have significant margin that allow them to use relatively low technology pressure fed rocket motors. Vertical takeoff rockets are basically pressurized balloons under an axial compression load and are subject to very little bending and no twisting moments during takeoff. Unlike horizontal takeoff vehicles, precise longitudinal control of center of gravity is not required which eliminates the need for multiple bulkheads inside their fuel and oxidizer tanks and eliminates the need for intertank propellant transfer pumps.

Vertical takeoff requires a prepared takeoff site. A portable "milk stool" type takeoff pad should be sufficient for a sub-orbital tourist vehicle. Launch preparation time does not need to be excessive. During the first Persian Gulf War the Iraqi were able to erect, fuel and launch their Scud missiles within 1 hour of arriving to a bare concrete pad. A 3-person, 100 km and Mach 3.5 capable space tourist vehicle should be smaller than a Mercury-Redstone, which was capable of 187 km (613,000 ft) altitude and Mach 7. Hence a milk-stool takeoff pad should be smaller than the one shown in the next picture.

Vertical takeoff has been picked by every space transportation study during the past 20 years as the preferred takeoff method for an earth to orbit

RLV. These studies include the European Space Agency's (ESA) Future European Space Transportation Investigations Program (FESTIP), Russian's Oryol program, Japan's HOPE, and the United States' Access to Space Studies, Space Transportation Architecture Studies, and most currently the US Space Launch Initiative (SLI) and Orbital Space Plane (OSP).[4]



Mercury-Redstone "Milk-Stool" takeoff pad

Horizontal Takeoff

Approximately half of the X-Prize concepts listed on the X-Prize web site are horizontal takeoff. This study will show that horizontal takeoff concepts should be unable to reach the X-Prize altitude goal of 100 km (328,000 ft) using current technology propulsion and structural materials.

Propellant mass fraction capability is much less for horizontal takeoff than for vertical takeoff vehicles. In addition to propellant tanks and rocket engines, horizontal takeoff concepts have wings and landing gear sized for their fully fueled takeoff weight. Furthermore, control of longitudinal center of gravity (CG) is required to keep the CG within a narrow longitudinal range, otherwise flight control will be lost. This may necessitate multiple fuel tanks and fuel transfer pumps to manage the fuel burn. This adds more weight.

This is not to say that horizontal takeoff aircraft with small empty mass fractions (and hence potentially large propellant mass fractions) have not been built. For example, foot launched paragliders have empty mass fractions less than 0.2. Also the University of California (UC) at Davis has been participating in an annual Society of Automotive Engineers (SAE) sponsored University aircraft design, construction, and fly off competition for the past 9 years. The goal is to carry the largest possible payload while powered by a single 0.61 model airplane engine. UC Davis students have built 15 different aircraft and the second author has been the faculty advisor. The best aircraft carried 27.5 lbs of payload and fuel while the vehicle had an empty weight of only 5.45 lb, or an empty weight fraction of 0.165. The Voyager is an example of a full-scale aircraft that had a very low empty weight fraction of 0.23. The Voyager is the only aircraft that flew around the world without refueling. Both the UC Davis models and the Voyager share many of the same flight characteristics. Namely, very low rate of climb, large deflections in the wings and fuselage that had low frequency bending modes, long takeoff distances, very small difference between cruise and stall speed, and very small structural safety margin beyond what is needed for straight and level flight. When fully loaded, they could easily breakup in-flight if banked too steeply, flown too fast, pulled-up too sharply, flown in turbulent air, or if the pilot's control inputs got out of phase with the deflections of the fuselage and wing.

A sub-orbital horizontal takeoff vehicle will need the characteristics demonstrated by aircraft with larger empty mass fractions (and hence lower payload and propellant mass fractions). These characteristics include a high rate of climb and a stiff structure. The vehicle must be stiff enough so that the fuselage and wing bending modes don't couple into the controls, can withstand a pull-up right after takeoff, turbulent air, supersonic flight, relatively high aerodynamic pressures, and have a reasonable flutter speed.

There have been two types of horizontal takeoff vehicles proposed:

(1) Rocket only power
(2) Combined jet and rocket power.

Rocket Powered Horizontal Takeoff. There have been several horizontal takeoff rocket powered aircraft built. These include the German Me-163, the Bell X-1, the Russian Mikoyan I-270, and recently the XCOR's EZ-Rocket. The Me-163 was the highest flying of these aircraft and had a demonstrated altitude of only 42,000 ft (12,800 m), although it had a calculated peak altitude of 52,000 ft (15,800 m).[5] The Bell X-1 was normally air launched, but Chuck Yeager flew it once from a runway to an altitude of 23,000 ft (7,000 m). The Me-163 was the only one of these aircraft equipped with a turbo-pump fed engine, which is one reason why it could reach the highest altitude.

Rocket engine thrust can be less than the initial takeoff weight in a horizontal takeoff vehicle, i.e., *T/W* can be less than 1.0. Typically, rocket engines weigh about 1% to 2% of the takeoff weight. In contrast wings and wheels weigh about 20% of takeoff weight for a horizontal launch vehicle. So although a rocket powered horizontal takeoff vehicle benefits from a small reduction in the size of its rocket engine, it does so at the penalty of a large increase in its overall empty weight due to its larger wings and landing gear.

Messerschmitt Me-163B (USAF Museum image)

Also it has been known for a long time that wings can help reduce the delta V required to reach orbit.[6] Almost all of the benefit from wings occurs high in the atmosphere once the vehicle is on its side and accelerating horizontally to orbital velocities. During this portion of the trajectory, lift from the wings can be used to reduce gravity losses, but at some increase in drag losses.

A common misconception is that wings can be used by a rocket powered horizontal takeoff vehicle to reduce the propellant for a sub-orbital trajectory. This is not the case since the goal of the trajectory is to momentarily reach an altitude and then return back to the launch site. There is no need to obtain and maintain large horizontal velocities as in the case for a trajectory to LEO.

Note that even if a rocket powered horizontal takeoff vehicle conducts a sharp pull-up to a vertical trajectory immediately after takeoff, it will use significantly more propellant as compared to a vertical takeoff vehicle because the horizontal takeoff trajectory requires an additional 20 to 60 seconds of propulsion firing to complete.

The amount of propellant required is directly related to the length of propulsive firing and is given by:

$$W_p = T \cdot t_b / I_{sp} \tag{3}$$

where propellant mass, W_p , is equal to rocket engine thrust, T , multiplied by engine run time, t_b , and divided by specific impulse, I_{sp} .

If a rocket powered horizontal takeoff vehicle chooses to fly an inclined flight path instead of pulling up to a vertical trajectory, then thrust will be less, but the engine run time to reach a particular altitude will be longer since the vehicle climbs along an inclined flight path. Hence if flight velocities are the same and drag is ignored, then propellant burnt is the same to reach an altitude whether flying an inclined or vertical trajectory. In reality, the inclined trajectory takes more propellant since the additional drag caused by the wing producing lift (known as induced drag) must be overcome by increased thrust.

Another way to look at this is that the Work (force multiplied by distance) done against gravity is the same for an object raised vertically as it is for an object raised along an inclined path if friction is ignored. If friction is included, then the shortest path (vertical) requires less Work.

<u>Horizontal Takeoff Combined Power</u>. Surprisingly many of the proposed X-Prize vehicles are horizontal takeoff concepts using combined jet and rocket power. Jet engines are very large in comparison to rocket engines and they weigh 10 to 20 times more than a rocket engine of similar thrust. On the other hand, a jet engine's specific impulse, if considered on a thrust per unit flow of propellant carried, i.e. kerosene only, is some 20 times higher than that of a rocket. This is why jet engines are preferable for cruise missiles and aircraft. Finally, a jet engines thrust decreases with altitude at subsonic flight speeds; approximately half of sea level thrust at 22,000 ft (6,700 m) and quarter at 40,000 ft (12,000 m), while a rocket engine's thrust increases by 15% to 25% in a vacuum as compared to sea level.

A combined powered vehicle must carry both jet engines sized to provide all the thrust needed to fly the aircraft and rocket engines also sized for the same task. The two propulsion systems not only add weight, but also use up internal volume that would otherwise be used to carry either propellant or payload. Propellant tanks must be divided to carry both jet fuel and rocket propellants. It is not surprising that these designs have the smallest propellant mass fraction available for their rocket motors of all the various concepts.

At least four different combined jet and rocket powered aircraft were built and flown. Of the four, the Lockheed NF-104 was the only one that could fly supersonic on the thrust of its jet engine alone. In 1959 Air Force Captain Joe Jordan set an altitude record of 103,000 ft (31,400 m) in a standard F-104 using jet power only. In 1963 the NF-104's rocket engine allowed Major Robert Smith to zoom climb to a record 120,800 ft (36,830 m), only 17,800 ft (5,430 m) higher. Of the three NF-104's built, one was lost to a rocket engine explosion and another was lost to an out of control flight accident. The last one is on a pole in front of the US Air Force's Test Pilot School at Edwards AFB. The NF-104's flew 302 flights accumulating 8.6 hours of rocket engine operation.[7]

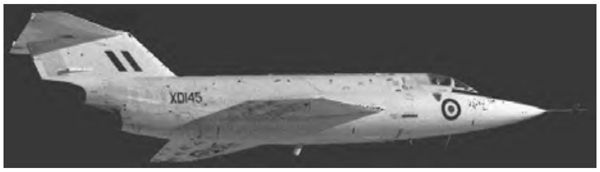
Lockheed NF-104 (USAF image)

The remaining three combined powered aircraft were capable of only subsonic flight when powered by their jet engines. In this respect, they are similar to all of the currently proposed X-Prize concepts in that none of these X-Prize concepts are expected to be capable of supersonic flight using their jet engines.

However, these historical aircraft differ in that they all used turbo-pumps to feed their rocket motors. In contrast almost all of the X-prize concepts avoid the complexity of a turbo pump by using a simpler pressure fed design. Not only is this heavier, but all of the propellant must be carried in the fuselage because the tank pressure will be far too high for wing tanks.

Republic XF-91 Thunderceptor (USAF image)

The Republic XF-91 Thunderceptor was first flown on jet power on 9 May 1949. The first rocket-powered flight was in fact unplanned and came on 11 September 1952 when the Thunderceptor's J47 turbojet flamed out on takeoff. Of the two built, one was destroyed when its rocket engine exploded, nearly blowing the tail off the aircraft. The other aircraft is on display at the Wright-Patterson AFB Museum. Peak altitude obtained with both rocket and jet power was 48,000 ft (14,600 m) and maximum flying time on jet only power was 25 minutes.[8]



Saunders-Roe SR-53

The British Saunders-Roe company built two SR-53 combined powered aircraft. One was damaged to a rocket engine explosion during a ground test in 1955. The SR-53 first flew on 16 May 1957. The test program was stopped when a SR-53 crashed and fatally injured its pilot during takeoff on 5 June 1958. Peak altitude with both rocket and jet power was 67,000 ft (20,400 m).[9]

Sud Aviation SO 9050 Trident

Finally, France's Sud Aviation built eight Trident prototypes of 3 different designs. First flight was on 19 July 1955 and they logged more than 600 flights including 220 on rocket power. One Trident was lost on its second flight and another crashed during the 1957 Paris air show. They were capable of zooming to 79,500 ft (24,200 m) when both jet and rocket engines were operating.[10]

Although almost half of the X-Prize entrants have chosen combined powered horizontal takeoff concepts, these historical examples demonstrate that they will have a difficult time reaching 100,000 ft (30,400 m), much less the X-Prize goal of 328,000 ft (100,000 m).

Air Launch

In an attempt to solve some of the problems of horizontal takeoff, several air launched methods have been proposed. As a minimum, air launch vehicles are two-stage consisting of a carrier aircraft and a rocket powered RLV. Air launched methods can be categorized into six methods:[11]

(1) Captive on top
(2) Captive on bottom
(3) Towed
(4) Aerial refueled
(5) Internally carried
(6) Balloon

Air launching reduces the propellant mass fraction required to reach 100 km as compared to a vertical ground launch. For example, the X-15 carried a propellant mass fraction, δ_p , of 0.55 and was capable of sub-orbital flight. "Zoom" launching a RLV with the carrier aircraft to a flight path angle of 50 to 60 degrees above to the horizon reduces the δ_p needed to reach 100 km to about 0.5. A RLV with a δ_p of 0.5 must carry its empty weight in propellant. In contrast, a ground launched vertical takeoff RLV with a δ_p of 0.63 must carry twice its empty weight in propellant. Hence air launching can reduce RLV size.

The reduction in RLV δ_p is due to the fact that the vehicle is two-stage. The RLV has a shorter climb distance (85 km to 94 km instead of 100 km) and its rocket motor has improved specific impulse, I_{sp} , because of better thrust expansion in the engine nozzle and to using a larger nozzle properly sized for the launch altitude.

Air launching also reduces the aft fuselage damage caused by acoustic energy from the engine since there is no reflection from the ground during launch and local air density is lower at launch.

Furthermore, air launch RLVs can operate with minimum launch site requirements. A takeoff pad is not required.

On the other hand, winged RLVs that are air launched may require precise control of longitudinal center of gravity. This means that fuel and oxidizer tanks may have to be divided into smaller tanks with additional tank bulkheads and transfer pumps. Both the X-15 and X-34 had propellant tanks subdivided into multiple tanks, but clever design can limit the number of tanks.

Air launching can either reduce or increase the peak aerodynamic pressure that the RLV is subjected to. Peak dynamic pressure is one of the elements that determine vehicle structural design. For example, the Orbital Science's air launched Pegasus XL experiences over 1,250 pounds per square foot (psf or 0.6 bar) aerodynamic pressure, twice the Space Shuttle's, even though the Pegasus is launched at 38,000 ft (11,500 m). On the other hand, zoom launching a RLV with the carrier aircraft, launching from a slow flying carrier aircraft, or balloon launching can reduce RLV peak dynamic pressure to as little as 1/3 of a vertical ground launch or to about 200 to 300 psf.

Air launched winged RLVs are subjected fuselage bending loads similar to horizontal takeoff vehicles. This means that their empty mass fractions are greater than vertical takeoff vehicles.

Air launching requires a specially modified carrier aircraft capable of carrying the RLV. The carrier aircraft will typically be heavier than the RLV itself; for example, the 480,000 lb (220,000 kg) B-52 carrier aircraft carrying a 33,000 lb (15,000 kg) X-15. This limits the size of the RLV and means that there is limited growth potential for air launching.

In some air launch concepts, parts (such as explosive bolt debris or cables) are designed to or have the potential to fall off. For this reason, government and safety regulators may require that an air launch be conducted over certain areas such as a government range or over the open ocean. This potentially can negate one of air launching's primary advantages, which is the ability to operate free of national range scheduling constraints.

Propellant boil off can be a major problem for those concepts that both use cryogenic propellants and have the RLV carried outside the carrier aircraft. Propellants are heated by radiation heating from the sun and convective heating from the air stream. For example, the X-15 boiled off 60% to 80% of its liquid oxygen (LOX) during its 45 minute to 1 hour climb and ferry while attached to its B-52 carrier aircraft. The LOX was replenished from an internal insulated tank carried in the B-52's bomb bay.

Finally air launched RLV engines are typically started after they are dropped from the carrier aircraft for the safety of the carrier aircraft. If the rocket engine fails to start, then propellant must be dumped quickly and an emergency landing must be completed. This happened several times during the X-15 rocket plane's 199 flights.[12]

Captive on top. No examples of captive on top RLVs have been actually built, but the Space Shuttle's approach and landing demonstrator, the Enterprise, used this method to test its landing. Advantages of this method include the capability to carry a large RLV on top of the carrier aircraft and lighter RLV landing gear sized only for landing. Disadvantages include penetrations on the windward side of the RLV's thermal protection system (TPS) for attachment hard points and extensive modifications (high cost) to the carrier aircraft. Also the RLV must have active controls at release from the carrier aircraft to prevent it from hitting the carrier aircraft. Since the RLV's wings must be large enough to support the RLV at separation from the carrier aircraft, the RLV itself may have to be a multi-stage vehicle and its wings may have to be released and staged after an aerodynamic pull-up into a vertical trajectory.

Placing a RLV on top of the carrier aircraft destroys the lift produced by the fuselage and causes a large amount of drag that in turn limits launch altitude. For example, during its approach and landing test flights, the Space Shuttle was launched at altitudes between 19,000 to 26,000 ft (5,800 to 8,000 m) from its carrier Boeing 747, even though a clean 747 normally cruises at 38,000 to 45,000 ft (11,500 to 13,700 m).

X-15 air launching from B-52 (NASA image)

Captive on bottom. Examples include the X-15, X-34, and Scaled Composites' SpaceShipOne. Advantages include proven and easy separation from the carrier aircraft, leeward side penetrations and hard points on the RLV that eliminate some TPS concerns, lighter RLV landing gear sized for landing, and the option of sizing the wing smaller than required for level flight at the release altitude and airspeed. Disadvantages include limits to RLV size due to under the carrier aircraft clearance limitations and the high cost of carrier modifications. A new design carrier aircraft with tall landing gear can eliminate the clearance limitations.

Towed. One of the first occurrences of towing a rocket-powered aircraft was during the summer months of 1942 at Peenemünde, Germany. Twin engined Bf-110C fighters were used to tow prototypes of the Me-163 rocket fighter for flight tests, typically to altitudes of 16,400 ft (5,000 m).

The primary advantages of a towed air launch are easy separation from the towing aircraft and low cost modifications to the towing aircraft. Safety concerns include broken towlines and a towing aircraft takeoff abort.

The principal disadvantage of towing is that the RLV's wings and wheels must be sized for takeoff with a full propellant load. Towing provides some improvement as compared to rocket powered horizontal takeoff, but in order to reach 100 km, a multi-stage RLV may be needed in which the wings and wheels are staged after the tow-line release and the completion of the aerodynamic pull-up maneuver.

Aerial Refueled. Aerial refueling is only proven for kerosene fuels. Cryogenic propellants like liquid oxygen have the potential of freezing the refueling probe to the refueling line. The principal advantage of aerial refueling is that it reduces the size of the RLV landing gear and wing. Note that aerial refueling does not reduce the size of the jet engines; they must be sized to maintain level flight for the fully fueled RLV, and aerial refueling does not reduce the strength of the wings, which must be strong enough to support the fully fueled RLV weight. Aerial refueling provides some improvement to a combined powered horizontal takeoff concept, but in order to reach 100 km, a multi-stage RLV may be needed in which the wings, jet engines, and landing gear are staged after the completion of a pull up maneuver.

Internally Carried. Internal air launch has been demonstrated before. On 24 October 1974 a C-5A Galaxy dropped a 78,000 lb (35,500 kg) LGM-30A Minuteman I missile using drogue chutes to extract the missile and its 8,000 lb (3,600 kg) launch sled. The missile was then successfully fired.

Minuteman launching form C-5A (USAF image)

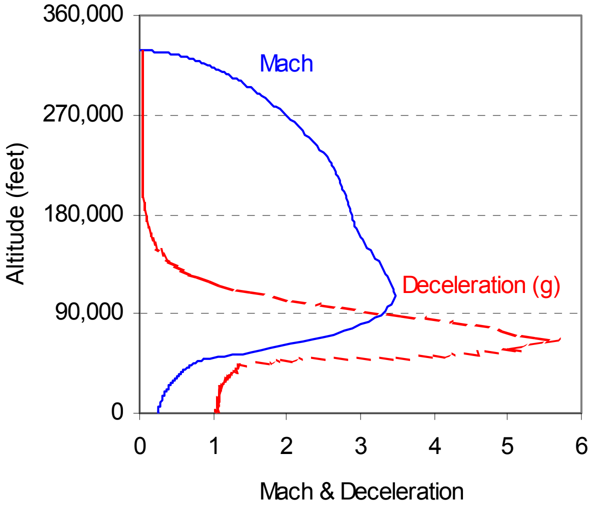
Advantages of internally carried concepts include little or no modification to the carrier aircraft. Most propellant boil-off concerns are eliminated since the RLV is not subject to either radiation heating or convective heating. The RLV is in a benign environment inside the carrier aircraft that allows maintenance and safety problems to be detected prior to launch. Release altitude can be at a higher altitude because the RLV does not increase the carrier aircraft's drag.

The main disadvantage is that the RLV must be sized to fit inside the carrier aircraft. Also operations must be conducted over the water since many parts such as a launch sled fall away.

Balloon Launch. Balloon launch requires operating a very large balloon. Launch can occur only on calm days. Since the balloon comes back unmanned, the potential to damage either the balloon or things on the ground is high.

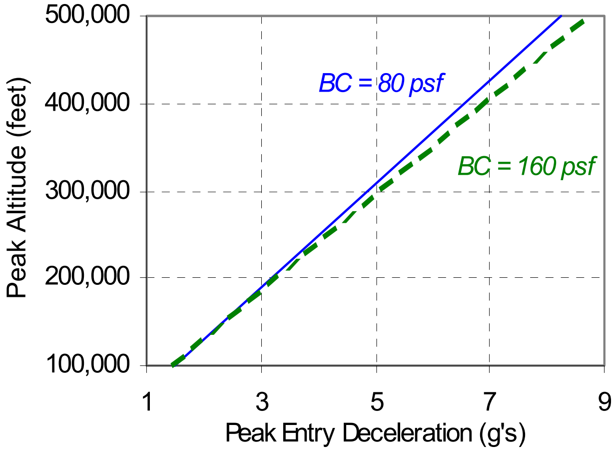
ATMOSPHERIC ENTRY

The next figure shows the Mach number and deceleration experienced by an object falling vertically. The figure was obtained by numerical time stepping of the equations of motion for a blunt object falling from 328,000 ft (100 km). The solid blue line represents Mach number, which peaks at 3.5 at 100,000 ft (30,500 m). The dashed red line represents deceleration, which peaks at 5.5 times the earth's gravity at 70,000 ft (21,300 m).

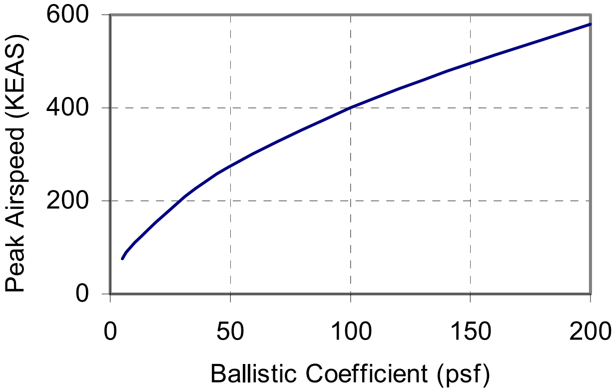


For objects entering the earth's atmosphere, peak entry deceleration is a function of the trigonometric sine of the entry angle and the square of the entry airspeed. Since a X-Prize sub-orbital trajectory is mostly vertical in both the up and down directions, then entry deceleration is a function of entry airspeed only, which in turn is determined by the trajectory's peak altitude (*h*).

The next figure shows the peak entry deceleration for two different ballistic coefficients (*BC*). *BC* is the ratio of the mass of a vehicle divided by the product of drag coefficient and drag area. Since drag coefficient varies with Mach number, then *BC* can be expected to vary with Mach number as well. A *BC* of 80 pounds per square foot (psf or 0.038 bar) is representative of the Mercury capsule whereas a *BC* of 160 psf (0.076 bar) is the Soyuz descent capsule. Notice that the X-Prize Foundation's altitude goal of 328,000 ft (100 km) is about the highest altitude that a tourist can be expected to tolerate comfortably. Also notice that peak deceleration does not vary too much with *BC*.



Reentry aerodynamic pressure is set by *BC* and the peak height of 100 km. The next figure shows the peak aerodynamic pressure in terms of equivalent airspeed in knots (KEAS). Peak dynamic pressure occurs between Mach 2 and 2.8 depending in *BC*. *BC* must be kept very low in order to use general aviation like structures. Otherwise stiffer structures similar to that used in fighter aircraft are needed.



Total temperature can momentary be expected to be approximately 1000 degree Fahrenheit (540 C) due to the Mach 3+ entry. The actual equilibrium surface temperature will depend on the heat sink characteristics of the vehicle structure. High temperatures will eliminate the large general aviation like Plexiglas windows seen in many concepts. Instead double pane high temperature windows may be required as well as some minimal thermal protection for the rest of the vehicle.

LANDING MODE TRADE

After a RLV decelerates to subsonic speeds, a landing mode must be selected. There are four major landing modes available:

(1) Wings
(2) Aerodynamic decelerators
(3) Rockets
(4) Rotors

In addition, a designer has the choice of landing the vehicle on its tail (tail sitter) or landing it on its side (horizontal lander). Tail sitters have the advantage of having only one structural load path; the vehicle can be designed mostly to axial loads. This saves weight and is the main reason that tail sitters have been considered in reusable Single Stage To Orbit (SSTO) vehicles studies, since weight is critical for such vehicles.

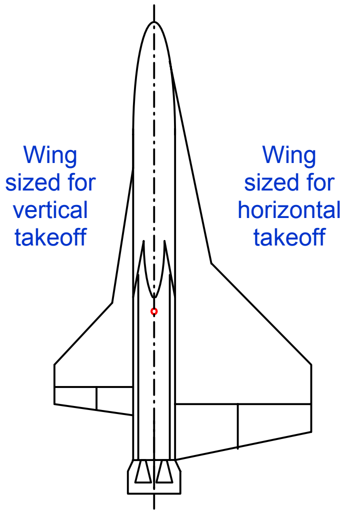
A disadvantage of a tail sitter is that they may fall over upon landing, unless the landing area is perfectly flat and the winds are low.

Wings

Horizontal landing using wings and wheeled landing gear are well proven and have been used by the American X-1, X-2, X-15, and Space Shuttle, and Russian Buran space vehicles. It provides the softest landing of all the landing methods with landing touchdown vertical velocities less than about 2 feet per second (fps or less than 1 m/s).

Wings and wheels can be sized to land even the largest RLV. For a vertical takeoff vehicle the wings can be sized for landing weight only, which significantly reduces their size and drag. For example, the left side of the next figure shows the wing size needed to land at 195 knots (100 m/s) an empty X-34 that weighs 18,000 lbs (8,200 kg). The right side of the figure shows the wing needed to horizontally take-off at the same airspeed a fully fueled X-34 weighing 48,000 lbs (21,800 kg).

In addition, a vertical takeoff RLV's wing can use blunt leading edges that reduce thermal protection problems. Sharp leading edges provide much better supersonic lift versus drag performance. However sharp leading edges will get much hotter as compared to a blunt leading edge. Heating rates are a square root function of leading edge radius.



Wings and wheels require long runways and either a highly skilled and proficient human pilot or a complex automated landing system. Based on historical data, wings and wheels will constitute about 20% of the landing weight. Although the ascent drag of the wings detracts from ascent performance, this turns out to be a minor loss.[3]

Critical to the design of a winged vehicle is the need for large dive brakes or some other means to minimize pullout acceleration g's because of the vertical nature of the entry trajectory. Pullout acceleration g's can be minimized by first allowing the vehicle to decelerate to subsonic speeds before transitioning from a vertical descent to a horizontal glide.

Aerodynamic Decelerators

There are three types of aerodynamics decelerators.[13] These are:

(1) Parachutes
(2) Parafoils
(3) Rigid or semi-rigid decelerator

Aerodynamic decelerators do not need a long runway and a highly trained human pilot or a complex automated landing system. However, the effort to develop a reliable man-rated system is illustrated by the X-38's four-year flight test program which consisted of 26 drops using 3 different size parafoils and 4 different test vehicles dropped from C-130 and B-52 aircraft.[14]

Parachutes. Parachutes are limited to landing weights less than about 40,000 lbs (12,200 kg). A parachute landing system can be the lightest weight recovery system with the parachute portion equal to only 2.8% to 6% of the landing weight.

Parachute landing needs a large flat landing area since there is little control over the precise landing spot unless a controllable parachute is used. The US Army has been successfully experimenting with a controllable drogue chute that allows relatively precise landings with a 330 ft (100 m) circular error probable (CEP), but the system is not operational yet.[15]

The main challenge with parachute system is in the attenuation of the landing impact. In many concepts, the crew compartment separates from the rest of the vehicle to allow the use of a better landing attenuator for the crew. There are five attenuation methods:

Water landing. Parachute landing into the water has been proven to be the lightest weight recovery system of all landing systems. This method was successfully used in the American Mercury, Gemini, and Apollo programs. There were no fatalities attributed to this landing method although a Mercury astronaut almost drowned.

The major disadvantage of water landing is the significantly increased cost and time to refurbish a RLV for another flight and the cost of a recovery ship. A several people would be required to recover the vehicle and landing in water would mean that the vehicle would need to be carefully disassembled and repaired after every flight. Currently there is no reusable thermal protection system that can withstand a dunking into the water.

Another disadvantage is that some tourists may become sea sick after their flight.

Retrorockets. The Russians have successfully used retrorockets to cushion the final touchdown impact for all their manned space flight missions. On the Soyuz capsule, the retro rockets are placed behind the heat shield to protect them from reentry heat. The heat shield is dropped at altitude, which not only exposes the retro rockets but also prevents the hot heat shield from heating up the cabin interior. The heat shield becomes a hazardous piece of debris.

For optimum weight, the rate of descent for a parachute retrorocket system is in the order of 35 fps (10 m/s) or above. This rate of descent is too high for manned vehicles if the requirement exists for minimum aircrew injury at retrorocket malfunction. Hence retrorockets must be very reliable. The retrorocket component weight for a 35 fps (10 m/s) parachute descent is approximately 2% of the overall landing weight.

Finally there is a possibility of a ground fire caused by the retrorockets.

Airbags. Kistler Aerospace planned on using airbags to cushion the parachute landing of their unmanned K-1 RLV. Kistler sized its parachutes for a 20 fps (6 m/s) rate of descent. The only manned operational use of parachutes and airbags was the F-111 crew escape capsule. This system had a very high landing impact at 26 fps (8 m/s) vertical, which was equal to a 10.5 ft (3 m) fall. As a result, a high percentage of crew were injured during an ejection. The F-111 airbag system weighed approximately 3% of the escape capsule's weight. This system was also considered for the B-1 bomber, but standard ejection seats were chosen instead.

Crushable Impact Attenuators. Crushables include balsa wood, several types of foams, and paper, plastic, and aluminum honeycomb. Balsa wood has the best energy absorption per pound of material weight (≈24,000 ft-lbs per lb)[13], followed by honeycombs, with foams having about 1/5 the capability of balsa wood. The rise of the force, called the onset rate in *g* per second, is important for manned vehicles, since the human body limits the onset rate. The Apollo moon lander, the LEM, used a crushable in its landing gear. Also the landing peak force (in excess of 10 *g*'s) may determine the vehicle structural design, since landing impacts can be expected to higher than any other load a RLV will experience. To limit deceleration to 10 *g*'s, the crushable must compress at least 30 inches (for a 28 fps parachute descent rate).

Pneumatic Retractor. The US Army is experimenting with a pneumatic retractor that would pull a parachute and its load together just before landing to reduce landing impact. The system is in its early development stage.

Parafoils. A parafoil is a rectangular ram-air lifting parachute. Its usage is limited to vehicles that have a landing weight less than 25,000 lbs (11,400 kg). The recently cancelled space station rescue vehicle, the X-38, used this landing method. Timing the landing flare is the main challenge. The X-38's average vertical landing velocity during 26 test landings was 20 fps (6 m/s), which is equal to a 6.2 ft (1.9 m) fall.[14] It's average during the last 4 test drops, which were considered by the test team to be very good, was 15 fps (4.6 m/s) vertical with an average impact acceleration of 12 g's. The hardest landing was at 27 fps (8.2 m/s) and 41 g's. These are hard landings. As a comparison, naval aircraft hit an aircraft carrier flight deck at 10 fps (3 m/s) vertical. The X-38 landing gear was damaged or destroyed often during its test landings.

A parafoil's landing rate of descent is not much different from that available from much lighter circular parachutes. Parafoils are heavier than circular parachutes because they have more than twice the fabric (for upper and lower surfaces plus vertical ribs). The X-38's parafoil alone weighed 9.8% of the X-38's landing weight as compared to the Apollo parachute's 2.8% of capsule weight. In addition to the parafoil, the weight of the landing gear, drogue chutes, and parachute compartments must be accounted for when comparing parafoils to other landing modes.

Rigid or semi-rigid decelerator. German DaimlerChrysler and Moscow-based NPO Lavochkin have developed a cone shaped aerodynamic decelerator known as IRDT (Inflatable Reentry Descent Technology). It was reentry flight tested in 2000 with an experimental Russian booster rocket and it survived its return to Earth, although it was damaged on the way down. IRDT technology is not intended for manned flight.

Such a decelerator weighs as much as a wing and wheel system and would require either an airbag or retrorocket to cushion its final impact. Probability of falling over is very high due to the large amount of area presented to ground winds.

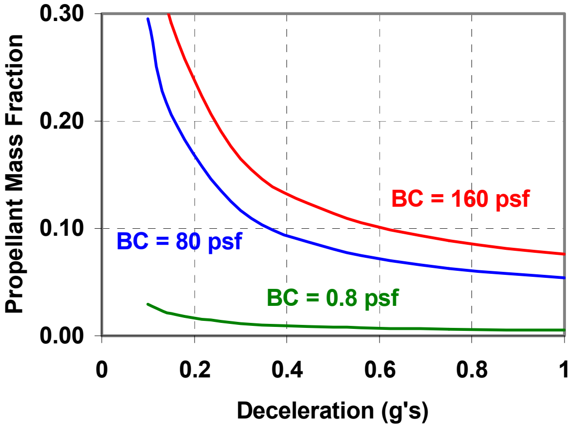
Rocket Recovery

The McDonnell Douglas DC-X is an example of a rocket powered vertical lander and tailsitter. The DC-X was 41 ft tall and 13 ft across its base. 47% of its 40,000 lb takeoff weight was propellant, of which a large percentage had to be reserved for landing, which in turn limited demonstrated peak altitude to only 8,700 ft (2,650 m). Furthermore during its test flights, the DC-X used its rocket engines as its primary control system, which meant that they could not be shut off. The DC-X was flown over desolate terrain because the rockets could ignite a fire in the ground foliage.

Four technologies are required if rocket recovery is to be weight competitive with the other landing modes. First a high specific impulse rocket motor is needed. The DC-X used a liquid hydrogen and liquid oxygen motor that had a sea level I_{sp} greater than 330 seconds at full throttle and 280 seconds at 30% throttle. Second, the motor must be very reliable and be able to start quickly. Third, the guidance and control system must be capable of accurately judging altitude above the ground. Finally, a high and sustained deceleration must be used during landing.

The next figure shows the relationship for propellant mass fraction, δ_p , and landing deceleration for a vertical lander. The figure was prepared assuming an average I_{sp} of 300 seconds and allowing no reserve propellant for hovering. Three ballistic coefficients (BC) are shown. 160 psf gives a terminal velocity of 368 fps (112 m/s or 217 knots), while 80 psf gives a terminal velocity of 260 fps (80 m/s or 155 knots), both at sea level. The DC-X's BC was between these two lines, depending on amount of propellant onboard. The 0.8 psf line represents a vehicle descending under a standard Army cargo parachute at 26 fps (8 m/s or 16 knots).

For rocket landing to be competitive with other landing modes, extremely aggressive maneuvers must be used. For example, to match parachute landing system weights, then a sustained landing deceleration of about 1 g is needed. The DC-X demonstrated peaks of 0.4 g's and sustained much less than this. As a comparison, an aggressive helicopter or Harrier jet deceleration is about 0.1 g's. If a 1 g deceleration is used, then the rocket motors are not started until the vehicle is 1,000 ft (300 m) above the ground. The motors are fired for only 8 seconds as the vehicle slows to a stop. They must be perfectly throttled in order to avoid hovering; otherwise extra propellant would be consumed. If the motors fail to start, the vehicle crashes into the ground only 4 seconds later. However if Harrier jet, helicopter, or Apollo moon lander landing decelerations are used, then the δ_p for rocket landing is greater than 0.3 even with high I_{sp} engines. In other words, over 30% of vehicle landing weight must be propellant.



The propellant mass fraction for a parachute retrorocket system (as indicated by the 0.8 psf line) is relatively insensitive to landing decelerations. Notice less than 2% of the landing weight must be propellant for the retrorocket. Hence the choice of combining a parachute recovery system with a retrorocket in the Soyuz makes sense.

Rotor Recovery

There are two types of rotor recovery systems. Those that use stored rotor inertia only to cushion the landing and those that use tip rockets. A tip rocket powered rotor is more complex but would be lighter since a pound of tip rocket fuel has 20 times more energy than the stored kinetic energy in a pound of rotor tip weight.[16]

The Rotary Rocket Company experimented with a tip rocket powered rotor recovery system. They built an Atmospheric Test Vehicle (ATV) that flew 3 times in 1999 and demonstrated hover and forward flight with flight speeds up to 50 knots (84 fps or 26 m/s) and altitudes of 75 ft (23 m). The ATV was 61 ft tall and 22 ft across its base, and although much larger than the DC-X, it was built and flown for about 10% of the cost of the DC-X program. The first author was the test pilot for all of the flight tests as well as the chief engineer for the ATV, and the vehicle was found to be very unstable and extremely difficult to fly.[17] This landing method was abandoned when later analysis showed that the rotor would have insufficient aerodynamic control power to control the vehicle through the high subsonic and transonic flight regime.

CANDIDATE ARCHITECTURES

Our study shows that vertical takeoff and some air launch methods are viable means of attaining the X-Prize altitude goal of 328,00 ft (100 km). Also wings with wheels and aerodynamic decelerators are technologically mature enough to serve as viable methods for recovery. As a result there are 4 architectures that can successfully win the X-Prize:

(1) Vertical takeoff, Aerodynamic decelerator
(2) Vertical takeoff, Wings with wheel landing
(3) Some Air Launch, Aerodynamic decelerator
(4) Some Air Launch, Wings with wheel landing

The preferred architecture for a vehicle that can not only win the X-Prize but also serve as a commercially successful sub-orbital tourist vehicle depends on the additional factors of safety, customer acceptance, and affordability.

SAFETY

Safety is the reasonable degree of freedom from those conditions that can cause injury, death to personnel, damage or loss of equipment or property; it is the freedom from danger. The advocacy of horizontal takeoff for many X-Prize concepts may be largely based on the intuitive belief that such vehicles would bring the greater safety of commercial airline aircraft to space transportation. In reality, direction of takeoff has little to do with safety. Previously built rocket powered airplanes do not appear to demonstrate remarkably better safety records as compared to vertical launch vehicles.

Sufficient data is available from expendable launch vehicles (ELVs) experience to pinpoint catastrophic failure modes sources for rocket-powered vehicles. The catastrophic failures during 1,176 ELV launches break down as:[18]

Sub system	Failure Rate
Propulsion	69.7%
Avionics	16.3%
Staging	7.0%
Environmental	4.7%
Structural	2.3%

Propulsion Safety

Propulsion failures accounted for almost 70% of all the catastrophic failures. Elimination of propulsion failures requires picking the right rocket engine type. There are three major types of rocket engines. Liquid propellant engines use a separate oxidizer, for example, liquid oxygen; and a separate fuel, for example, kerosene or liquid hydrogen. Solid propellant motors use a solid propellant grain that contains both the oxidizer and the fuel. Finally a hybrid motor typically uses a liquid oxidizer such as nitrous oxide or liquid oxygen and a separate solid fuel grain such as rubber, wax, or plastic.

Liquid propellant engines can fail either catastrophically or benignly. Roughly 3 out of 4 kerosene and liquid oxygen (LOX) engine failures are benign, in the sense that the engine failure results in loss of thrust, but not in immediate destruction of the vehicle. The historical benign failure ratio for kerosene-LOX engines is 0.6% (benign failures / engine flights) while the catastrophic failure ratio is 0.2%. While the number of solid rocket motor failures is small, they have all been catastrophic, rather than benign failures.[19] Hence designers should limit the number of liquid engines or solid motors in a vehicle since a large number of either would increase the chance of a catastrophic failure.

On the other hand, according to the Department of Defense Explosives Safety Board, hybrid motors can be fabricated, stored, and operated without any possibility of explosion or detonation.[20] Other advantages include the ability to be stopped, restarted, and throttled; easy (and hence potentially cheaper) ground handling; and relative insusceptibility to grain flaws.

Multiple hybrid motors can be used to improve propulsion system reliability by providing redundancy in the case that one hybrid motor fails to produce adequate thrust. Such active redundancy (also referred as to as ‘engine out’ and ‘fail-safe’ capability) can allow a vehicle to complete a flight following the failure of any one engine, provided of course that the engine failure is benign. In this respect, hybrid motors are like jet engines, which have an almost zero probability of catastrophic failure, but sometimes may not produce thrust. Note that hybrid motors and jet engines can catch on fire, so a fire suppression system is needed.

Experience has also shown that a significant number of propulsion failures occur during engine start. Although there has been some good progress in understanding steady state combustion process, the prediction and modeling of a new rocket engine during a start up, especially those using turbo pumps, is immature.

Historically, air launched RLV engines are started after the RLV is dropped from the carrier aircraft to ensure carrier aircraft safety. If the engine does not start or has some other malfunction that would require an immediate engine shutdown then propellant must be dumped and an emergency landing must be completed. On 9 November 1962, Jack McKay was seriously injured and the X-15 severely damaged when its engine failed to throttle up after release from the carrier B-52 aircraft. The X-15’s landing gear failed during the emergency landing due to overstress caused by a faster than normal landing speed (296 mph instead of the normal 230 mph) which was caused by an incomplete propellant jettison.[12]

Experience has shown that the initial few seconds after ignition tends to determine whether a rocket engine will or will not fail for the remainder of its operation. This means that in the case of a ground launch, a rational way to prevent vehicle failure would be to hold the vehicle on the pad until all systems appear to be in order. In event of problem, a controlled shutdown on the pad can be executed. Pad hold-down, generally for a few seconds after ignition, makes it possible in the event of engine failure to shut down all engines and abort the flight on the pad.

Once released from the takeoff pad, enough engines on a vertical takeoff vehicle must operate until the vehicle is high enough to dump its remaining propellant and conduct an emergency landing – an altitude that is likely to be at least 10,000 ft (3,000 m) above the ground. Using active redundancy with multiple hybrid motors and sizing the motor’s thrust so that the vehicle can fly away with a motor out can allow a vertical takeoff vehicle to complete an abort as long as a single motor failure does not cascade into other failures. For example, a vehicle with 4 hybrid motors and a lift-off thrust-to-weight ratio (*T/W*) of 1.6 can climb away in the event of a motor failure, even at lift-off.

Advocacy of horizontal takeoff may be based on the mistaken notion that such a vehicle is safer at takeoff. However, propulsion failure at takeoff rotation will also most likely result in a loss of vehicle (for example, the Sanders-Roe SR-53 takeoff fatality discussed previously). There is no data that supports the contention that horizontal takeoff reduces rocket engine propulsion failure causes or rates. In addition, horizontal takeoff adds failure modes not found in the other takeoff methods. For example, 4 of the 19 SR-71 Blackbirds destroyed in accidents were due to blown tires on takeoff.

Avionic Safety

Aircraft practices can be used to minimize avionic failure modes in all four viable sub-orbital architectures. Installing redundant systems can reduce avionics and electrical failures, as this is done in commercial aircraft. Most ELV’s have only single string avionics and electrical systems. In ELV’s, redundancy to ensure mission success has been relegated to duplication of the complete ELV.

Staging Safety

The X-Prize altitude goal of 100 km can be reached with a single stage vertical takeoff vehicle. Air launch introduces the additional possibility of a separation failure, such as a RLV and carrier aircraft collision. Hence vertical takeoff is favored over air launch to improve staging safety.

In some concepts that use parachute or parafoil recovery, the crew compartment separates from the rest of the vehicle to soften the landing impact for the crew. Hence crew compartment separation represents a critical failure mode – one that is difficult to minimize with a redundant design. Also the historical fatality rate for sport parachute jumping is much higher than that for landing an airplane or glider. Hence a winged landing is favored over an aerodynamic decelerator to improve staging safety.

Environmental Safety

Launching in bad weather causes environmental related failures; for example, the Challenger shuttle accident. Tourist vehicles do not have to be launched in bad weather and they do not have to make an orbital launch window or time slot. Again wings are favored over aerodynamic decelerators since the wind limit for landing with wings is much higher than that for landing with either a parachute or parafoil. Parachute landing into the water adds the consideration of sea state; large waves could sink the RLV or drown the passengers.

Structural Safety

ELV's are built with a small structural factor of safety (typically 1.2) because they have to be light enough to make it to orbit. A sub-orbital vehicle can afford more empty weight; hence structural factors of safety can be increased to commercial aircraft standards (typically 1.5), which have been proven to reduce structural failures.

CUSTOMER ACCEPTANCE

Prospective customers are expected to be spectators first and will observe several takeoffs and landings before they purchase a ride. They would also like their family and friends to watch their flight. One reason for the numerous horizontal takeoff X-Prize entrants may be the perception that customers would prefer horizontal takeoff. Unfortunately such vehicles cannot reach X-Prize altitudes with today's technology.

Vertical launch provides a spectacular event that can serve as the centerpiece of a space based theme park or an air show. It can be easily filmed and televised. In contrast, air launching at 20,000 to 50,000 ft (6 km to 15 km) may provide very little for a spectator located on the ground to watch.

Similarly a winged landing along a steep glide path onto a runway located adjacent to the takeoff pad some 15 to 20 minutes after the launch is another exciting event. A parachute landing, perhaps miles away from the launch site or into the water may hold little interest for a spectator.

AFFORDABILITY

The costs to operate a sub-orbital tourist vehicle are highly dependent on launch rate. The more an RLV flies, the cheaper it gets. This may create a chicken and egg dilemma. The investment to build a vehicle cannot be justified unless there is a demand for many flights, but the demand for flights depends on a low ticket price.

The ticket price for a ride on a sub-orbital tourist vehicle also depends on the number of passengers carried per flight since fixed costs such as the pilot and the mechanic's salary can be divided among a larger number of ticket fares as the vehicle becomes larger. Also vehicles do not scale directly with number of passengers – a 4 passenger vehicle weighs less than twice as much as a 2 passenger vehicle. Hence, vertical launch and winged landing are favored since there is no limit to the size of the vehicle using these takeoff and landing modes.

Affordability is also driven by the overall complexity of the vehicle systems, which in turn determine operational support requirements. Advocacy of horizontal takeoff for many X-Prize concepts may have been based on the intuitive belief that such vehicles would bring the improved operational features of airplanes to space transportation. Note that horizontal takeoff vehicles have systems not found in the other two takeoff modes, i.e. jet engines (in addition to the rocket engines for some concepts), landing gear retract, and multiple propellant tanks and transfer pumps to manage center of gravity location.

When comparing landing methods, a vehicle using winged landing would take less effort to turn around for the next flight as compared to a vehicle using a parachute or parafoil recovery. The X-38 parafoil weighed almost 2,000 lbs (900 kg) and took weeks to inspect and repack. Because parachutes and parafoils have a limited weight capability, a RLV using parachute recovery may also have to separate into several parts, which would further increase the effort necessary to ready it for another flight.

Thus for the four viable architectures capable of the X-Prize, vertical takeoff with winged landing should take the least effort to turn around for the next flight. Air launching with parachute landing into the water should take the most effort to get ready for another flight. The air launched RLV also requires a custom carrier aircraft that must be developed and operated and it requires two pilots, one for the carrier aircraft and another for the RLV. For commercial sub-orbital flights, FAA certification costs will be double since both the carrier aircraft and RLV must be certified.

However, costs also depend on the size of the vehicle. Here the order is reversed. An air launched RLV can be the smallest RLV with a launch weight between than 6,000 lbs to 7,000 lbs (2,700 kg to 3,200 kg) for a 3 person craft, not including the weight of the carrier aircraft. The heaviest architecture is vertical takeoff with winged landing with a takeoff weight in the order of 40,000 lbs to 50,000 lbs (18,000 kg to 23,000 kg). The other architectures have takeoff weights that are between these weights for a 3 person vehicle. Obviously propellant cost is a function of takeoff weight, thus air launching would have the lowest propellant cost.

Thus there is no clear resolution at this point on the architecture that would have the lowest cost to develop and operate.

CONCLUDING REMARKS

This paper shows that both vertical takeoff and some air launch methods are viable means of attaining sub-orbital altitudes and wings and aerodynamic decelerators are viable methods for recovery. These conclusions are based on statistical methods using historical data coupled with time-stepped integration of the trajectory equations of motion. As a result there are 4 architectures that can successfully win the X-Prize.

Based on the additional factors of safety, customer acceptance, and affordability, we also feel that the preferred architecture for a commercial vehicle that will successfully and profitability carry tourists on sub-orbital flights is an architecture that uses Vertical Takeoff and winged un-powered Horizontal Landing onto a runway (VTHL) powered by hybrid rocket motor propulsion.

Rockwell's 1995 X-33 Concept (NASA image)

This preferred configuration would have the following features:

Vertical Takeoff – Vertical takeoff provides the capability to reach X-Prize and commercially viable altitudes. In addition, it has significant growth capability to reach higher altitudes and carry large number of passengers. Vertical takeoff provides a spectacular launch event for spectators.

Single Stage – Single stage can be used for sub-orbital flights. Single stage eliminates parts falling off the vehicle that would restrict operation to either a government range or over the ocean flight. Using a single stage architecture eliminates staging separation catastrophic failure modes.

Multiple hybrid motors – This propulsion arrangement can eliminate catastrophic propulsion failure modes when coupled with a takeoff pad hold-down system that allows motor health to be determined during the first few seconds of motor operation. In event of a problem, the motors can be shutdown. In this way, vehicle reliability can be greatly enhanced.

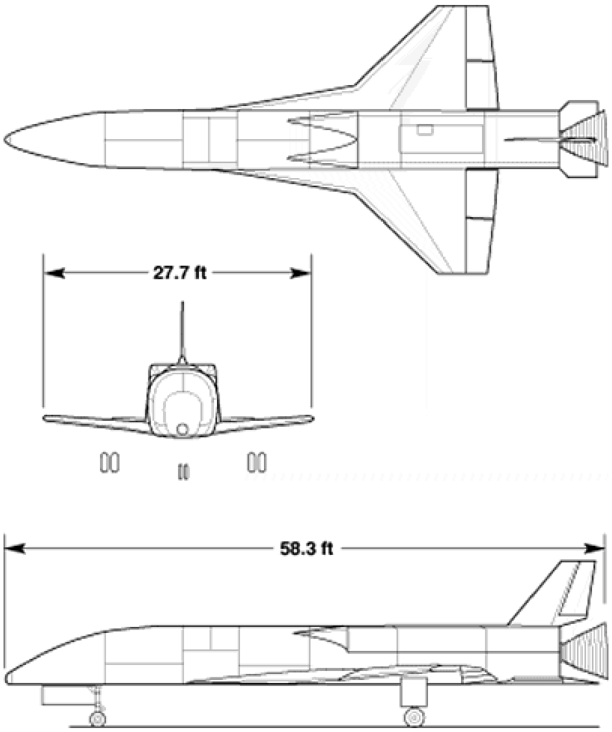
Wings and Wheeled Landing – This landing mode can provide an airliner-like soft landing at an intended point and provide a spectacular recovery event for spectators. The ability to land at a predetermined point will simplify regulatory approval and increase the number of sites at which the vehicle can operate from. Since the sub-orbital trajectory is directly above the launch site, a winged vehicle is always within glide range of an airport.

We expect that a commercially successful sub-orbital tourist vehicle would look like a scaled down version of Rockwell's 1995 vertical takeoff and horizontal landing concept for the X-33 program. However, our concept would use the outer mold line of the later NASA X-34 because of the quality of public domain wind tunnel and computational fluid dynamic (CFD) data published.[21] Producing this data cost NASA approximately $16 million and it will significantly reduce the cost and risk of developing a space tourist vehicle.

Note that our recommendations would change if the trajectory were different. For example, for an earth to orbit vehicle, we would recommend a multi-stage vehicle since all payloads placed into orbit to date have been launched on multi-stage vehicles that have some expendable components.

During the past year, we have been working on a hybrid rocket powered VTHL concept that uses the X-34's outer mold line. We have completed a conceptual design on all the vehicle's subsystems, trajectory analysis, weight and balance, and layout drawings. A 150-page PowerPoint presentation provides details of our concept. We can provide briefings to parties that would be interested in helping us establish sub-orbital tourism. Our current efforts include students working on a high-fidelity flight simulation and on a detailed finite element model of the vehicle's structural design.

We believe that a successful sub-orbital tourist vehicle will take the cooperation of industry, federal and state governments, and universities. Governments will provide regulatory stability, facilities such as airports, NASA data, tax credits, jobs, and a favorable environment for business. Universities will provide "out-of-box" thinking, research, and future employees. Innovative companies will actually build and market the vehicle, create new jobs, products, services, profits, and pay taxes that ultimately fund the other two sectors.



X-34 Outer Mold Line (NASA image)

Finally, establishing space tourism as a commercial business will require taking some business risks. However, we hope that this paper shows how to avoid taking unnecessary technical risks by selecting a vehicle architecture that works and avoiding those architectures that violate physical laws or are beyond current state of the art.

ACKNOWLEDGEMENTS

The authors would like to thank SpaceDev, Inc. and California Technology and Space Alliance (CTSA) for their assistance.

REFERENCES

[1] NASA NRA 8-27 Harris Poll, 2000.

[2] www.xprize.com accessed May 2002.

[3] R.W. Humble, el al, “Space Propulsion Analysis and Design,” McGraw-Hill, 1995.

[4] C.H. Eldred, al el, “Future Space Transportation Systems and Launch Vehicles,” Progress in Astronautics and Aeronautics, Vol. 172, 1997.

[5] W. Green, “Rocket Fighter,” Ballantine Books, 1971.

[6] P. V. Tartabini, el al, “Multidisciplinary Analysis of a Lifting Body Launch Vehicle,” AIAA Journal of Spacecraft and Rockets, Vol. 39, No. 5, Oct 2002.

[7] S. Libis, “Lockheed NF-104 Aerospace Trainer,” Air Force Legends Number 204, 1999.

[8] S. Pace, “Republic XF-91 Thunderceptor Rocket Fighter,” Air Force Legends Number 210, 2000.

[9] H. Matthews, “The Saga of SR 53,” HPM Publications, 2001.

[10] H. Matthews, “Trident, the Saga of the Unbeatable French Rocket Fighter,” HPM Publications, 2001.

[11] M. & N. Sarigul-Klijn, “A Study of Air Launch Methods for RLVs,” AIAA Paper, September 2001. (AIAA 2001-4619)

[12] M. Thompson, “At the Edge of Space, the X-15 Flight Program,” Smithsonian Institution Press, 1992.

[13] T. W. Knacke, “Parachute Recovery Systems Design Manual,” Para Publishing, Santa Barbara, CA, 1992.

[14] R. A. Machin, el al, “Flight Testing the Parachute System for the Space Station Crew Return Vehicle,” AIAA Journal of Aircraft, Vol. 38, No. 5, September 2001.

[15] S. Dellicker, el al, “Guidance and Control for Flat-Circular Parachutes,” AIAA Journal of Aircraft, Vol. 38, No. 5, September 2001.

[16] N.Sarigul-Klijn, “Rotor Landing Recovery Methods and 1/8 scale subsonic flight tests,” SmartLab Report TR-0056, University of California, CA, 1999.

[17] M. Sarigul-Klijn, “I Survived the Rotary Rocket,” Smithsonian Air & Space magazine, March 2002.

[18] I-Shing Chang, “Investigation of Space Launch Vehicle Catastrophic Failure,” AIAA Paper, July 1995. (AIAA 95-3128)

[19] National Research Council, “From Earth to Orbit,” National Academy Press, 1992, pp 20.

[20] U.S. Department of Transportation, “ Hazard Analysis of Commercial Space Transportation,” May 1988.

[21] H. D. Fuhrmann, el al, “Special Section: X-34,” AIAA Journal of Spacecraft and Rockets, Vol. 36, No. 2, March 1999.