A Conceptual Analysis of Spacecraft Air Launch Methods

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Air launch spacecraft have numerous advantages over traditional vertical launch configurations. There are five categories of air launch configurations: captive on top, captive on bottom, towed, aerial refueled, and internally carried. Numerous vehicles have been designed within these five groups, although not all are feasible with current technology. An analysis of mass savings shows that air launch systems can significantly reduce required liftoff mass as compared to vertical launch systems.

Nomenclature

Δv	=	change in velocity (m/s)
μ	=	gravitational parameter (km^3/s^2)
CG	=	Center of Gravity
CP	=	Center of Pressure
g_0	=	standard gravity (m/s^2)
h	=	altitude (m)
I_{sp}	=	specific impulse (s)
ISS	=	International Space Station
LEO	=	Low Earth Orbit
m_f	=	final vehicle mass (kg)
m_i	=	initial vehicle mass (kg)
m_{prop}	=	propellant mass (kg)
M_R	=	mass ratio
NASA	=	National Aeronautics and Space Administration
r	=	orbital radius (km)

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T/W = thrust-to-weight ratio

v = velocity (m/s)

v_c = carrier aircraft velocity (m/s)

I. Introduction

THE cost of launching into space is often measured by the change in velocity required to reach the destination orbit, known as delta-v or Δv. The change in velocity is related to the required propellant mass by the ideal rocket equation:

$$\Delta v = I_{sp} * g_0 * \ln\left(\frac{m_i}{m_f}\right) \quad (1)$$

where I_{sp} is the specific impulse, g_0 is standard gravity, m_i initial mass, and m_f is final mass. Specific impulse, measured in seconds, is the amount of time that a unit weight of a propellant can produce a unit weight of thrust. For example, a propellant with an I_{sp} of 150 seconds consumes 1 pound of propellant for every 1 pound of thrust it produces for 150 seconds. Different propellants have different I_{sp} values, and I_{sp} increases from sea level to vacuum altitude. An everyday analogy to I_{sp} is miles per gallon in motor vehicles; for both variables, designers strive to achieve the highest possible values.

Standard gravity, g_0, is the average acceleration of gravity at Earth's surface, 9.81 m/s^2. This is a constant and therefore does not change for different propellants, launch vehicles, etc. The initial mass, m_i, is the mass of the launch vehicle upon takeoff. The final mass, m_f, is the mass of the vehicle upon propellant burnout. The ratio of m_i to m_f is known as the mass ratio, M_R. Assuming that no vehicle parts are jettisoned, the difference between m_i and m_f is the mass of the propellant, m_{prop}. Thus, for a given amount of propellant, the ideal rocket equation calculates the maximum change in velocity that can be provided to the vehicle.

A useful characteristic by which to compare spacecraft is their propellant mass fraction, f_{prop}. The propellant mass fraction is the amount of propellant with respect to the overall vehicle mass, and it is related to M_R by the following relationship:

$$M_R = \frac{1}{1 - f_{prop}} \quad (2)$$

Thus, the propellant mass fraction and specific impulse are the only variables needed to calculate Δv using the ideal rocket equation.

The amount of Δv required for a mission depends on the desired orbit. For simplicity, consider launching a satellite into a circular orbit around Earth. The orbital velocity is:

$$v = \sqrt{\frac{\mu}{r}} \qquad (3)$$

where μ is the standard gravitational parameter, 398,600 km^3/s^2 for Earth, and r is the orbital radius from the center of Earth. For example, the orbital velocity of a satellite 250 km above Earth's surface is 7.76 km/s. Satellites in circular orbits have the same orbital speed everywhere in the orbit, whereas satellites in elliptical orbits have variable speeds that depend on the distance from Earth. Satellites are often placed into low Earth orbit (LEO), where their velocity is on the order of the 7.76 km/s calculated above. Satellites in higher orbits have slower orbital velocities.

Aerodynamic properties of launch vehicles also affect the vehicle's trajectory. The four forces of flight acting on a vehicle during the atmospheric portion of ascent are the weight, lift, thrust, and drag. The weight is the downward force that Earth's gravity imposes on the vehicle. The weight force is so strong that it causes significant Δv losses, called gravity losses, on launch vehicles. (This is especially true for vertical launch vehicles and is discussed further below.) The lift force is the aerodynamic force perpendicular to the vehicle's direction of motion. Vehicles use aerodynamic surfaces, such as wings, to create lift forces. Thrust is the force output by a vehicle's engines that propels the vehicle forward. The thrust-to-weight ratio, T/W, is a common parameter used to compare launch vehicles. Drag, also known as air resistance, is the aerodynamic force that opposes a vehicle's motion and therefore slows it down. Significant Δv losses also result from the drag forces on a vehicle. Two important points on the vehicle that relate to these forces are the center of gravity (CG) and center of pressure (CP). In order for a vehicle to be aerodynamically stable, the locations of both the CG and CP must be controlled, with CP slightly forward of CG. Since CP changes with the vehicle's pitch angle and CG changes with the loss of fuel, designing a launch vehicle that balances these locations can be challenging.

II. Launch Mode Comparison

There are three major launch types for spacecraft: vertical takeoff, horizontal takeoff, and air launch. All three are discussed below, with a strong emphasis on the air launch method.

A. Vertical Take-off

Vertical take-off is the traditional and by far the most popular launch mode. Vertical takeoff rockets typically are able to achieve necessary propellant mass fractions with enough margin to permit the use of relatively low technology pressure fed rocket motors. Precise longitudinal control of the CG location is not necessary as it is with the other two launch modes, which makes propellant storage and routing significantly simpler. Additionally, vertically-launched vehicles are exposed to less bending and no twisting moments during launch, unlike vehicles that are launched horizontally or in the air.[1]

Launch site location is extremely important for vertical launches. Vertically-launched spacecraft can only be directly launched into an orbit with an inclination at least as large as the latitude of the launch site. For example, a vertical launch at Kennedy Space Center in Florida cannot put a satellite into an equatorial orbit because the launch site is at a 28.5 degree latitude, as opposed to the 0.0 degree latitude at the equator. In order to transfer into an orbit with a different inclination, an expensive plane change maneuver must be performed. Additionally, to avoid dropping vehicle parts on populated areas, vertical launches are performed over large bodies of water or deserts. Since spacecraft are almost always launched eastward (to gain a Δv assist from the earth's rotation), this limits launch site locations to East coasts (or deserts) at the lowest possible latitude.

Vertical launches require a launch pad. Depending on the size of the launch, the launch pad can be extremely large and complicated. For example, the launch pad for the space shuttle had launch towers, movable arms, and a water sound suppression system.[2] Vertical launches also have significant gravity and drag losses. A medium-sized vehicle, such as an Atlas or Delta rocket, can expect to have gravity losses around 600-1,200 m/s and drag losses on the order of 150 m/s for a vertical launch to an altitude of around 100 km.[1] These losses contribute to the large amount of propellant used up in the initial stage of the trajectory. For example, the space shuttle burned 25% of its propellant by the time it reached air launch altitude, while only adding 0.16% of the required kinetic energy to the system.[3]

B. Horizontal Take-off

Horizontal take-off vehicles launch from a runway, similar to an aircraft. This eliminates the need for an expensive launch pad. It also allows the vehicle to fly to any latitude before entering space, which eliminates the need for costly inclination change maneuvers. Horizontal launch vehicles may be powered by rocket engines only or by a combination of jet engines and rocket engines.[1]

While horizontal take-off vehicles are similar to aircraft, they need larger empty mass fractions and lower propellant mass fractions than regular aircraft. The vehicles must be sturdy enough to endure intense bending modes, turbulent air, high aerodynamic pressures, and supersonic flight. The propellant mass fractions of horizontally-launched vehicles are less favorable than those of vertical launches and air launches.[1]

Of the three launch modes, horizontal launch has the highest drag loss, since it consists of a winged body for the entire flight duration. It also takes the most Δv to reach orbit, because it must accelerate horizontally then pitch up toward the vertical to achieve orbit.[1]

C. Air Launch

Air launches typically involve two vehicles: a winged carrier aircraft and an upper stage spacecraft. There are numerous advantages of air launch systems over the other two launch modes.

While vertical launches are constrained to a launch azimuth of the launch site's latitude or higher, air launch systems (like horizontal launch systems) can be flown to any latitude before launch. This opens up any orbital inclination to the spacecraft, including equatorial orbits. Since plane changes from American launch sites to an equatorial orbit are very expensive, the capability to launch into any azimuth is a significant advantage of air launch systems. Additionally, for rendezvous with a current satellite, such as the ISS, air launches permit the spacecraft to be launched directly into a rendezvous orbit immediately, without waiting for the satellite's orbital plane to pass over the launch site. The need to launch over a desert or source of water is eliminated, since the carrier is a reusable vehicle that does not drop parts. While a horizontal launch takes the most Δv since it accelerates horizontally then must pitch vertically, an air launch vehicle can be released from the carrier at a pitched angle, reducing the Δv required as compared to a horizontal release.[4,5]

Air launches do not need fancy, expensive launch pads with launch towers, sound suppression systems, etc. (The rocket launch takes place at a high altitude, where sound does not reflect off the ground and the atmosphere is thinner.) Instead, the carrier can take off from a normal runway. Not only does this make air launches more secure – if something such as a hurricane, earthquake, or terrorist attack were to destroy a launch pad, upcoming vertical launches would be pooched – but it also makes scheduling launches easier since there are more runways available than launch pads. Additionally, military operations can be more covert with air launches, since they can use any runway rather than a publicized launch pad. The runway launch also makes air launches a safer option for crew than a vertical launch in cases of an emergency abort.[4,6,7]

A high percentage of vertical launches are postponed due to weather, which is expensive. Air launches provide the vehicle system with the ability not only to fly around inclement weather, but also to fly above inclement weather, since weather is constrained to the troposphere and air launches can take place in the stratosphere. This ability can significantly reduce the number of launch aborts, which are expensive both financially and in terms of schedule creep.[4]

Using an air launch as opposed to a vertical launch reduces the propellant mass fraction necessary to reach 100 km. For example, the air-launched X-15 has a propellant mass fraction of 0.55, and this number could be reduced to about 0.50 if the vehicle were dropped at an angle of 50-60 degrees to the horizon. This means that the vehicle would be carrying propellant equal to its empty mass. On the other hand, a vertically-launched vehicle with a propellant mass fraction of 0.63 has to carry propellant equal to twice its empty weight. Thus, spacecraft size can be reduced by using an air launch.[1]

Finally, the flexibility of air launches can provide quick access to space. With large vertical launch vehicles, the time required to prepare a launch means that there is essentially no emergency access to space. Air launches, on the other hand, can launch with short notice and can even receive mission instructions while climbing to the proper launch altitude. In cases where an emergency crew rescue or urgent aerial reconnaissance is required, the ability of air launches to provide fast space access is a major advantage compared to the other launch methods.[5,6]

While the advantages of air launches are plentiful, there are also several disadvantages. Modifying a carrier aircraft to be capable of supporting an upper stage vehicle can be complicated and expensive. Additionally, using a carrier aircraft limits the size of the spacecraft, meaning that smaller payloads are available. However, these payloads are often easier to integrate into the vehicle than those of vertical launches. Depending on the mode of air launch, separation of the spacecraft from the carrier can be dangerous, especially in cases of strong aerodynamic flow.[7,8]

Propellant boil off is a concern for upper stages with cryogenic propellants (except in the internally carried configuration, as discussed below), since the spacecraft is exposed to radiation heat from the sun and convective heat from the air stream. For example, the X-15 lost 60-80% of its liquid oxygen during its one-hour climb, and the attached B-52 carrier aircraft had to refuel the X-15 before it was released.[1]

III. Air Launch Configurations

There are five types of configurations of air launch systems: captive on top, captive on bottom, internally carried, towed, and aerial refueled. The following sections describe each configuration and provide examples of vehicle designs in each category.

A. Captive on Top

In the captive on top method of air launch, a spacecraft is attached to the top of a winged carrier aircraft. Attaching the spacecraft on the top of the carrier allows the carrier to lift large spacecraft. However, the carrier must undergo extensive modifications to be capable of supporting the spacecraft, which can be very expensive. Additionally, the spacecraft must have active controls and wings large enough to support it immediately after separation. The following are examples of captive on top air launch vehicles.[4]

1) *Spiral 50-50* was a Soviet project from 1965 to 1978. It is an advanced concept; the carrier aircraft is powered by four hydrogen-burning air-breathing turbojets that would boost the carried rocket at a speed of Mach 7. The spacecraft carried on top consists of a two-stage expendable rocket and a single-person orbital spaceplane. The liftoff weight was estimated at 280,000 pounds. Although the Soviet Union tested a proof-of-concept vehicle dropped from a Tu-95 aircraft, the technology required for the Spiral 50-50 is still not available today.[4]

2) *Saenger II* is a German research and development vehicle that was funded from 1985 to 1994. Like the Spiral 50-50, the technology required for the Saenger II is not available yet. The first stage of Saenger II is a winged carrier powered by six co-axial air-breathing turboramjets that releases the upper stage at Mach 6.6. The upper stage is a small rocket-powered vehicle that would deliver two crew members and 6,600 pounds of payload to LEO. The gross liftoff weight was predicted to be over 750,000 pounds, and the project was cancelled due to high development costs.[4]

3) *Interim HOTOL* is a British conceptual vehicle studied from 1989 to 1991, but that is not possible with current technology. It uses a six-engine Ukrainian An-225 Mriya as the winged carrier, with the addition of two extra Lotarev D-18 engines. The carrier brings the Interim HOTOL vehicle to an altitude of 30,000 feet before releasing the vehicle at Mach 0.8. The Interim HOTOL design requires densified super cooled liquid hydrogen and liquid oxygen fueling to prevent propellant boil-off during carried flight, and the tanks

and wings must be made of newer materials in order to reach an acceptable dry mass fraction for LEO. The design also calls for two-position nozzles that switch position during operation to increase the I_{sp}. Finally, the Interim HOTOL vehicle is not aerodynamically stable due to the mismatched locations of the center of gravity and center of pressure.[4]

4) *MAKS* is a draft project completed by NPO Molniya, a Russian scientific group that works on reusable launch systems, in 1989. The MAKS has four different versions: a manned version (MAKS-OS), an unmanned cargo carrier (MAKS-C), a sub-orbital demonstrator (MAKS-D), and an advanced unpiloted version (MAKS-M). The manned version is estimated to have a liftoff mass of 1.3 million pounds. The carrier, an An-225, would release the captive spaceplane at an altitude of 30,000 feet and a speed of 480 knots. A unique feature of the MAKS is that the spaceplane's fuel tank is external to the vehicle. Having an external fuel tank not only reduces the vehicle's overall mass, but it also improves abort scenarios since the external fuel tank naturally detached from the orbiter upon abort. Additionally, the external fuel tank solved the CG and CP stability problem that tormented the Interim HOTOL.[4,5]

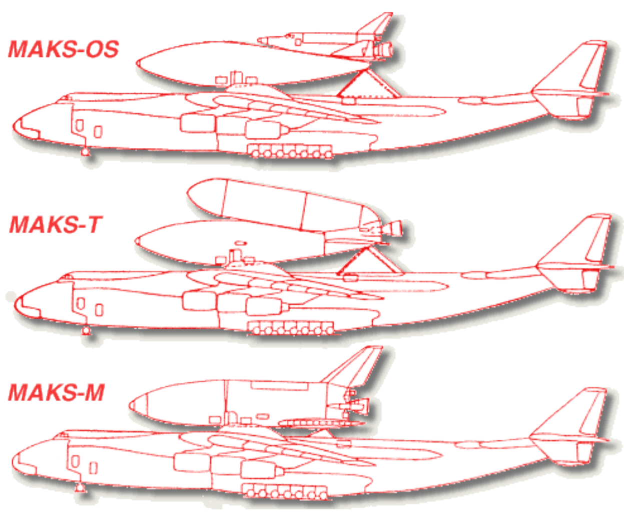

Fig. 1 Three models of MAKS captive on top air launch system.[5]

5) *AirLaunch* is a Boeing design that was started in 1999 and is achievable with today's technology. It can support the launch into LEO of a conventional payload module or a Space Maneuver Vehicle, a small unpiloted spacecraft used in a variety of military space missions. The AirLaunch has three stages – the first two use existing solid rocket motors and the third stage uses a new design. The solid rocket motors can

withstand the variation of G-forces throughout the mission profile without adding much weight to the vehicle. The AirLaunch is essentially a variation of Lockheed Martin's Athena rocket, with the rocket rotated onto its side and with wings attached. The AirLaunch is carried by a modified Boeing 747, which releases the AirLaunch at 24,000 feet.[4]

B. Captive on Bottom

Captive on bottom air launches involve a winged carrier aircraft as the first stage and a captive spacecraft as the upper stage(s), with the spacecraft carried and released from the bottom of the carrier. Spacecraft separation from the carrier is easier with a captive on bottom configuration than a captive on top configuration. Additionally, the spacecraft can have smaller wings than required for flight at the altitude and velocity of release, since it can free-fall after release. Disadvantages of the captive on bottom setup include the high cost of suitably modifying a carrier and size limits to the spacecraft due to ground clearance limitations under the carrier. The following designs are examples of captive on bottom air launch configurations.[4,6]

1) *X-15* is considered by many to be the first successful air launch to space. The X-15 was designed and built as a joint effort between the U.S. military, NASA, and North American Aviation. It was carried under the wing of a B-52, which released the X-15 at an altitude of 45,000 feet and a velocity of approximately 500 miles per hour. The X-15 was shaped like a missile with small wings and a tail. The X-15 was designed to provide in-flight information on high-speed, high-altitude flight, such as aerodynamics, structures, flight controls, and physiological effects. Three X-15 vehicles were manufactured, and they were flown from June 1959 to October 1968.[9]

2) *Pegasus* was the first privately developed space launch vehicle and the first air-launched rocket to put satellites in orbit. It is developed by Orbital Sciences Corporation and is still an operational air launch vehicle today. Its first launch was in 1990, and as of June 2012 it has completed 41 launches, 38 of which were successful. The original winged carrier was a NASA B-52, and the current carrier is the L-1011 Stargazer, which launches the Pegasus at an altitude of 40,000 feet. Pegasus has an expendable three-stage solid rocket booster, and delta wings are attached to its first stage. Pegasus is capable of putting 1,000 pounds into LEO. It has been launched from six different launch sites in the U.S., Europe, and the Marshall Islands, illustrating the flexibility of air launch vehicles.[10]

3) *SpaceShipOne* was developed by Mojave Aerospace Ventures and Scaled Composites and won the X Prize in 2004 when it completed the first privately-funded manned spaceflight. It was carried under WhiteKnightOne, a Scaled Composites jet carrier aircraft. SpaceShipOne used a hybrid rocket motor. It was retired soon after its historic flight, and Scaled Composites is currently developing the replacement SpaceShipTwo.[11]

4) *SpaceShipTwo* is under development by Virgin Galactic and Scaled Composites. It will be carried by WhiteKnightTwo, which is based on WhiteKnightOne but is significantly larger. Whereas SpaceShipOne fit under WhiteKnightOne's fuselage, SpaceShipTwo is about twice the size of SpaceShipOne and therefore is too large to fit under a carrier fuselage. Thus, WhiteKnightTwo has a twin fuselage layout, with SpaceShipTwo attaching between the two fuselages. The fuselages are 50 feet apart, which allows for a large SpaceShipTwo that will carry a payload of 35,000 pounds to an altitude of 50,000 feet. SpaceShipTwo will primarily be a vehicle for space tourists, with a spacious cabin that fits six passengers and two pilots.[12]

Fig. 2 A size comparison of SpaceShipOne and SpaceShipTwo.[12]

5) *Yakovlev High Altitude Aerial Launch (HAAL)* is not currently in use, but the concept is feasible with today's technology. The carrier aircraft is a Tu-160 supersonic bomber, and it would release the spacecraft at an altitude of 45,000 feet and a speed of Mach 1.7. The spacecraft is based on a Russian ICBM, weighs

70,000 pounds, and uses non-cryogenic propellants. While the technology to build the HAAL is available, the development cost is projected at $100 million with a $5 million launch cost.[4]

6) *Yakovlev Skylifter* is a large conceptual vehicle designed in the late 1990's. The carrier aircraft would be a conglomeration of parts from the Antonov An-225 and Yakovlev Yak-40 aircraft, with the wings and fuselages sitting high above the runway. The carrier would be capable of supporting a large spacecraft between the two fuselages and under the wing, with dimensions as large as 23 feet by 79 feet.[4]

7) *LauncherOne* is a new system in development by Virgin Galactic. LauncherOne will be carried and launched by a WhiteKnightTwo, like SpaceShipTwo. However, unlike SpaceShipTwo, which is primarily a tourist vehicle, LauncherOne is a satellite launcher. It is designed to launch 500 pounds to orbit for less than $10 million. Virgin Galactic expects to begin commercial flights of LauncherOne by 2016.[12]

Fig. 3 LauncherOne carried underneath WhiteKnightTwo.[12]

C. Towed

A towed air launch system consists of a winged carrier and a spacecraft that is attached via a towline behind the carrier. The two major advantages of a towed configuration are easy spacecraft separation from the carrier and low cost carrier modifications. A disadvantage is sizing the spacecraft wings and landing gear for a full-propellant take-off, which significantly increases the spacecraft's structural mass. Additionally, since the spacecraft is not attached to the carrier, it cannot replenish its propellant from the carrier and therefore must have its own supercooled propellants to prevent propellant boil off. Safety concerns with a towed configuration include a broken towline and a take-off abort scenario. The following is an example of a towed air launch system.[4,6,13]

1) *Astroliner* is a conceptual project that was conceived by Kelly Space and Technology in 1993 and that received over $6 in NASA funding. The Astroliner is towed by a Boeing 747, which drops the Astroliner at an altitude of 20,000 feet. After the tow line is dropped, the Astroliner uses its rocket engines to clear the atmosphere before releasing its payload into orbit. The expensive Astroliner upper stage, which contains avionics, a flight computer, a high performance engine, etc., is expendable, which makes the concept uneconomical. Additionally, the published empty mass fraction is only 29%, which is lower than that of any successful supersonic aircraft. Since the Astroliner contains both jet and rocket engines, as well as carries all of its propellant on take-off and therefore has large wings and landing gear, it is improbable that this empty mass fraction is achievable.[4,14]

Fig. 4 Astroliner, a towed air launch vehicle.[4]

D. Aerial Refueled

Aerial refueling is different from the other types of air launch systems in that the upper stage spacecraft is not attached to the carrier aircraft during lift-off and the initial ascent. As mentioned above, a spacecraft's wings and landing gear must be significantly larger and heavier if they are to support a large propellant mass on takeoff. Thus, the primary advantage of an aerial refueled configuration is that the upper stage can have smaller landing gear and wings, or the upper stage can be slightly larger to allow for a larger payload. (Note that larger landing gear and wings are not needed for a runway landing, since the vehicle will be virtually empty of fuel at this point.) Since typically 72-88% of a vehicle's propellant mass is oxidizer, all of the fuel is usually loaded into the spacecraft on the ground, and just oxidizer is transferred to the spacecraft in the air. However, aerial refueling does not reduce the jet engine size, since the engines must be large enough to maintain level flight at the same altitude as the fully fueled winged carrier. The following are examples of aerial refueling systems.[4,6,7]

1) *Pathfinder* is a concept developed in the late 1990's by Pioneer Rocketplane that received $2 million of NASA funding. Pathfinder employs both jet and rocket power; it uses two turbofan engines to take-off and rendezvous with a Boeing 747, and after refueling it lights its single RD-120 rocket engine. During the refueling process, the 747 transfers 130,000 pounds of liquid oxygen to Pathfinder, which essentially doubles Pathfinder's gross weight. Thus, Pathfinder's landing gear and wings only have to be about half as massive as they would have been with the additional fuel on takeoff. Unfortunately, this mass savings is not enough to make the Pathfinder concept feasible with current technology. Pathfinder is supposed to carry crew, payload, and propellant that add up to 4.6 times its empty weight, and the published empty weight fraction is not small enough to allow staging at the proposed speed of Mach 15. According to the ideal rocket equation, the staging cannot take place at a speed greater than Mach 7. Additionally, today's technology cannot support staging at Mach 7 due to the large aerodynamic pressure on the vehicle, so in reality the Pathfinder would have to release the third stage at an even slower velocity. Finally, the Pathfinder is an expendable vehicle, which makes the concept very uneconomical.[4]

Fig. 5 Pathfinder, an aerial refueled air launch system.[4]

2) *Alchemist* is an innovative but unfeasible spaceplane designed by Andrews Space & Technology in the late 1990's with over $3 million of NASA funding. Similar to the Pathfinder, the Alchemist would take-off

without oxidizer and therefore save about 50% of the potential wing and landing gear mass. However, rather than rendezvousing with a carrier aircraft to receive its oxidizer, the Alchemist has an on-board oxidizer production plant that uses the atmosphere and on-board liquid hydrogen to generate 900,000 pounds of liquid oxygen during a 1-3 hour climb to launch altitude. After all of the oxidizer is produced, the Alchemist lights its seven rocket engines and releases its second stage orbiter at a proposed speed of Mach 8. However, the published empty weight fraction of the first stage is 0.19, which is unachievable with technology today. The 75,000 pound-forces of thrust produced by the four turbofans is not sufficient to keep the vehicle airborne at 20,000 feet. It is predicted that the vehicle would become unstable during the oxidizer production due to the uneven distribution of weight. The oxidizer production plant, including the extra-large liquid hydrogen tanks that holds the liquid hydrogen used in the oxidizer generation process, becomes excess dead weight once the oxidizer is generated. Finally, the large number of engines – eleven – becomes a safety concern, since each additional engine increases the probability of an engine failure.[4]

E. Internally Carried

Internally carried air launch systems require little or no modifications to the winged carrier, which is a significant advantage over other air launch configurations since it reduces both developmental and operational cost. Since the carrier aircraft shields the launch vehicle from the sun's radiation heating and the air stream's convective heating, propellant boil-off concerns are virtually eliminated. Internally carried configurations are considered safer than other air launch configurations for several reasons. Maintenance crews are able to access the launch vehicle right up until the launch, which reduces safety concerns for the pilots of the carrier aircraft. The launch vehicle is shielded not only from the airstream, but also from any malevolent weather the carrier may encounter. The carrier can quickly jettison the launch vehicle, which reduces the flight crew safety concerns of carrying and especially firing internal rocket engines. The overall drag on the system is significantly reduced when the launch vehicle is housed within the carrier, which allows the carrier to carrier heavier vehicles and release the vehicles at higher altitudes. There are two primary disadvantages of internally carried air launch systems: the launch vehicle must be sized to fit within the winged carrier, and the launch vehicle cannot use a liquid hydrogen and liquid oxygen propellant combination due to safety concerns of containing the combination in the carrier aircraft. The following are examples of internally carried air launch systems.[4,6]

1) *Air Start* is in development by the Energia, Polyot, and Antonov companies in Ukraine and Russia. The carrier aircraft is an Antonov An-124 with four engines, and the upper stage is an expendable liquid-fueled Polyot rocket with two stages. The upper stage weighs 100 tons, including a payload of 6,600-8,800 pounds.[4]

Fig. 6 Air Start, an internally carried air launch system.[4]

2) *BladeRunner* is a reusable U.S. military vehicle concept for a rocket-powered airplane. The upper stage is launched from a transport jet aircraft with a new launch tube technique, and the infrastructure of the transport aircraft should not need any major adjustments to accommodate the BladeRunner. The upper stage itself consists of a two-stage rocket with movable wings, and both stages use a liquid oxygen and kerosene combination propellant.[4,15]

IV. Propellant Savings

When a carrier flying at a velocity v_c releases a spacecraft at an altitude h, it imparts upon the spacecraft a potential energy of mg_0h and a kinetic energy of $\frac{1}{2}mv_c^2$. Writing the equation for the equivalent kinetic energy of the spacecraft

$$\frac{1}{2}m\,\Delta v^2 = \frac{1}{2}mv_c^2 + mg_0h \qquad (4)$$

and solving for Δv yields

$$\Delta v = \sqrt{v_c^2 + 2g_0h} \qquad (5)$$

This is the equivalent Δv imparted to the spacecraft upon separation from the winged carrier. Now examine the following equation:

$$\frac{\Delta v}{I_{sp}g_0} = \sqrt{(lnM_R)^2 + \frac{2sin\theta}{\frac{T}{W}}\left(1 - lnM_R - \frac{1}{M_R}\right)} \qquad (6)$$

The Δv calculated above can be used to solve this equation for the mass ratio, M_R. Once the mass ratio is known, the ratio of propellant mass to total liftoff mass can be calculated using

$$\frac{m_{prop}}{m_i} = \frac{M_R - 1}{M_R} \qquad (7)$$

This ratio of propellant mass to total liftoff mass indicates the mass savings acquired by using an air launch.[16]

A. Example: Falcon 9

Consider the Falcon 9 launch vehicle by SpaceX. On October 7, 2012, it was the first commercial vehicle to resupply the International Space Station (ISS). The Falcon 9 uses nine Merlin 1C engines with an I_{sp} of 275 seconds to vertically launch into orbit. The overall thrust-to-weight ratio, T/W, is approximately 1.53.

Imagine putting a Falcon 9 on a winged carrier for launch into space. A Boeing 747 typically cruises at an altitude of approximately 10,700 m with a speed of 250 m/s,[17] so say that the winged carrier is flying at an altitude of 10,000 m and a velocity of 200 m/s when it releases the Falcon 9.

Using the equations above, the Δv imparted to the Falcon 9 is 486 m/s. Solving equation 6 with a θ of 90 degrees and the values above yields a mass ratio of 1.33. Finally, solving for the fraction of propellant mass to total liftoff mass produces a ratio of 0.25. This means that launching the Falcon 9 with an air launch, as opposed to a vertical launch, can save 25% of the Falcon 9's liftoff mass. Without this mass, the Falcon 9 could operate using only seven Merlin 1C engines instead of the original nine engines. However, the original liftoff mass is approximately 325,000 kg, so the remaining 75% of that is still about 250,000 kg. This is a lot of mass for a winged aircraft to carry. Thus, finding a suitable winged carrier may be the largest challenge associated with designing an air launch system for the Falcon vehicle.[16]

V. Conclusion

The United States currently does not have a method of transporting crew to space, and therefore pays Russia approximately $60 million per seat to transport U.S. astronauts to the ISS. Additionally, the market for space tourism is growing and is expected to be a multibillion dollar industry. Air launches offer significant advantages and potential cost savings as compared to vertical and horizontal launch options. While there are few operational air launch systems currently in use, the significant operational advantages and potential cost savings that air launch systems can offer suggest that they will become increasingly more popular in the upcoming years.

References

[1] Sarigul-Klijn, M. & N., "Flight Mechanics of Manned Sub-Orbital Reusable Launch Vehicles with Recommendations for Launch and Recovery," AIAA Paper, January 2003. (AIAA 2003-0909)

[2] www.nasa.gov accessed December 2012

[3] Bergin, C. and Graham, W., "Commercial space flight shows reignited interest in the Air Launch System," www.nasaspaceflight.com accessed November 2012

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

[5] Skorodelv, V.A. "The MAKS Multipurpose Aerospace System," www.buran.ru/htm/molniya6.htm accessed November 2012

[6] "Report of the Horizontal Launch Study: Interim Report," NASA and DARPA, June 2011

[7] Zubrin, R. and Clapp, M., "Black Horse: One Stop to Orbit," *Analog Magazine*, June 1995

[8] Pfeffer, H., "Towards Reusable Launchers – A Widening Perspective," European Space Agency, www.esa.int accessed November 2012

[9] www.dfrc.nasa.gov accessed December 2012

[10] www.orbital.com accessed December 2012

[11] "SpaceShipOne," Encyclopedia Astronautica, www.astronautix.com accessed December 2012

[12] www.virgingalactic.com accessed November 2012

[13] "RLV Design," Sky Ramp Technology, www.g2mil.com/rlv.htm accessed November 2012

[14] www.spaceandtech.com accessed December 2012

[15] Hampsten, K. and Walker, J., "BladeRunner Military Aerospace Vehicle," *AIAA Space Technology Conference & Exposition*, A99-4616, AIAA, Albuquerque, NM, 1999.

[16] Kantha, L., University of Colorado, Boulder, Colorado 2012 (unpublished).

[17] www.boeing.com accessed December 2012