AIAA 2001-4619

A Study of Air Launch Methods for RLVs

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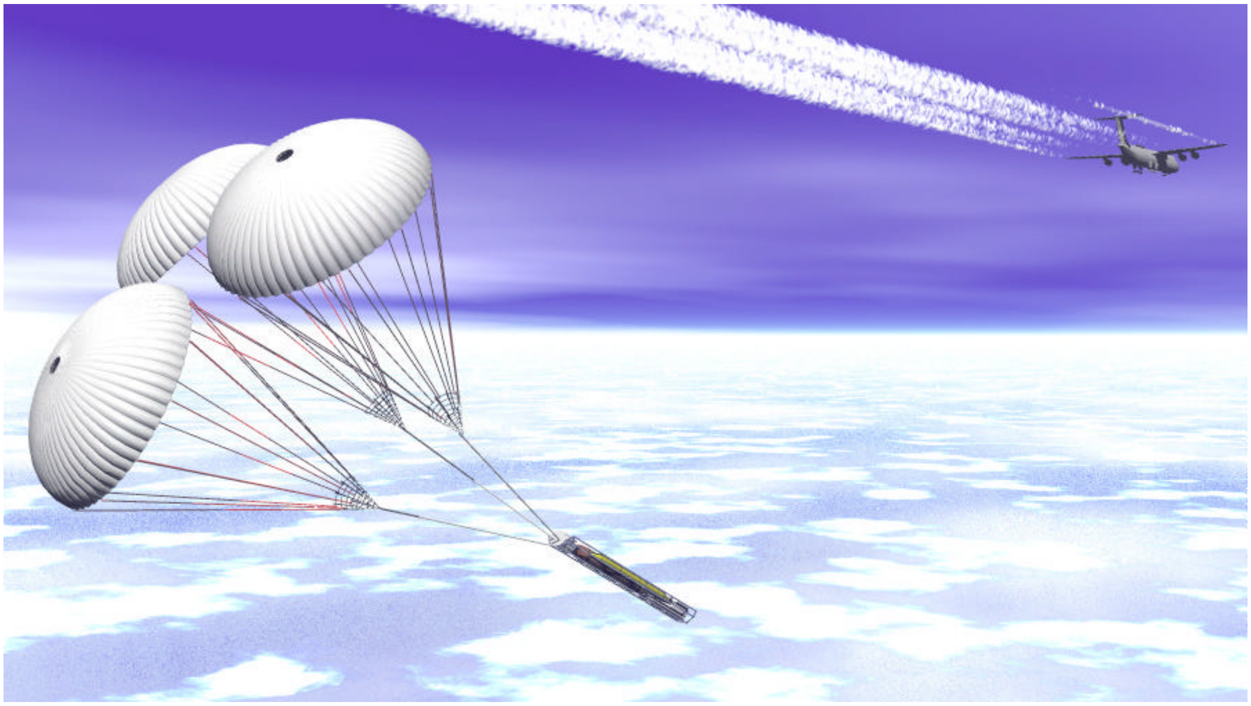
Many organizations have proposed air launch Reusable Launch Vehicles (RLVs) due to a renewed interest generated by NASA's 2nd Generation Space Launch Initiative. Air launched RLVs are categorized as captive on top, captive on bottom, towed, aerial refueled, and internally carried. The critical design aspects of various proposed air launch RLVs concepts are evaluated. It is found that many concepts are not possible with today's technology. The authors introduce a new air launch concept that is possible with today's technology called SwiftLaunch RLV.



INTRODUCTION

Air launching provides mobility and deployment advantages over surface launching. Air launch Reusable Launch Vehicles (RLVs) can fly over or around launch constraining weather. They can chase orbits and achieve any launch azimuth without out-of-plane orbital maneuvers that consume large amounts of on-orbit propellant - important for International Space Station (ISS) emergency access or military launch on demand missions. Air launch RLVs can operate free of national range scheduling constraints, have minimum launch site requirements, and they may have reduced range safety concerns. Air launching significantly reduces the acoustic energy from the engine since there is no reflection from the ground and air density is lower. The strength of the thermal protection system (TPS) and structures near the base of a surface launch vehicle are sized by acoustic energy at launch. Finally, some air launch methods can improve mass inserted into orbit over a similarly sized surface launch vehicle.

Shuttle mission STS-101 of May 2000 illustrates the problem with surface launch RLVs. Its ISS logistic mission was delayed by total of 25 days

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due to a combination of waiting for suitable launch weather, waiting for other launch vehicles that shared the same range resources, and waiting for the ISS orbital plane to pass overhead the launch site. Historically, few surface launch vehicles make their first scheduled launch date.

In contrast, air launch RLVs offer the potential for aircraft-like operations that provide responsive launch on demand or launch on schedule. However, modifying an existing aircraft into an air launch carrier aircraft limits the size of air launch RLVs payloads. Still many organizations have proposed air launched RLVs in response to NASA's 2nd Generation Space Launch Initiative because of the operational advantages since an air launch RLV could complement a large surface launched RLV. Large payload and volume would be available from the surface launched RLV while the smaller air launched RLV provides responsive launch on demand or schedule, quick turnaround times, assured access, emergency crew rescue, low cost for small payloads, and for some concepts – improved safety. Air launch concepts have also been proposed in other countries.

SCOPE

This paper will discuss horizontal take-off launch vehicles that have more than one stage and have some reusable component(s). Our analysis is limited to information found in the public domain such a company's web sites, journal articles, or press releases and will discuss only the major deficiencies found in each concept. Limits to the length of this paper prevent mentioning all the air launch concepts that have been proposed.

GETTING INTO ORBIT

The velocity of an object in an 100 nautical mile (nm) circular low earth orbit (LEO) is about 25,600 feet per second (fps). However, the change of velocity (called delta V) that a launch vehicle must provide is greater than this amount because of several losses. Gravity loss arises because part of the launch vehicle's energy is wasted in holding it against the pull of Earth's gravity (g). It is given by:

$$\int g \sin g \, dt \qquad (1)$$

with integration carried from ignition to burnout. Flying a trajectory that zeros out the flight path angle (γ) between the vehicle velocity vector and the local horizontal as soon as possible minimizes gravity loss. Typical gravity losses are about 3,500 to 5,000 fps. Drag loss is another loss and is caused by the friction between the launch vehicle and the atmosphere. It is given by:

$$\int D / m \, dt \qquad (2)$$

Where both the drag force D, and the mass of the launch vehicle, m, are continuously changing. Drag losses are in the order of about 500 fps for medium sized rockets and can be minimized by flying a vertical trajectory to clear the atmosphere as soon as possible and by building a low drag rocket. A long slender cylinder with a pointed nose is a favored shape since over ¾ 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, surface area increases with the square of the dimension while 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 150 fps. Finally, steering loss is the mismatch of the engine's thrust vector with the vehicle's velocity vector and is caused by the need to steer the launch vehicle. Steering losses are typically 100 to 600 fps.

Notice a compromise trajectory must be chosen to minimize losses. A vertical trajectory that would minimize drag losses increases gravity losses while a trajectory that pitches early to the horizontal would decrease gravity losses while increasing drag losses as the vehicle plows through the atmosphere. Computer programs, such as NASA's POST (Program to Optimize Simulated Trajectories) are used to find the trajectory with the lowest losses. For a typical surface launched rocket the various losses amount to about 5,000 fps.

Finally, delta V depends on launch location. The best place to launch is from the equator in a due east direction because the Earth's rotation helps with a free velocity increment of 1,520 fps. The actual increment depends on launch site latitude and launch direction. Hence a baseline vertical launch from the surface to the east requires a total delta V of between 29,000 to 30,000 fps.

AIR LAUNCH PERFORMANCE BENEFITS

Air launching can reduce the delta V required to reach orbit. The forward speed provided by a subsonic carrier aircraft can provide 600 to 800 fps. Launch at altitude can reduce gravity and drag losses as well increase engine efficiency due to better thrust expansion in the engine nozzle and due to using a large area ratio nozzle properly sized for the launch altitude.

Surprisingly, a typical straight and level subsonic horizontal air launch such as used by the X-15 research rocketplane does not result in any significant changes in the delta V requirement as compared to a baseline vertical surface launch. Horizontal launched vehicles like the X-15 must accelerate to a higher airspeed after being dropped so that their wings can produce enough lift in order to conduct an aerodynamic pull-up maneuver. Typically a descent of 4,000 to 7,000 feet (ft) occurs until sufficient airspeed is obtained. The pull-up maneuver is limited to 2 to 3 G's due to airframe and wing structural limits and takes about 1 minute to reach a climb-out angle of 45 to 80 degrees nose-up. During the one-minute pull-up maneuver, aerodynamic pressure increases, and the launch vehicle is subjected to both high sideways bending moments as well as high aerodynamic pressure. For example, the Orbital Science's air launched Pegasus XL experiences over 1250 pounds per square foot (psf) aerodynamic pressure, twice the Space Shuttles, even though it is launched at 38,000 ft.

To provide a performance benefit, the carrier aircraft must be capable of releasing the launch vehicle at a positive flight path angle (γ) above the local horizon. A subsonic release at $\gamma = 25^o$ provides about 1,600 fps delta V benefit for a winged launch vehicle. Further increases in γ above 25^o provide little additional benefit for winged launch vehicles but does provide additional benefit for unwinged launch vehicles. Unfortunately, possible carrier aircraft such as the Boeing 747 or Lockheed C-5 Galaxy need thrust augmentation in order to maintain a $\gamma = 25^o$ while flying above 30,000 ft. Adding a liquid fueled rocket to the carrier aircraft appears to be the best choice, since a jet engine's thrust decreases with altitude. At 20,000 ft altitude a jet engine produces 1/2 of its sea level thrust and at 40,000 ft, thrust is 1/4 of sea level. In contrast, a rocket engine thrust increases by about 5 to 10% as it leaves the atmosphere.

A wingless launch vehicle released from under a parachute at 30,000 ft altitude gains about 1,200 fps delta V over a baseline vertical surface launch. In contrast, a winged vehicle launched horizontally from the surface, such as the cancelled X-30 National Aerospace Plane, carries a 700 to 1,000 fps delta V penalty.

MASS FRACTIONS

In order to reach LEO, a sizable portion of a launch vehicle's mass must be propellant. The mass of the propellant (M_P) relative to the mass of the total vehicle before ignition (M_i) is called propellant mass fraction. The mass of the rest of the vehicle (M_F) relative to the ignition weight is called dry mass fraction. The dry mass fraction includes the payload, structures, engines, residual and reserve propellant, avionics, on-orbit maneuvering and reentry propellant, reentry thermal protection, and landing system. For manned vehicles, dry mass fraction also includes the crew, escape systems, and life support systems. The LEO payloads of current expendable launch vehicles are typically only 1 to 3.5% of the ignition weight. Mass fraction depends on propellant combination and number of vehicle segments or stages. By staging a vehicle it is possible to reduce propellant mass fraction, employ different types of propellants or types of power plants, and use entirely different configurations in successive stages of any one vehicle. A kerosene-liquid oxygen (RP-LOX) single stage to orbit (SSTO) vehicle must have at least a 94% propellant mass fraction while a two-stage to orbit (TSTO) vehicle with optimum staging must have 90% propellant in each stage. In other words, a RP-LOX launch vehicle must carry 9 to 16 times its dry weight in propellant in order to reach orbit. Note that optimum staging occurs when the lower stage is roughly 5 times more massive then the upper stage.

Also notice that for a TSTO vehicle, one stage can have propellant mass fraction less then the optimum number. For example, if the first stage of a TSTO RP-LOX vehicle had a propellant mass fraction of 50%, then the second stage could compensate with a fraction of 92% and still reach orbit. Because staging adds additional engines and interstages (the structure that joins the stages together), it is impractical to have more than 4 to 7 stages in a vehicle.

Liquid hydrogen-LOX (LH2-LOX) is a propellant combination with a higher specific impulse (Isp). Isp is a measure of the efficiency of a propellant and engine combination. A LH2-LOX SSTO needs a propellant mass fraction of 90% while a TSTO needs roughly about 85% to reach orbit. However, LH2-LOX engines weigh twice as much RP-LOX engines for the same amount of thrust. This is due to the large passageways in the engine required to flow the low-density LH2. LH2 density is only 8.8% of RP. Also LH2-LOX propellant tanks weigh about 2.8 times more than RP-LOX tanks when carrying the same mass of propellant.[1] Again this is due to large volume tanks required to hold the LH2. These factors erode many of the benefits of using high Isp LH2-LOX.

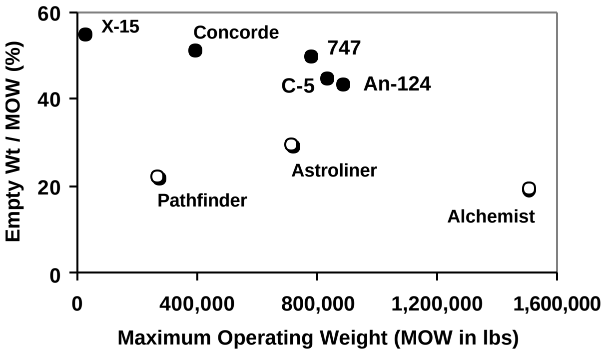
WING-BORNE VS ROCKET-BORNE FLIGHT

Rockets can carry propellant mass fractions of 90% or more. For example the lower stage of the TSTO Titan II rocket has a propellant mass fraction of 96.4%.[2] The Titan II's lower stage carries 35 times its dry mass in the form of lower and upper stage propellants, upper stage dry mass, and payload mass. Rockets are basically pressurized balloons under compression and are subject to very little bending and no twisting moments.

Wing-borne vehicles can not be built with large propellant mass fractions. In addition to propellant tanks and engines, wing-borne vehicles have wings, control surfaces, and landing gear – all which add to dry mass. Some air launch concepts even add jet engines which increases dry mass further. Wing-borne vehicles are also subject to high bending and twisting moments which increases structural mass. Aircraft are quite flexible, especially in fuselage longitudinal bending, wing spanwise bending, and wing torsional deflection. These have a major effect upon stability characteristics that in turn affects structural mass. For example, a typical swept-wing transport at high subsonic speeds will have a reduction in elevator effectiveness of about 50% due to fuselage flexibility effects. Aileron effectiveness is reduced by 50 to 100% because deflecting the ailerons twist the wing in the opposite direction causing a condition known as "aileron reversal." Thus many parts of an aircraft are not designed to strength limits, but to stiffness requirements which greatly increases structural mass.

For example, the X-15 carried propellant equal to 55% of its launch mass even though its wings and landing gear where sized for landing and not take-off. This is similar to other supersonic aircraft, such as the Concorde. Figure 1 plots the empty weight fraction of various existing aircraft and some proposed carrier aircraft. Empty weight fraction is the aircraft empty weight divided by its maximum operating weight (MOW). It differs from dry mass fraction in that it does not include payload since aircraft payloads are 5 to 35% of MOW. MOW includes the aircraft's empty weight, aircraft fuel, and payload.

Fig. 1 - Empty Weight Fractions (%)



AIR LAUNCH METHODS

We have categorized air launched RLVs into five launch method categories:

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

Several examples are used in the following discussion of each launch method.

Captive on top. The advantage of the captive on top launch method is the capability to carry a large RLV on top of the carrier aircraft. Disadvantages include penetrations on the windward side of the RLV's thermal protection system (TPS) for attachment hardpoints and extensive modifications (high cost) to the carrier aircraft. Also the RLV must have active controls at release from the carrier aircraft and the RLV wings must to be large enough to support it at separation from the carrier aircraft. Examples include:

Spiral 50-50 credited © Dan Roam

Spiral. The Sprial 50-50[3] represents a very advanced concept that is still not possible with today's technology since it requires advanced materials, TPS, and engines. It was funded from 1965 to 1978 by the Soviet government and consisted of an air-breathing Mach 7 booster aircraft powered by 4 hydrogen-burning air-breathing turboramjets, an expendable two-stage rocket, and a one-person orbital spaceplane. Take-off gross weight was projected at 280,000 pounds (lbs). A proof-of-concept prototype of the orbital spaceplane was flown at least 3 times from 1976 to 1978 after being airdropped from a Tu-95 aircraft. As an example of advanced technologies needed for this concept, NASA's is just now testing a small prototype hydrogen-burning air-breathing Mach 7 engine in the X-43 flight demonstration program.

Saenger II credited © Mark Lindroos

Saenger II. Saenger II[3] represents a very advanced concept that is still not possible with today's technology. It was funded from 1985 to 1994 by the MBB company and the German Ministry for Research and Development. It consisted of a large air-breathing Mach 6.6 booster aircraft powered by 6 co-axial turboramjets and a small rocket-powered upper stage (HORUS). The HORUS would deliver a crew of two and 6,600 lbs of payload to LEO. Take-off gross weight was projected at over 750,000 lbs. As part of the program a liquid hydrogen ramjet was run for 25 seconds in a simulated Mach 4 environment by MBB in 1991. The program was cancelled due to development cost.

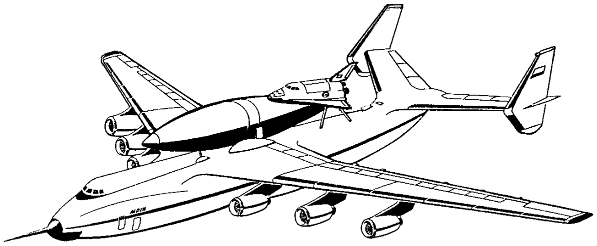
Interim HOTOL. The British Aerospace Interim HOTOL[4] was studied from 1989 to 1991 and was an air-launched version of the original HOTOL that eliminated the ambitious RB-545 combined cycle air-breathing propulsion system for four modified Russian RD0120 LH2-LOX rocket engines. The carrier aircraft was to be a Ukrainian An-225 Mriya (Dream) aircraft, currently the world's largest aircraft. Modifications to the aircraft including adding two Lotarev D-18 engines to increase number of engines to 8. The Interim HOTOL would separate from the carrier aircraft at Mach 0.8 at 30,000 ft. It wings would assist its pull up for the ascent to orbit and it would return via a gliding re-entry and conventional runway landing.

Interim HOTOL credited © British Aerospace

Interim HOTOL represents an advanced concept that is still not possible with today's technology. It required fueling with densified super cooled LH2 and LOX to prevent propellant boil-off during the climb and cruise to the launch point. External carriage of the Interim HOTOL meant that its propellants were subjected to both radiation heating from the sun and convective heating from the atmosphere. As an example of propellant boil-off, the X-15 that carried 1,000 gallons of LOX internally needed to be topped off from its B-52 carrier aircraft with 600 to 800 gallons of LOX during the 45-minute to 1-hour climb and ferry to the launch point. The B-52 carried 1,200 gallons of LOX in an internal insulated tank.

Interim HOTOL needed new materials for its tanks and wings in order to achieve the dry mass fraction required for LEO. To improve Isp, the engines would incorporate a two-position nozzle that would be deployed while the engines were operating – something that has never been attempted before. Although two-position nozzles are currently used, they are deployed and locked into place before the engine is started.

Finally, the designers of Interim HOTOL were unable to achieve a satisfactory solution to its stability and control problems. Reusable launch vehicles must control their center of gravity (CG) position both during ascent and reentry. During the wing borne portion of flight, the CG must be reasonably close to the wing's lift or center of pressure (CP). With engines mounted in the rear, then empty CG is dominated by the engine location, and the wings must be in the rear for reentry. The resulting configuration suffers from a severe CP / CG mismatch during ascent as the CP shifts forward, due to the wide Mach range, the large fuselage cross section to wing area ratio, and the long overhang of the forward fuselage while the CG moves aft as the propellant is burnt.



MAKS-OS credited © NPO Molniya

MAKS. NPO Molniya developed MAKS[5] in a draft project that was completed in 1989. The MAKS was to consist of a manned version (MAKS-OS), and unmanned cargo carrier (MAKS-C), a sub orbital demonstrator (MAKS-D), and an advanced fully reusable unpiloted version (MAKS-M), similar to Interim HOTOL. The MAKS-OS is shown and it weighed 1.3 million lbs on takeoff. It consisted of a An-225 carrier aircraft that would piggy-back the 600,000 lb MAKS to an altitude of about 30,000 ft and 480 kts, an external tank, and a 40,000 lb and 63 ft long spaceplane designed for 100 reuses. It would carry a crew of two and a payload of 18,000 lbs to a 100 nm 51^o inclination orbit and was powered by two RD-701 tripropellant engines designed for 15 re-uses. These engines initially used RP-LOX and then switched to higher specific impulse LH2-LOX at reduced thrust later in the trajectory. This reduced the size of the external tank and was expected to reduce the mass of the engines to half as compared to pure LH2-LOX engines.

MAKS pioneered the idea of an orbiter pushing an external tank. This significantly reduced the tank's weight as compared to a fully reusable integral tank. For example, the reusable LOX tanks for Lockheed's X-33 demonstrator weighed more than 3.4 times (at 2.16 lbs/ft^3) than the Shuttle's expendable LOX tanks (0.62 lbs/ft^3) even though the X-33 tank's factor of safety was only 1.25.[6] Pushing the external tank also allowed for aborts without the weight of escape rockets since during the atmospheric portion of the ascent trajectory the external tank was always denser than the orbiter. This meant the orbiter and external tank would naturally separate if released. The orbiter and external tank concept also reduced the amount of orbital maneuvering propellant required. Finally, the external tank concept solved the stability and control problem that plagued Interim HOTOL.

At the time of the cancellation, a 20,000 pound force (lbf) thrust experimental engine with 19 injectors had been tested with 50 test burns demonstrating a smooth switch between RP-LOX and LH2-LOX operation. The RD-701 would have had a thrust of 440,000 lbf each. Also, mock-ups of both the orbiter and the external tank had been finished.

The MAKS concept required the development of new TPS materials for the orbiters leading edges since it had a smaller radius (and hence higher heating rate and temperatures) than the Buran's leading edges. It also required the use of supercooled propellants to prevent propellant boil-off. The orbiter's payload capability appears a bit optimistic, equaling 50% of the orbiter's empty weight. The larger Space Shuttle is capable of less than 30% of its empty weight. Finally, the fully reusable MAKS-M would require advanced materials for the tanks as well as a solution to ascent and reentry stability and control problems.

Boeing AirLaunch credited © Boeing

Boeing AirLaunch. Conceived in 1999, AirLaunch is feasible system design based on today's technology. Its design goals were to keep development and recurring costs to a minimum. It can support two configurations, placing a Space Maneuver Vehicle (SMV) into LEO, or launch civil, commercial and military payloads with a Conventional Payload Module (CPM). Thiokol Propulsion would provide existing Castor 120 solid rocket motors for the first two stages and a new design for the third stage. Solid rockets have shown that they can withstand both the sideways G's and the high aerodynamic pressure of a horizontal air launch with little penalty in weight. This is because their outer motor case must be sized to withstand the internal pressure of combustion. Solid motor wall thickness is several times thicker (and heavier) than a liquid fueled propellant tank wall thickness. Also the solid propellant itself provides some structural strengthening, particularly in compression. Note that the SMV is a small, unpiloted reusable spacecraft designed to support a variety of military space missions ranging from satellite deployment to terrestrial and on-orbit support.

The AirLaunch is basically the Lockheed Martin Athena rocket on its side with wings attached. The launch price of the Athena is currently $22 to $26 million. Adding a wing will increase the cost by a few more million. Unfortunately, the Athena has demonstrated a poor launch record, with 2 failures in 5 launches. The extra drag of the AirLaunch limits launch altitude to about 24,000 ft since mounting it on top of its 747 carrier aircraft causes a great amount of drag. The inherent low Isp (280 seconds) and low propellant mass fraction of solid propellant motors limits AirLaunch to about 6,600 lbs for inserted orbital mass. AirLaunch would need a specially modified 747, which Boeing estimates at $500 million to build and ten of millions of dollars a year to operate. Boeing AirLaunch is an expendable launch vehicle except for its 747 carrier aircraft and the SMV.

Captive on bottom. The advantages of the captive on bottom launch method includes proven and easy separation from carrier aircraft, leeward side penetrations and hard points on the RLV that eliminates some TPS concerns, and the option of sizing the wing smaller then required for 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 carrier aircraft can eliminate clearance limitations.

Pegasus. Pegasus is the world's only operational air launch vehicle with over 30 launches to its credit. It consists of expendable 3-stage solid rocket booster with wings attached to the 1st stage. It is launched from Orbital Science's L-1011 Stargazer carrier aircraft. Estimated launch price is $12 - $15 million and maximum payload is 1,000 lbs to 100 nm equatorial launch. Only the carrier aircraft is reusable.

Yakovlev HAAL. Initially conceived in 1994 as Burlak (barge-hauler) and now called High Altitude Aerial Launch (HAAL)[7], this concept is possible with today's technology. The system would consist of a two stage expendable rocket launched from the Tu-160 "Blackjack" swing-wing supersonic bomber at an altitude of 45,000 ft and Mach 1.7. The 70,000 lb launch vehicle is based on a Russian ICBM and is fueled with non-cryogenic propellants (N2O4/UDMH) and is carried under the Tu-160. Payload is 2,500 lbs to a 100 nm orbit. Launch price is estimated at $5 million and development cost is estimated at $100 million. Getting the necessary permission to use the big Tupolev bombers - the most advanced bombers the Russians have ever built – required that the US and the Ukraine agree to lift certain conditions of the Strategic Arms Limitation Treaty. The aircraft were modified so that they cannot again be used for weapons delivery.

Yakovlev HAAL photo by Vic Stathopoulos

Yakovlev Skylifter. Conceived in the late 1990s, Skylifter is proposed as a large twin fuselage aircraft that could carry a 900,000 – 1 million lb payload. It would use modified landing gear from the Antonov An-225, the outer wing sections from an Antonov AN-124, and the cockpit, nose and forward fuselage from the Yakovlev Yak-40 airliner. Twin boom assemblies support a pair of vertical stabilizers connected by a high-mounted horizontal stabilizer. Two tall vertical pods that would house the landing gear, hence the wing and fuselages would sit high above the runway. The resulting configuration can carry a large RLV (23 ft high by 79 ft wide) below the wing and between the twin fuselages.

Towed. The primary advantages of a towed concept are easy separation from the towing aircraft and low cost modifications to the towing aircraft. Safety concerns include broken towlines and a towing aircraft take-off abort. Propellant boil-off can be a major problem unless supercooled propellants are used since there is no means to replenish the propellant from the towing aircraft. Another disadvantage is sizing the RLV's wings and landing gear for take-off with a full propellant load.

Astroliner credited © Kelly Space

Kelly Space's Astroliner. Conceived in 1993 and receiving over $6 million in NASA funding, the Kelly Space and Technology Astroliner[8] concept is a combined jet and rocket powered aircraft that was to be built using existing technology and off the shelf components. The fully fueled 720,000 lb Astroliner would be towed off of a runway using the thrust of its own jet engines and the excess thrust from a stripped down Boeing 747 acting as a tow aircraft. At 20,000 ft, the tow line would be dropped and once clear of the 747, the Astroliner would light its rocket engines and it was expected to accelerate to Mach 5 and then coast to 65 nm altitude. Clear of the atmosphere its nose would open and release a 56,000 lb upper stage capable of placing a 10,000 lbs into LEO. Except for towing, new technologies were not expected to be needed for the Astroliner.

Although the Astroliner's basic towing concept is sound, its current sizing is not possible with today's technology. A stripped-down 747 has only about 40% of its 192,000 lbf of sea level thrust available for towing. As a comparison, the Concorde supersonic airliner requires 152,000 lbf from its engines to take-off at a 400,000 lb gross weight for a take-off thrust to weight ratio of 0.38. The Astroliner not only weighs 80% more then the Concorde but also has more drag because its truncated tail, which houses its rocket engines, greatly increases subsonic drag. For example, the drag of the Space Shuttle is 70% more with its tail fairing off than with it on.[9] The 80,000 lbf of excess thrust from the 747 is only capable of towing off about a 200,000 lbs Astroliner. A 720,000 lb Astroliner would need enormous jet engines installed in it to augment the 747 tow aircraft's thrust.

The Astroliner's published empty weight fraction is only 29%. No supersonic aircraft has achieved this low empty weight, and certainly not one that has to carry both jet engines and rocket engines. The Astroliner's wings and landing gear must be sized for take-off with a full load of propellant and payload on board. The Astroliner is expected to carry 3.5 times its empty weight in propellant, crew, and upper stage when current supersonic aircraft can only carry 1 times their empty weight.

Even if the Astroliner worked as published, the launch method does not make economical sense since the upper stage, the most expensive part, is expended. It contains tanks, a high performance engine, telemetry, flight computer, flight termination system, and avionics.

Aerial Refueled. The principal advantage of aerial refueling is that it reduces the size of the carrier aircraft's wing and landing gear. Note that aerial refueling does not reduce the size of the jet engines – they must be sized to maintain level flight for a fully fueled carrier aircraft.

Pioneer Rocketplane. Conceived in the late 1990's and receiving $2 million in NASA funding, the Pioneer Pathfinder Rocketplane[10] concept is a combined jet and rocket powered aircraft that was to be built using existing technology and off the shelf components. It would use its two turbofan engines for take-off, rendezvous, and refueling with a 747 aerial tanker where it would take on 130,000 lbs of LOX, effectively doubling its gross weight to 274,000 lbs. This refueling concept would reduce the size of the Pathfinder's wings and landing gear to about 1/2 of an aircraft that had to carry all its oxidizer at take-off. Once clear of the 747, it would light its single RD-120 engine and it was expected to climb to 70 nm altitude and Mach 15. Clear of the atmosphere it would open its payload bay doors and release a 34,000 lb upper stage capable of placing a 4,400 lb satellite into LEO. Except for LOX aerial transfer, new technologies were not expected to be needed for Pathfinder.

Pathfinder credited © Pioneer Rocketplane

Although the Pathfinder's basic aerial refueling concept is sound, its current sizing is not possible with today's technology. Its published empty weight fraction is only 22%. Even with the savings in landing gear and wing weight, the Pathfinder is expected to carry 4.6 times its empty weight in propellant, crew, and upper stage. Furthermore the published empty weight fraction is too large to allow staging at Mach 15. The rocket equation shows staging at Mach 7 using published weights and expected gravity and drag losses. However with realistic weights using today's technology Pathfinder's staging would be much slower. It would still be subject to significant aerodynamic pressure during staging making release from Pioneer's payload bay extremely hazardous.

Like the Astroliner, Pioneer Rocketplane launch method does not make economical sense since the upper stage, the most expensive part, is expended.

Andrews Space Alchemist. Conceived in the late 1990's and receiving over $3 million in NASA funding, the Andrews Space & Technology (AST) Alchemist TSTO RLV uses an airbreathing / rocket combined cycle propulsion system where each system operates largely independent of the other.[11] The AST concept consists of a first stage booster called the "Gryphon" and a second stage orbiter called the "Merlin" which rides piggyback style on the Gryphon. Like the Pioneer Rocketplane, the Alchemist takes off without any oxidizer on board. An on-board LOX production plant makes over 900,000 lbs of LOX from the atmosphere by using compressed air from its 4 turbofan engines and 70,000 lbs of on-board liquid hydrogen (LH2). Onboard LOX generation would reduce the size of the Alchemist wings and landing gear to less than 1/2 of an aircraft that had to carry all its oxidizer at take-off. LOX generation takes 1 to 3 hours during which time the Alchemist flies to the launch point. After LOX generation is completed, all 7 rocket engines fire and the combined vehicles climb. Staging of the Merlin orbiter is proposed at Mach 8 and the Gryphon booster would restart its 4 turbofan engines after reentry to fly back to the launch site.

The published empty weight fraction of the Gryphon booster is an unachievable 0.19. Also its four turbofans produce only 75,000 lbf of thrust at 20,000 ft altitude, insufficient by a factor of at least 3 to keep a 1.5 million lb aircraft airborne (especially with the drag caused by the booster's truncated tail and the piggybacked orbiter). Serious stability and control problems may occur during LOX generation since the LH2 used to generate the LOX would occupy a 15,900 cubic ft (equal to four X-33 LH2 tanks) while the LOX would occupy a 13,500 cubic ft. Unfortunately, this volume must be located in different tanks. Also when Alchemist begins its rocket powered ascent, it must carry the dead weight of large empty LH2 tanks and a LOX generation plant.

Finally, the Alchemist uses a total of its seven LH2 - LOX engines plus its four turbojets for a total of 11 engines. The probability of an engine failure is very high with this number of engines. A catastrophic engine failure can be expected once every 200 to 300 missions and a safe shutdown failure can be expected every 30 to 40 missions if the failure rate data for the Shuttle Main Engine is assumed. The Alchemist does not represent a feasible system that can be implemented as designed or accomplish its design goals with current technology.

Internally Carried. An advantage of internally carried concepts include little or no modifications to the carrier aircraft (lowers both development and operations cost). Most propellant boil-off concerns are eliminated since the launch vehicle is not subject to either radiation heating from the sun or convective heating from the airstream. Maintenance crews have access to the launch vehicle until just before the launch, which reduces the safety concerns of carrying a launch vehicle with a manned carrier aircraft. The launch vehicle is in a benign environment inside the carrier aircraft and maintenance and safety problems can be detected and resolved. Also, internal carriage eliminates weather induced launch failures (such as the Shuttle Challenger) by launching into a known and benign environment (the stratosphere) from the protection of the carrier aircraft.

Also, all the internal carriage concepts can jettison the launch vehicles quickly. This compares to some concepts that we have already discussed that propose a manned rocket-powered booster with no means of jettisoning the internally carried rocket engines and no rapid means of dumping the internal propellant load. Flight crews are exposed to the risks of carrying and firing internally carried liquid fueled rocket engine(s). In contrast, internally carried launch concepts require carrying rockets inside manned aircraft, but not firing them.

Internally carried launch concepts are also able to carry heavier RLVs and release at the higher altitudes as compared to externally carried RLV concepts. Externally carried RLVs increase the carrier aircraft drag while internally carried RLVs don't. Since the carrier aircraft's jet engine thrust must equal its drag, then either its gross weight or launch altitude is reduced for externally carried RLVs.

Drop of Minuteman missile from C-5A in 1974
photo US Air Force

Internal air launch has been done before. On 24 October 1974 a C-5A Galaxy dropped a 78,000 lb LGM-30A Minuteman I missile using drogue chutes to extract the missile and its 8,000 lb launch sled. Parachute airdrop of the 195,000 lb and 92 inch diameter LGM-118 Peacekeeper MX missile was also considered. In January 1997, the second stage of a Minuteman I was successfully parachute airdropped from a C-130.

A disadvantage of internal air launch is that the launch vehicle must be sized to fit inside the carrier aircraft. Also LH2-LOX powered RLVs can not be carried because air and gaseous hydrogen explode over a wide range of mixture ratios – 4% to 76% by hydrogen volume ratio – not a safe situation for the interior of a cargo airplane.

Vozhushny Start credited © Air Launch Aerospace Corp.

Vozdushny Start (Air Start). The Energia, Polyot and Antonov companies are currently developing Air Start.[12] Like Boeing AirLaunch, its design goals are to keep development and recurring costs to a minimum. Air Start would carry a 100 ton, two-stage expendable liquid-fueled (RP-LOX) Polyot rocket inside a four-engine Antonov An-124, the world's largest operational aircraft. Payload is expected to be 6,600-8,800-lb to LEO. The rocket is packaged inside a special launch canister and at the launch point and altitude, a charge of air injected into the canister ejects the rocket. Compressed air is proposed to extract the rocket due to the unavailability of high load capacity parachutes in the Ukraine and Russia. After a five-second drop the rocket engine ignites.

How the Air Start achieves an upward launch trajectory is unclear from the published data. The Polyot rocket does not have wings and our trajectory simulations show that a horizontal launch results in the rocket impacting the ground. Other than this concern, it appears to be a feasible system concept based on today's technology.

BladeRunner. The BladeRunner concept is a fully reusable vehicle concept sponsored by the Air Force Research Laboratory (AFRL).[13] It calls for using high-pressure air expulsion to launch a

70,000 lb liquid fueled (RP-LOX) two stage rocket from a C-141 cargo aircraft. The BladeRunner uses a composite, folding scissors biplane wing for lift during ascent. The fuselage is built mostly from metals, titanium for the upper stage and aluminum for the lower stage. Parachutes are used for recovery of both stages.

Although the BladeRunner looks like a rocket, it is actually rocket powered airplane, but with moveable wings. The BladeRunner should have mass fractions similar to the X-15 or the X-34 since it is subjected to similar sideways launch and climb-out loads. The propellant mass fraction for the horizontally air launched X-15 was 55% and the X-34 was 63%, far less than the 90% required to reach LEO. Although the BladeRunner is carried internally, it is launched at a horizontal flight path angle that provides no significant performance gain over a similarly sized surface launch vehicle. It will lose over 5,000 to 7,000 feet in altitude before it starts climbing. The published payload of 2,000 lbs for the fully reusable BladeRunner is optimistic since it is twice that of the similarly sized but fully expendable Pegasus.

<u>SwiftLaunch RLV</u>. The SwiftLaunch RLV is a privately funded concept that uses the lesson learned from previous air launch concepts. It is feasible system based on today's technology with a design goal to keep development and recurring costs to a minimum. It consists of a reusable orbiter and an expendable tank (ETank) carried on a launch sled that is extracted with parachutes from a cargo aircraft. No permanent modifications are required to the cargo aircraft. Like MAKS, the SwiftLaunch RLVs are air-launched 1 ½ stage launch vehicles that expend their propellant tanks prior to reaching orbit. A reusable single engine powers the orbiters. Several orbiters are proposed including a 3-person crew transfer vehicle, an ISS cargo transfer vehicle, a space maneuver vehicle, and a commercial cargo vehicle. The orbiters are capable of executing an abort throughout their powered ascent and parachutes recover the orbiters after reentry. The SwiftLaunch RLVs are described in detail in a patent application.[14] The SwiftLaunch RLV consist of the orbiter and ETank and are 89 feet long when attached together with an ignition weight currently base-lined at 264,000 lb. The SwiftLaunch RLV and launch sled are collectively called the parachute load, estimated at 290,000 lb.

The SwiftLaunch RLV uses horizontal integration with the launch sled providing almost all of the ground support. The SwiftLaunch RLV concept allows a high visibility space activity to be stationed in a part of the country that traditionally has no space industry. A hangar and a compatible runway (10,000 ft long) are required. When a launch mission arises, carrier aircraft arrive to pick up the SwiftLaunch RLV's. Redundant carrier aircraft and SwiftLaunch RLVs are recommended to ensure a successful launch on demand or launch on schedule mission with a 90% or better schedule completion rate.

The two carrier aircraft candidates are the U.S. Air Force's C-5 "Galaxy" and the Ukrainian An-124 "Ruslan" commercial transport. The U.S Air Force currently has 126 C-5's while 59 An-124's were built and 20 are commercially available worldwide from Volga-Dnepr Airlines, Air Foyle or Polyot airlines. The An-124 carried a world record payload of 377,473 lbs to 35,269 ft on 26 July 1985. The SwiftLaunch concept does not require any permanent modifications to the carrier aircraft. Unlike other air launch concepts, no money is spent modifying an aircraft and more importantly, no money is spent maintaining a one of a kind carrier aircraft.

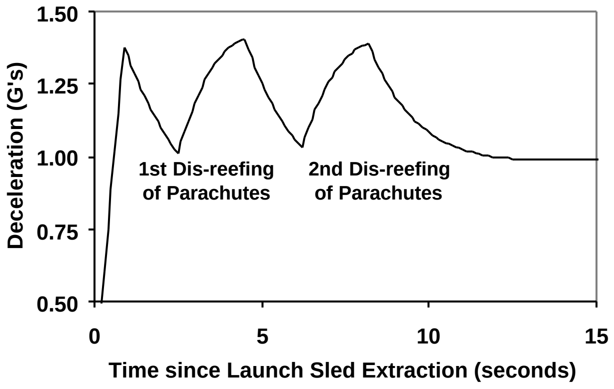
Propellant is loaded into the SwiftLaunch ETank in about 6 hours at a coastal airport near the launch point. The ETank consists of a LOX tank made of Aluminum-Lithium (Al-Li) flanked by two carbon-epoxy composite RP tanks. This concept:

- Is lighter since it eliminates a compressive intertank between a RP and LOX tank, a compressive truss structure between the orbiter and ETank, and compressive loads on the orbiter.
- Increases exit clearance through the aft airdrop opening in the carrier aircraft.
- Limits heat transfer area between the RP and LOX tanks.
- Reduce the mixing of LOX and fuel in the event of a leak, minimizing accidental explosions. Note that a RP-LOX propellant combination has an explosive yield 1/6 of LH2-LOX and 1/10 of solid rocket propellant combinations.
- Eliminates attaching the engine directly to the propellant tank, which further reduces the chance of an accidental explosion. Instead the engine is attached to a firewall located on the backside of the orbiter.

The weight of the ETank is conservatively base-lined at 3,100 lbs, which is 32% heavier than the Shuttle's 1st generation external tanks (0.82 lb/ft^3 versus the Shuttle's 0.62 lb/ft^3). Note that the Shuttle's current 3rd generation Al-Li tanks weigh only 84% of the 1st generation tanks.

The launch sled supports the SwiftLaunch while inside the carrier aircraft. The SwiftLaunch RLV is extracted by two 54 ft diameter Shuttle solid rocket booster (SRB) drogue parachutes and three 136 ft diameter SRB main chutes stabilize the descent. During parachute extraction there are no sideways accelerations from the parachutes and the launch sled absorbs any bending moments caused by temporary off-alignment of the parachutes with the launch sled. The launch sled takes all the extraction parachute loads (estimated at only 1.3 G) which means that the SwiftLaunch can be designed to normal rocket loads and does not need any heavy reinforcements for extraction loads. Wheels, in the front and back of the sled, guide it out of the carrier aircraft.

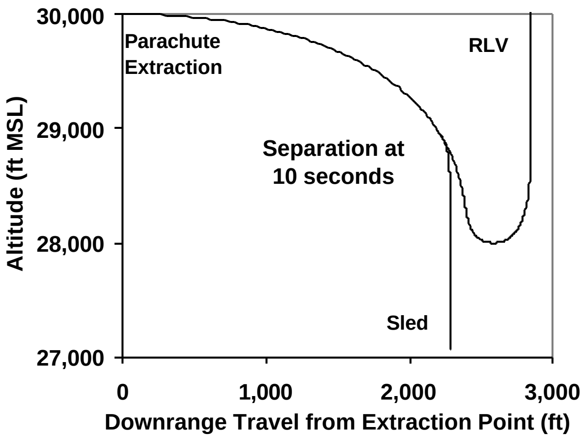
LAUNCH SLED EXTRACTION DECELERATION



A zero G maneuver is used to prevent overloading the carrier aircraft's rear ramp and to prevent the aircraft from experiencing an uncontrollable pitch up as the parachute load moves aft. Our analysis shows that while flying within the parachute airdrop airspeed limits of 150 ± 10 knots indicated, over 10 seconds of zero G flight is available, far more than the required 4 seconds. The zero G maneuver also eliminates most carrier aircraft structural loads and provides plenty of structural margins for piloting errors.

The SwiftLaunch RLV descents only 2,000 ft under its SRB parachutes before rocketing upward, which compares favorably to the 4,000 ft to 7,000 ft lost in a typical horizontal air launch (such as the X-15). After launch, the launch sled is towed back to shore for reuse. It is half the length and less than 1/3 the mass of the Shuttle SRB's which are towed over 110 miles after every shuttle launch.

EXTRACTION & SEPARATION TRAJECTORY



The SwiftLaunch launch point is selected based on the following criteria:

- It has suitable launch weather
- It has an over the water ascent trajectory
- It is locally clear of other aircraft, ships, and launch vehicles
- It is directly under the desired orbital plane. For ISS missions there is no need to wait several days for the ISS to pass over a fixed ground location.
- It has proper orbit phasing that allows a direct ascent rendezvous in one orbit. This reduces electrical power requirements, which maximizes payload weight.

For high inclination launches (such as to the ISS), the carrier aircraft can chase the orbital plane by flying to the west when at high latitudes. This capability can increase the launch window time.

SwiftLaunch RLV does not need active flight controls and engines at extraction. Engine starts about 10 seconds after extraction and when it is more than 2,500 ft horizontally and 1,000 ft below the carrier aircraft. The SwiftLaunch RLV ascent trajectory does not cross the carrier aircraft's flight path. When the SwiftLaunch RLV climbs through the carrier aircraft's altitude, the carrier aircraft is more than 3 nm away and it is flying away from and perpendicular to the RLV and not parallel to it as in other air launch concepts. There is no risk of collision with the manned carrier C-5 or An-124 aircraft.

The SwiftLaunch separates from the sled when the sled pitch attitude is about 60 degrees below the horizon and the launch sled slows down quickly once relieved of the launch vehicle load, which ensures separation. Our analysis shows that separation steadily increases with no danger of sled to launch vehicle impact.

SwiftLaunch RLV during ascent

The engine is throttled to maintain 3 G's of ascent acceleration, except for the final 70 seconds when acceleration increases to a peak of 5.2 G (due to main engine throttle limits). The main engine is currently proposed as the 3,260 lb RP-LOX Aerojet AJ26-60, which is the former Russian NK-43 engine. Thrust to weight of 122 to 1 compares to the Space Shuttle Main Engine's (SSME) 67 to 1 and specific impulse (Isp = 348.3 seconds vacuum) is 50 to 60 seconds better than the Atlas II, Delta II, or Delta III RP-LOX engines. A total of 831 engines have been tested for 194,000 seconds. These engines are available for $4 million each, which is about 10% the cost of a SSME.

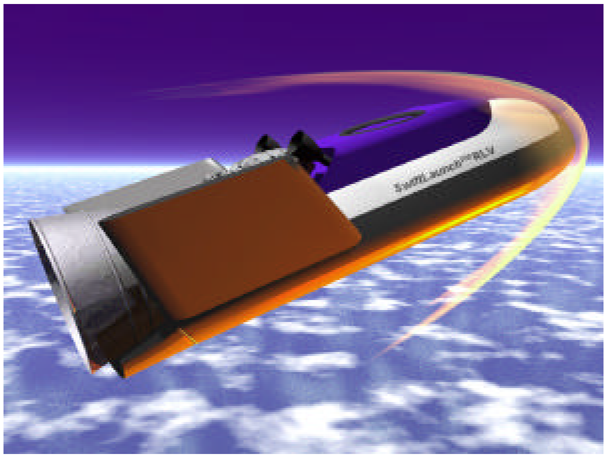
The SwiftLaunch uses a single main engine to minimize the possibility of propulsion leaks that are the cause of over 70 percent of current launch vehicle mishaps.[15] The single engine SwiftLaunch has less risk of a catastrophic failure as compared to any multiple engine launch vehicle by a factor equal to the number of engines. The SwiftLaunch is expected to have a loss of vehicle probability of less than 1 in 1,000 due to its single engine design. Its SafeAbort capability (discussed below) gives it a loss of crew or mission equipment probability of less than 1 in 10,000.

The SwiftLaunch RLV is statically stable during ascent since its center of gravity is forward of its center of pressure because its low-density orbiter and its fins are located aft of the of the high density ETank. Unlike other launch vehicles which are statically unstable (since the low density payload is on top), the SwiftLaunch does not need to constantly gimbal its engine to prevent it from flipping over end to end. The SwiftLaunch's statically stable configuration minimizes steering losses.

The ETank separates after main engine shutdown. SwiftLaunch's single staging event minimizes separation and staging failures as compare to other launch vehicles. The ETank is too slow to enter orbit so it burns completely up during reentry because of its high velocity and its construction (no steel or titanium components). Although the SwiftLaunch could be considered as an air launched stage and a half vehicle, it has many of the operational range safety benefits of a SSTO vehicle.

Only one of the orbiter's two redundant Orbital Maneuvering System (OMS) engines is needed to circularize its orbit. They are currently base-lined as two shuttle Reaction Control System (RCS) thrusters. Either the standard nitrogen tetroxide and hydrazine Marquardt engines or the LOX-ethanol Aerojet 870 lbf thrust engines could be used.

The orbiter is located below the ETank so that an emergency separation, called SafeAbort, can occur anytime. Separation is exactly like a normal upper stage and lower stage separation event since the partially full ETank is denser compared to the orbiter throughout the atmospheric portion of the ascent. If the rocket engine is shut down, the orbiter and ETank will separate naturally. Because of parachute air launch the SwiftLaunch's peak dynamic pressure (Max Q) is only 325 psf, less than that experienced by jet airliners, and half of the Space Shuttles. The low dynamic pressure of the SwiftLaunch RLVs trajectory makes SafeAbort possible and it also reduces drag losses. Escape rockets, which can weigh 30 to 60 percent of the orbiter's weight, are not needed and the orbiter experiences no high escape rocket abort acceleration loads. Escape rocket abort loads can account for up to 1/3 of an orbiter's structural weight.[16] After a SafeAbort separation the SwiftLaunch orbiter is statically stable since it has a full load of OMS propellant in its nose. The OMS propellant is then dumped during the coast to trajectory apogee. After dumping the OMS propellant, a normal lifting reentry and parachute landing is possible. Some cross range is available depending on when the SafeAbort is executed and a water landing is survivable because a parachute recovery is used. SafeAbort even works if the engine fails to start during a parachute air launch since there is plenty of time (about 4 minutes) to separate the orbiter from the launch sled and ETank, dump the OMS propellant, and deploy the landing parachute. Finally, note that the SwiftLaunch RLVs uses its normal ETank separation equipment and its redundant landing parachutes as its emergency system. This means that it is operated and proven in every flight. Equipment designed purely for emergency use has a poor history of actually working. For example, only 50% of flight crews survive an ejection in ejection seats.



SwiftLaunch RLV orbiter during reentry

The orbiter shape is currently base-lined as the Japanese flight-tested HYFLEX shape (launched on the J-1 rocket in February 1996). This shape has a high volume to external surface area ratio and the minimum number of sharp leading edges that would require heavy or advanced TPS. Internal cabin or payload volume is similar to the Soyuz descent module. Orbiters are equipped with either an ISS docking port or a shuttle like payload bay doors depending on version. Proposed orbiters include a 3-person crew transfer vehicle, an ISS cargo transfer vehicle, a space maneuver vehicle, and a commercial cargo vehicle. They all share the same outer mold line hence their aerodynamic and mass property characteristics are similar. This will reduce development time and cost by eliminating duplicate analysis, ground tests, and flight tests. Customers seldom know what they want or need and system objectives rarely remain fixed throughout the life of a system. The SwiftLaunch concept accepts upgrades to modify the vehicle to accommodate broader objectives and to satisfy future customer needs without having to repeat expensive analysis, ground tests, or flight tests.

POST shows that a 14,700 lb orbiter can be placed into a 150 nautical mile circular orbit at the ISS's 51.6^{o} inclination using a 30,000 ft parachute air launch. Payload is estimated at a very conservative 12 % of the orbiter's weight or 1,800 lbs. Payload size may be increased 3,500 to 5,000 lbs by flying a Once Around the Earth (OAE) orbit. An OAE orbit is an elliptic orbit with a 100-mile apogee and a 35-mile perigee. The payload is released at apogee and it circularizes itself with onboard propulsion using about 150 to 200 lbs propellant for a circular 100-mile orbit. OAE trajectories have been proposed before for ground launched RLVs but have been found not to be practicable due to the limited number of return to launch site orbital inclinations. Air launching allows launching into almost any orbital inclination while still having a single orbit return to the landing site. The carrier aircraft would position itself to the east of the landing site with the separation distance depending on launch inclination and latitude.

SwiftLaunch RLV Gross Ignition Weight

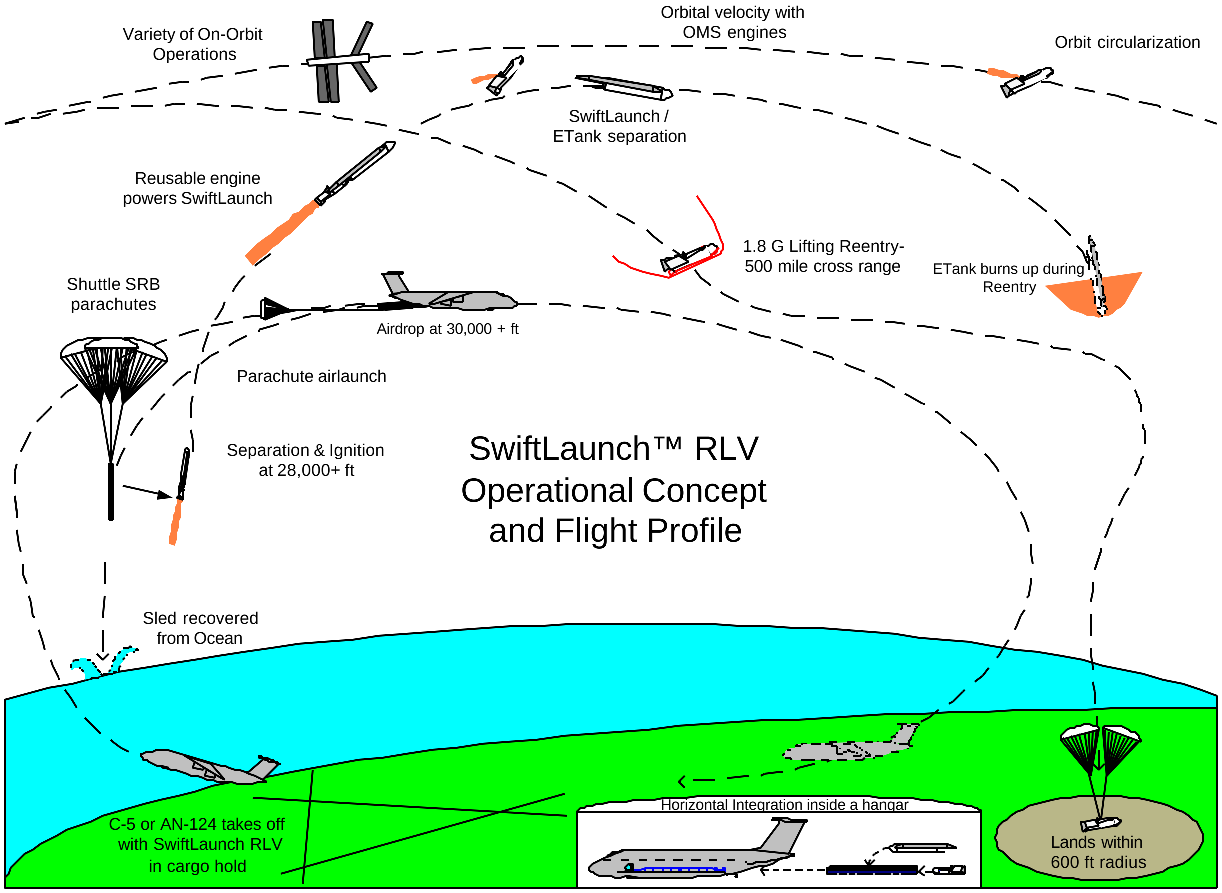
SwiftLaunch RLV	Weights (lbs)	Percent (%)
Etank Propellant	242,300	92.1
Etank Dry weight	3,100	1.2
Residuals & Ullage gas	800	0.3
OMS Circularization Burn	2,300	0.9
Common Core Orbiter	14,700	5.6
Total	263,200	100.0

Upon completion of its mission, the SwiftLaunch fires its redundant OMS engines again for a reentry burn. The SwiftLaunch's HYFLEX shape is capable of a shuttle like lifting reentry. Its moderate L/D of about 1.1 results in a reentry cross range of over 500 nautical miles and a maximum reentry acceleration of 1.8 G. A trailing body flap trims the orbiter for a range of center of gravity locations, which allows for a variety of reentry payloads. Determining exact weight and balance is very difficult while on orbit, and is not required for the SwiftLaunch orbiter because of its central cabin/payload location and its trailing body flap. At Mach 2 (about 80,000 ft altitude and 7 nm up range from the landing zone) a supersonic drogue chute is deployed to stabilize the orbiter. At subsonic speeds the drogue is steerable and provides a lift over drag (L/D) ratio of about 0.1, sufficient to correct reentry errors and ensure touch down within 600 feet of the intended aim point. Precision landing using small drogue chutes is under development by the US Army.

The recovery system has a powerful multiplier effect on the orbiter weight, since it must be carried to orbit and then returned. Each additional pound of recovery system then increases TPS weight, OMS propellant, structures, etc. Historical data shows that a parachute based recovery system is much lighter than a wing and wheel based recovery system. Powerful examples include the 11,300 lb 1-man Dyna-Soar as compared to the 3,200 lb Mercury capsule or the 33,000 lb and 3-man Hermes space plane as compared to the 6,600 lb and 3-man Soyuz descent capsule. Parachutes allow SafeAbort throughout the ascent without having to find a suitable 12,000-ft runway and autonomous operation with parachutes is simple, requiring only a timer and accelerometer based control system as compared to a much more complicated system required for winged vehicles. Currently, Apollo style circular parachutes are base-lined since they are much lighter than an X-38 type parafoil and three parachutes provide redundancy in the event that one chute fails to open.

Pneumatic retractors under development by the U.S. Army pull the SwiftLaunch and the parachutes together just before landing and reduce landing impact. They allow normal land touchdowns or emergency ocean landings.

The SwiftLaunch concept is a near (0-5 years) term concept that would cost approximately $1



billion to develop to initial operating capability. The ETank production price is estimated at $200,000 to $1.5 million each and a launch would cost $5 million to $15 million. These cost estimates are based mostly on parametric studies and are preliminary Pre-Phase A cost estimates. The SwiftLaunch RLV concept has technology maturity level of 5 or greater.

The SwiftLaunch RLV represents a conservative stage and half launch vehicle design. It is based on the idea that a simple single engine design with an inherent SafeAbort capability is the safest. It is also based on the idea that the lightest vehicle is the one with the lowest loads imposed on it. Lightness then leads to the best payload performance and the lowest operation costs. It can be implemented as designed and it can accomplish its design goals.

CONCLUSIONS

Air launching provides mobility and deployment advantages over surface launching. It can also provide performance advantages over surface launching, but only if the release flight path angle is above the horizon.

Many air launch concepts require advance technologies. Of the concepts discussed in this paper only the following are possible with today's technology; Orbital Science's Pegasus, Boeing AirLaunch, Yakovlev HAAL, Yakovlev Skylifter, SwiftLaunch, and perhaps Vozdushny Start.

The SwiftLaunch RLV introduced here is based upon the lessons learned from earlier air launch concepts. The SwiftLaunch RLV concept:

- Lowers cost since it does not need a dedicated carrier aircraft and it only expends its propellant tank.
- Provides a significant improvement in safety over other concepts due to its simple single engine design, reusability, ascent stability, and SafeAbort capability throughout its ascent.
- Can return payloads from orbit.
- Has orbiters that can be configured as a 3-person crew transfer vehicle, an ISS cargo transfer vehicle, a space maneuver vehicle, or as a commercial cargo vehicle.
- Has the range safety benefits of a SSTO vehicle since its ETank is expected to burn-up.
- Minimizes technical risk by using current technology, off the shelf components, and generous weight margins.

ACKNOWLEDGEMENT

The authors would like to thank Mr. Ken Doyle and Mr. Jonathan Byron for their drawings.

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