The Future of Spacecraft Launch: Vertical Vs Air Designs

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Abstract

The objective of this report is to put forth new spacecraft air launch design concepts currently being contemplated by private and non private sources, which would gradually replace vertical launch to air launch, thus creating the opportunity for military and civilian expansion of the industry. This will report will identify the viability of providing a resilient and dependable air launch capability for future spacecraft operations. The author will compare the inherent limitations of the current vertical method, and subsequently put forth the advantages of the alternative method of air launch. Favorable logistical and operational elements of the proposed air launch method will be thoroughly discussed, from the opportunities of launch windows, weather flexibility, and safety, to environmental and financial considerations.

Introduction

Since Konstantin Tsiolkovsky, father of Russian cosmonautics, first calculated in 1880 the escape velocity required for journey beyond earth's atmosphere, and suggested that burning a combination of liquid hydrogen and liquid oxygen could improve rocket efficiency, humans have long desired to achieve the goal of spaceflight. In the 1960's humans started to venture into space through various missions, and since then the process has been conducted through the use of rockets as the principle mean of transport.

Today, placing a spacecraft in orbit requires a great amount of logistics, facilities and, of course, personnel. Through this report, the author will try to convey the idea that in order for the industry to keep expanding, and make it possible for not just government agencies to participate in the space phenomenon, but a greater pool of candidates, it will be necessary to search for operationally and financially feasible alternatives to the current status quo, thus simplifying the process in its entirety.

According to Sellars (2008), current operations systems include: 1. manufacturing and testing facilities to build the spacecraft, 2. launch facilities to prepare the launch vehicle and get it safely off the ground, and 3. communication networks and operations centers for the flight control team. Needless to say that all the above elements play a crucial role for the safe and efficient operation of a spacecraft; however, the author proposes the idea of replacing the second variable above, which will considerably reduce financial stress and in the long term cause a gradual evolution on the other two variables.

Vertical Launch Analysis

A summary of the current vertical launch method will first be rendered, in order to identify the inherent problems the method poses. This will be analyzed utilizing the "PESTA" theory, whereby political, environmental, social and technological factors will be contemplated; to be addressed as follows:

Political: This element comprises a synergy of everything, from safety concerns to environment and finance. Nonetheless, the foremost historical note applicable to the subject at hand may very well be safety. Specific attention should be placed on the Columbia disaster in 2003, caused when a piece of foam insulation the size of a small briefcase broke off from the space shuttle's main propellant tank under the aerodynamic of the launch. The debris struck the leading edge of the left wing, damaging the Shuttle's thermal protection system (TPS), which serves as a shields from the intense heat generated from atmospheric friction during re-entry (Gehman, 2003).

The other, directly attributable to the vertical method, was the Challenger disaster in 1986, caused when an O-ring seal in its right solid rocket booster (SRB) failed at liftoff. The O-ring failure caused a breach in the SRB joint it sealed, allowing pressurized hot gas from within the solid rocket motor to reach the outside and impinge upon the adjacent SRB attachment hardware and external fuel tank. This led to the separation of the right-hand SRB's aft attachment and the structural failure of the external tank. Subsequently, the aerodynamic forces broke up the shuttle (Rogers Commission report, 1986).

From the latter, a logical argument can be sustained in that the lives of astronauts lost in the Challenger disaster was greatly contributed to the vertical launch method, due to the inherent risks it poses.

Therefore, an alternative launch method such as the ones to be presented herein should be seriously considered by all parties involved, so that our country can continue to play a safe leading role in the space industry for years to come.

Also worthwhile mentioning is the recent Laws passed by this administration in extending rights to the private sector for future research & development of the industry, thereby transmitting their objective and desire of establishing and evermore increasing participation for this sector in the space arena for years to come.

Economic: After safety, this is perhaps the most predominant factor to support an alternative launch method. According to NASA (2012), the average cost to launch a space shuttle was about $450 million dollars per mission.

According to Sellars (2008), the launch can sometimes account for nearly 30% of a mission's cost. Therefore, if we take the above estimate given by NASA of $450 million, then 30% of the general cost would render a launch cost of $135 million dollars per mission. Again, this is just for the launch part of the mission; without considering manufacturing and testing, or communications and mission operations.

Environmental: The existing rocket propulsion system consumes a great amount of fuel "propellant" in the form of liquid oxygen and liquid nitrogen. For instance, according to Clark (1972), a three stage solid rocket booster has a launch mass of 23,130 kg, low earth orbit payload is 443 kg, for a payload fraction of 1.9%., compared to a Delta IV Medium, 249,500 kg, payload 8600 kg, payload fraction 3.4%. At liftoff an orbiter and external tank carries 835,958 gallons of the principle liquid propellants: hydrogen, oxygen, hydrazine, monomethylhydrazine, and nitrogen tetroxide. The total weight is 1,607,185 pounds.

Also important to point out, despite the above chemicals currently in use, perchlorate was an ingredient heavily used in rocket fuel and some fireworks and fertilizers; and still has been regularly detected in public drinking water supplies. According to the EPA (2000), exposure to perchlorate has been shown to inhibit thyroid functions, subsequently causing developmental problems. It would therefore also be a legitimate question to also ask the long term effects of the chemicals currently replacing perchlorate, and the side effects that might surface in coming years.

Social: This involves the perception of the public, of this and future generations, and their overall evolution in thinking of space related activities; as well as their desire and willingness in acquiring deeper knowledge of space. The acquisition of this knowledge comes with the realization that financially feasible alternatives, such as the proposed alternatives herein, would be considered by the general public as a positive step for the government, in order to help balance the financial deficit dependent on their tax contributions.

Technological: Under this variable a great number of specificities are applicable. Nevertheless, I will concentrate in identifying the launch window variable and the forces exerted on the spacecraft during launch, respectively.

1. Launch window is the precise period of time, ranging from minutes to hours, within which a launch must occur for a rocket or space shuttle to be positioned in the proper orbit (NASA, 2012). Logically, this is much more prevalent when the launches are

vertical, since it directly depends on the orbital plane. In this sense, a launch site at a particular point on earth will intersect the orbital plane only periodically as earth rotates, thus narrowing the window for launches from Kennedy Space Center, or wherever it may be.

Sometimes this window is determined by the passing of an orbiting spacecraft with which the orbiter must rendezvous, such as the International Space Station or an ailing satellite. At other times, the space shuttle or an unmanned rocket must be launched within a certain window so that it can release its satellite payload at the right time to place it in an orbit over a certain region of earth (Sellars, 2008).

Because a rocket must follow a trajectory governed by Newton's laws of motion, a launch window restricts a vertical launch much more than the proposed air launch, where alternatively a spacecraft can be flown to a desired location and then launched with much more flexibility.

2. So that the reader can have a basic understanding of the risks involved with the vertical method; as follows, a brief technical note on the forces acting upon the spacecraft during launch; as well as the hurdles which would be greatly minimized, if not overcome completely, by the implementation of the alternative launch method.

According to Clark (1963), the product of the normal force acting on the spacecraft and the distance from its center of pressure to the moment reference center, which is large ($\approx 2.1\hat{c}$) produces large destabilizing pitching moments. Generally large decreases in longitudinal stability can be noted for all spacecraft with increases in Mach number, which directly relates to a variable which would be greatly minimized through the proposed air launch method.

Newtonian impact theory predicts the pressure drag coefficient on the ballistic spacecraft to be about 0.0089., the drag coefficient for a blunted nose rocket spacecraft is estimated to be 0.0015 and the flare drag coefficient with assumed free-stream Mach number along the cylindrical body is estimated to be 0.0075 (as shown in chart I), rendering a total pressure drag coefficient of 0.0090 for a rocket spacecraft (Clark, 1963).

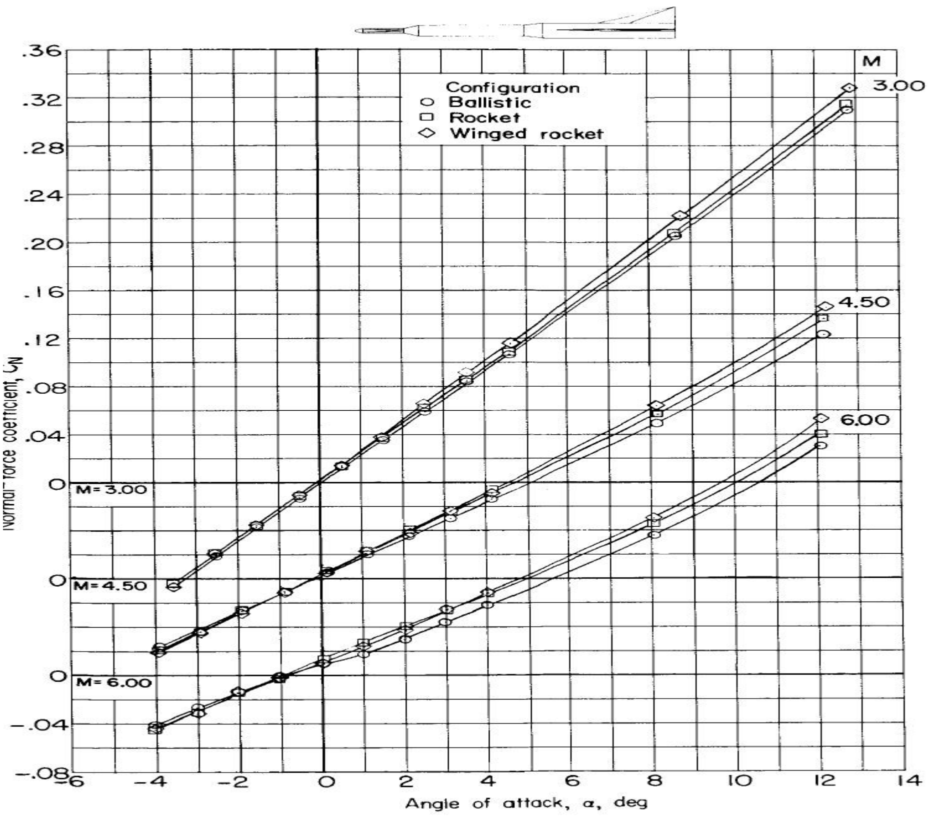

Chart I. Comparative sketch image of drag coefficient of ballistic spacecraft. Retrieved from "Aerodynamic characteristics of preliminary vertical take-off launch", 1963, Clark, L.R., p. 30.

Proposed Air Launch Designs

Now that we have thoroughly identified the inherent limitations the current vertical launch poses for the industry, we will now put forth proposals and designs from private and non private sources alike; so that the reader can have a laconic idea as to whether this is a suitable launch replacement for the industry.

Non-Private: Under this section, we will consider both NASA and military proposals. Horizontal launch, as is termed by the military, is not a new concept in its entirety. Various studies have been conceived in order to study the feasibility of this method of launch, the most recent being the Horizontal Launch Study (HLS) by NASA in 2011, which will be taken into account for this report.

The only currently available horizontal launch system is Pegasus, a bottom-mounted launch vehicle with a two-stage solid rocket released from a modified L-1011 aircraft (NASA 2011). It can deliver 950 pounds to orbit at a price per pound of over $30,000.

According to NASA's HLS study (2011), a categorization of various design concepts were contemplated judged on three payload classes: less than 500 pounds, 500 to 10,000 pounds, and more than 10,000 pounds. The following eighteen air launch system options were considered by NASA to determine their respective feasibility:

1. Fighter jet + multistage solid rocket
2. Commercial jet + multistage solid rocket
3. Commercial jet + multistage liquid rocket
4. Ground sled + multistage liquid rocket

5. New custom subsonic carrier + multistage liquid rocket
6. Advanced fighter jet + multistage liquid rocket
7. Commercial jet + reusable all-rocket vehicle with drop tanks
8. New subsonic carrier with air collection and enrichment system (ACES) + reusable all rocket vehicle
9. New supersonic carrier + multistage liquid rocket
10. Maglev + reusable rocket-based combined cycle (RBCC) vehicle
11. New supersonic carrier with revolutionary turbine accelerator (RTA) + multistage liquid rocket
12. New supersonic carrier with turbo-ramjet + reusable rocket vehicle
13. Commercial jet + reusable turbine-based combined cycle (TBCC) vehicle + reusable all rocket vehicle
14. TBCC vehicle + reusable all-rocket vehicle
15. RBCC vehicle + reusable all-rocket vehicle
16. Hypersonic vehicle with liquid air combustion engine (LACE) and scramjet + expandable rocket
17. New supersonic carrier with RTA + reusable RBCC vehicle
18. Compressed air rocket vehicle + expendable rocket

Once the above options were presented, a process was developed to narrow the number of concepts through prescreening, screening, and evaluation of point designs; not just for the best design, but rather for the most financially feasible (NASA, 2011).

The previous options were placed into three subdivision of time frame, ranked in order of importance:

- Short Term (1 to 5 years): options 2, 5, 1, 3, 4
- Mid Term (6 to 12 years): options 7, 6, 12, 9, 11, 8, 10
- Long Term (13 to 18 years): options 14, 17, 13, 15, 18, 16

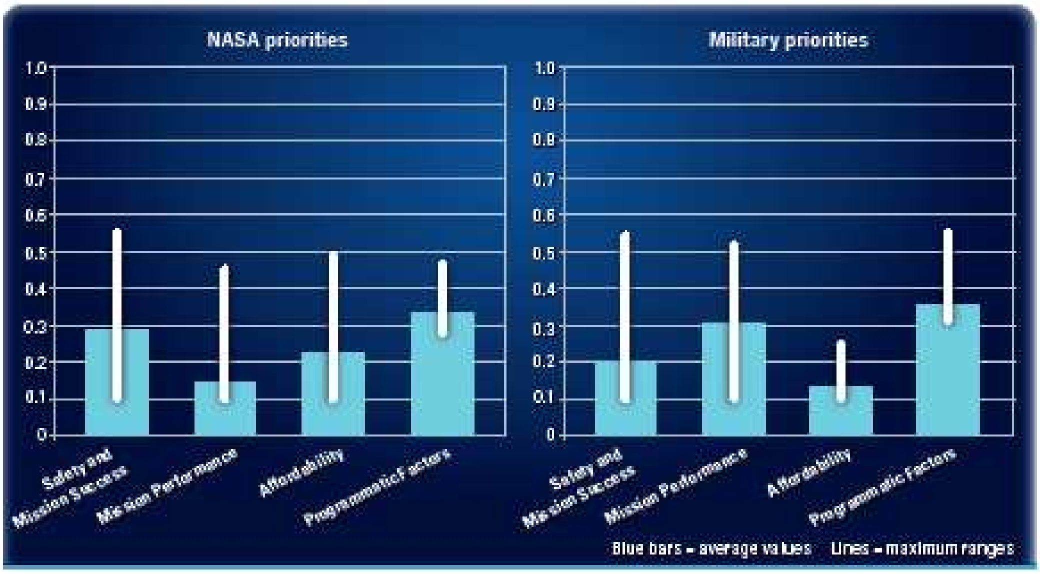

Table I. Comparison of non private priorities between NASA and the Military. Adapted from “HLS Study” by NASA, 2011, HLS-SP 2011-215994, p.12.

As important as the right configuration combination is, the selection of the carrier is another crucial decision. According to NASA (2011), the option of a small supersonic carrier aircraft was found to have very small payload capacity of up to one hundred pounds. Larger supersonic aircraft like the B-1 Lancer was also considered, and was found to have sufficient capabilities to support a 75,000 pound launch vehicle, but inadequate internal volume for internal carriage of the launch vehicle, nor did it have the needed transonic thrust-minus-drag performance to enable external carriage (NASA, 2011).

The NASA HLS study team (2011), found that many of the supersonic and hypersonic system concepts could be very competitive if launch rates increased over current market projections of six flights per year. The remaining aircraft considered were existing subsonic carriers, being the Boeing 747-400F the most widely available option with the advantage of modifying it to carry a payload of 308,000 pounds (as shown in figure IV). Another commercially available option was the Airbus 380-800F, modifiable to carry a payload of 320,000 pounds (NASA, 2011).

Figure I. Conceptual image of air launch method from a B747-400 aircraft. Courtesy of NASA, 2011, HLS-SP 2011-215994, p. 30.

Table II.
Comparison of Air Launch System Configurations

Carrier aircraft	External weight capacity (lb)	Maximum payload to LEO (lb)
White Knight X	176,000	11,180
747-100 SCA-911	240,000	15,440
A380-800F	264,550	17,090
747-400F	308,000	20,000
An-225 Mriya	440,930	30,380
White Knight XX	750,000	49,940
Dual-fuselage C-5	771,620	52,290

Table II. Comparative air launch system concept configuration. Adapted from “HLS Study” by NASA, 2011, HLS-SP 2011-215994, p. 20.

Finally, the team also considered a variant of the WhiteKnight Two, the WhiteKnight XX, based out of scaled composites. This design, which will be thoroughly discussed in the following section, was conceived to carry 750,000 pounds. Nevertheless, its sole disadvantage is that the landing gear is very wide, in fact wider than 175 feet, which would not easily take off from a standard runway.

Civilian: Currently, the foremost investor and supporter of the air launch method from the civilian side would have to be Virgin Galactic. After analyzing the air launch concept and the use of composite materials from one of the worlds' leading spacecraft designer Burt Rutan; Richard Branson, owner of Virgin Galactic, took Rutan's "X" prize model winner under his wings and produced "spaceshipone" and "spaceshiptwo" for commercial purposes. In 2004, the company successfully performed an air launch from 50,000 feet and reaching low earth orbit; subsequently re-entering the atmosphere through the use of a new patented feathering technique to reduce re-entry drag (Virgin Galactic, 2012). From this successful business venture, we can identify the following positive elements:

- Fiber carbon scaled composite: Virgin Galactic constructed its "spaceshipone" and "spaceshiptwo" (shown in figure II), with fiber composite materials. This material is four times stronger than steel and a quarter of its weight, meaning less energy is required to propel both vehicles. However, not only is it very light and strong, but it also has a virtually unlimited fatigue life. As long as the stresses are kept below the ultimate, it does not deteriorate in use in the same way that metal fatigues.

- Feathering Technique: Further analysis of the launch and subsequent re-entry process of Virgin Galactic's design is perhaps the unique way it returns into the dense atmosphere from the vacuum of space. Although not the main topic of this report, a brief synopsis will be rendered so that the reader understands how it functions. Once out of the atmosphere the entire tail structure of the Virgin Galactic spaceship can be rotated upwards to about 65º. The feathered configuration allows an automatic control of attitude with the fuselage parallel to the horizon. This creates very high drag as the spacecraft descends through the upper regions of the atmosphere (Virgin Galactic, 2012).

Figure II. Conceptual image of Virgin Galactic's air launch method. Courtesy of Virgin Galactic, 2012, Air launch method, safety. Retrieved from http://www.virgingalactic.com/overview/safety.

According to Virgin Galactic (2012), the feathering configuration is also highly stable, effectively giving the pilot a hands-free re-entry capability, something that has not been possible on spacecraft before, without resorting to computer controlled fly-by-wire systems.

The combination of high drag and low weight, due to the very light materials used to construct the vehicle, means that the skin temperature during re-entry stays very low compared to previous manned spacecraft and thermal protection systems such as heat shields or tiles are not needed, which is important to mention since it would avoid the constant headaches associated with the monitoring of tiles for re-entry, which of course was the main culprit for the Columbia disaster in 2003. Following re-entry at around 70,000 feet, the feather lowers to its original configuration and the spaceship becomes a glider for the flight back to the spaceport runway (Virgin Galactic, 2012).

- Hybrid Rocket: Virgin Galactic is implementing a type of rocket propulsion known as a hybrid motor. Here the fuel is in solid form and the oxidizer is a liquid. The passage of the oxidizer over the fuel is controlled by a valve which allows the motor to be throttled or shut down as required. This means that the pilots will be able to shut down the rocket motor at any time during its operation and glide safely back to the runway.

One of the most important factors is that the oxidizer is nitrous oxide and the fuel a rubber compound; both benign and stable, as well as containing none of the toxins found in solid rocket motors. Since rockets have long been considered the primary source of our transportation into space, the safety risks have always been great, and due to this, missions have not been able to acquire a true notion of a standard operating procedure.

This by far, is the predominant factor which should propel scientists and engineers to contemplate and gradually apply an alternate launch method. Because a rocket has to operate in the very thin upper atmosphere, where oxygen for fuel combustion is scarce, and in space, where there really isn't any, it has to carry its own oxidizer. Their great advantage is that they are very simple. But the big disadvantage is that, once lit, they can't be stopped. They burn until all the propellant is used up, hence the risks we all now come to understand.

There are two main types of rocket propulsion: liquid engines and solid motors. Unsurprisingly, liquid engines mix two liquids together and ignite them to produce thrust. Typically these may be liquid hydrogen and liquid oxygen, both potentially volatile substances that need careful separate storage and highly specialized pumps to supply them to the combustion chamber.

On the other hand, liquid engines have the advantage of high efficiencies; they are throttle-able and can be shut down early if necessary. But they are relatively complex and expensive to build. Therefore, the third type of rocket being implemented by Virgin Galactic is fuel in solid form and the oxidizer as a liquid. The passage of the oxidizer over the fuel is controlled by a valve which allows the motor to be throttled or shut down as required (Virgin Galactic, 2012).

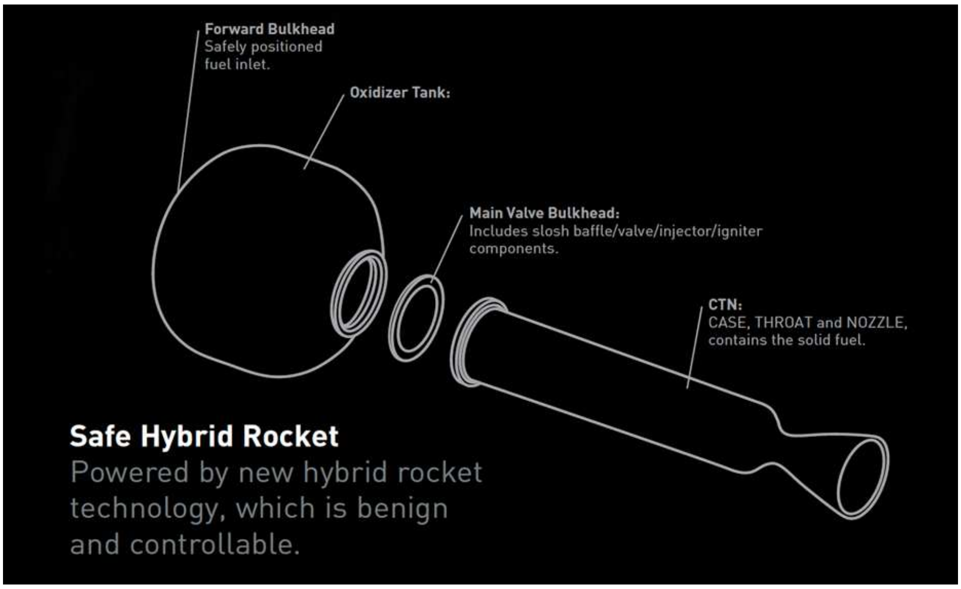

Figure III. Conceptual image of Virgin Galactic's hybrid rocket utilized on air launch method. Courtesy of Virgin Galactic, 2012, Air launch method, safety. Retrieved from http://www.virgingalactic.com/overview/safety.

Review of Relevant Literature

Indeed, there is an importance of having an empirical assessment of comparing the safety, financial and operational performances of the vertical and horizontal launch methods, respectively; as well as a thorough analysis of what this represents. Thus, the main objective is to review the advantages of the air launch method, as well as the contrast of the inherent benefits which might be lost from the vertical method.

The linking of reliable literature information towards this end will provide the necessary relevant sources to further sustain one outcome or the other, and will be imperative in this research denoting to research questions as well as hypothesis.

Questions:

1. What are the characteristics of the current vertical launch method?
2. What are the characteristics of the proposed air launch design methods?
3. What tasks, procedures and facilities are required for the vertical launch method?
4. Are there statistics on mission cancellations due to adverse weather condition for a vertical launch method?
5. Are there statistics on human error directly related to the current vertical launch method?
6. Are private companies, such as Virgin Galactic, contemplating flight simulators with their new proposed air launch method?

Furthermore, emphasis will also be placed on prior evidence that shows vertical launch method is responsible for various financial and logistical impediments, but most importantly on the automation variables induced during the crucial stage of the launch. According to Woods (1994, p. 3), “automation merely changes how work is accomplished." To further support additional literature publications, Wiener (1989) has even claimed that in some instances the introduction of automation may increase the workload. He also cautioned that too often automated systems, perhaps such as the ones astronauts are indefensibly exposed to during launch, might operate well under periods of low workload and becomes a burden during high workload periods.

Singh, Molloy, and Parasuraman (1993) found that automation could reduce the human operator's workload to an optimal level, but only if it is suitably designed. In contrast, if the automation is implemented in a clumsy manner, workload may not be reduced.

Thus, the above analysis raises a logical realization in that most tasks during launch are practically automated; hence the astronauts are defenseless and very limited to react to any unforeseen variables during this crucial stage. The latter is precisely one of the main reasons why an alternative air launch method should be sought out, and would undoubtedly provide ample reaction time for astronauts to take safe and decisive action.

Summary

This report has made an attempt to establish the inherent limitations of vertical launch, the designs being implemented by both private and non private sources, and subsequently the advantages the alternative air launch method represents for the industry.

Financial implications of the current launch method reach as high as $135 million dollars per mission. Again, this is just for the launch part of the mission; without considering manufacturing and testing, or communications and mission operations. Increased safety would also be obtained with the implementation of the air launch method, since launch would generally be carried out at an altitude of about 50,000 feet, which gives the pilot ample amount of time to abort a launch and glide back for a safe landing.

The report also addressed the use of new carbon fiber composite materials. This material is four times the strength of steel and a quarter of its weight, meaning less energy to propel both vehicles. Not only is it very light and strong, but it also has a virtually unlimited fatigue life; as long as the stresses are kept below the ultimate, it does not deteriorate in use in the same way that metal fatigues (Dharan & Grimmer, 2010) .

Further innovations, such as the “feathering technique”, designed and in use by Burt Rutan for Virgin Galactic, should also be further studied. This innovation is an interesting approach to re-entry, which should be contemplated not just for other private business ventures, but also by NASA and the military. This part of space flight has always been considered as one of the most technically challenging and dangerous, and the ability to provide a failsafe solution through simplicity should always be a priority, thus striving to obtain as standard launch operating procedure as possible.

Conclusion

Ground launch comes with intrinsic dangers. The spacecraft has to pass through the lower denser regions of the atmosphere while rocket motor's exhaust is ejected at a high velocity; and for the motor to work efficiently the spacecraft velocity must also be high. Traveling at very high speeds in the lower atmosphere creates a great deal of drag, produces high structural loads and needs a stronger heavier fuselage (Anderson, 2008). Large quantities of fuel are required for the longer duration burn, meaning an even bigger fuselage, leading to yet more weight, leading in turn even more fuel to lift the extra weight, and so on. Effectively launching vertically means everything has to go right the first time, if it doesn't there are generally few options for those inside.

After analyzing all the variables presented herein, as well as the different launch design options, the author supports the idea that the safest and most efficient strategy is to air launch a spacecraft from around 50,000 feet, a height which is already above most of the Earth's atmosphere. This also means the rocket motor would burn only for a short time in order to reach space, and in the event of any problems during the boost phase, the rocket motor could be shut down and the spaceship would glide back to the runway.

This research, and others written throughout the years of similar topics, is a valuable stepping stone that ignites curiosity and interest in future generations of students and engineers to develop a safer and more financially feasible technology; and eventually simplify the launch process, thus making it possible for a growing number of ordinary people to venture into space. It is the author’s opinion that this would in turn further increase the probabilities for a sustained growth in space commerce and tourism for the next century.

Outline Comments:

In order to help preserve the logic of the research itself, the outline will identify the main ideas, define subordinate ideas (See Appendix A), and will overall help discipline the research at hand (APA, 2010, p.70).

The first approach for this research will be to (a) write the outline itself in a concise manner to help with the overall strategy; (b) review relevant texts and journals written on similar topics; (c) investigate the current vertical launch method that will be utilized for a comparative analysis; (d) obtain from NASA and private sources research on proposed air launch designs that would substantiate the argument of replacing the current launch method; (e) analyze the socio-political consequences of implementing an air launch method within the space community, in terms of future training, facilities and financial evolution, as well as the possibility of gradually integrating more and more non pilot astronauts, such as scientist, that in turn will focus on non piloting tasks, once the levels of safety are at a high.

After the first draft is written, considering the above criteria, the following steps will also be contemplated (f) set aside the first draft paper, then rereading it later; (g) read the paper aloud to enable to identify faults originally overlooked on the previous draft; and finally (h) get critiques from at least two colleagues for a review process.

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Appendix A

Outline for the Research and Writing Process of the Topic: The Future of Spacecraft Launch: Vertical Vs Air Designs

I. Title page

II. Reason for Paper and Goal of Study

1. Abstract
2. Introduction

III. Launch Methods

1. Vertical Launch Method Analysis
2. Proposed Air Launch Designs

- *Non Private Sources (Military & NASA)*
- *Private Sources*

IV. Review of Relevant Literature

1. Review
2. Questions
3. Summary
4. Conclusion

V. Outline Comments

VI. References

1. List all appropriate sources
2. Refer to Publication Manual of the APA (6th Edition)

VII. Appendix

1. Appendix A – Outline