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The Crossbow Air Launch Trade Space

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Effective air launching of a rocket is approached from a broad systems engineering viewpoint. The elementary reasons for why and how a rocket might be launched from a carrier aircraft are examined. From this, a carefully crafted set of guiding principles is presented. Rules are generated from a fundamental foundation, derived from NASA systems study analyses and from an academic vantage point. The Appendix includes the derivation of a revised Mass Multiplier Equation, useful in understanding the rocket equation as it applies to real vehicles, without the need of complicated weight and sizing programs. The rationale for air launching, being an enormously advantageous Earth-To-Orbit (ETO) methodology, is presented along with the realization that the appropriate air launch solution may lie in a very large class of carrier aircraft; the 'pod-hauler'. Finally, a unique area of the system trade space is defined and branded 'Crossbow'. Crossbow is not a specific hardware design for air launch, but represents a comprehensive vision for commercial, military and space transportation. This document serves as a starting point for future technical papers that evaluate the air launch hypotheses and assertions produced during the past several years of study on the subject.

Nomenclature

A = area
C_D = drag coefficient
C_{fv} = coefficient for fractional velocity where $C_{fv} \equiv v_1 / v_2$
E = energy
F_{Drag} = drag force
f = switching function (a value of 1 indicates dry mass does not include payload and 0 if it does)
g = gravity constant (9.81 m/s^2)
Isp = specific impulse
L = length
M = mass
MF = mass fraction
R = radius
T = time
v = velocity
V = volume
ΔV = change in velocity
λ = propellant mass multiplier (ratio of propellant-sensitive structure mass to expended propellant mass)
ρ = density
ε = dry mass multiplier (ratio of dry mass-sensitive structure mass to dry mass)
Φ = gross mass multiplier (ratio of gross mass-sensitive structure mass to gross mass)

I. Introduction

A modest effort has been dedicated over the past six years by engineers at NASA to air launching a rocket from a carrier plane. This initially germinated from the first requirement of the Space Launch Initiative (SLI) for improving launch risk to meet a goal of 1-in-10,000 probability of loss of crew.[1] It was believed by some at the time that efforts to "tweak" hardware or streamline procedures would not come close to achieving that level of safety.

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Much of what was being done (and often still is) was a call for increased "technological advances" to improve safety, when in fact that can have the opposite effect by introducing unknowns and complexity, while operating at ever slimmer engineering margins. Sticking to "tried and true" old technology neither provides the payload/cost desired or the reliability as illustrated by the recent failed Russian Dnieper rocket.[2] The physics of vertical launch impose fixed limitations that hamper safety. They are:

- Zero initial velocity
- Slow accelerations
- Close proximity to the ground
- The exponential nature of the rocket equation on mass fraction
- Atmospheric effects on engine optimization and rocket design

Each of these is discussed in terms of the economic and safety advantages for air launching the rocket.

A classical (university) systems-engineering approach is applied. A trade space is defined, the various options identified (all with the permutations and combinations described), inherent advantages and disadvantages of each are listed, and weighting factors applied for analysis. Much of the technical input has been condensed from various design meetings, systems studies and general knowledge of the art of rocketry and aviation. The systems level examination is relatively top-level and each area can be significantly expanded in other more comprehensive documents. The need for detailed engineering analysis or testing is also noted whenever appropriate. Nonetheless, the results and conclusions are important to understand. As noted by many sources, the vast majority of all life-cycle costs, programs risks, technical changes, etc. are fixed by fundamental (program) decisions at the outset. A good example from the NASA Systems Engineering Handbook states, "It has been estimated that at least 80 percent of a vehicle's life-cycle cost is locked in by the concept that is chosen."[3] Thus, the understanding of the inherent benefits and limitations to any option is vital even before the conceptual design stage is begun. Equally important are the requirements and stated objectives of the project, which cannot be changed midstream of the engineering process. It must be clearly understood what requirements, if not absolutely met, summarily end the project.

II. Air Launch Inherent Advantages

Fundamentally, there is only one reason to begin a trip to orbit using an aircraft - lower total cost than the alternative. Total cost here includes the value of safety, technical efficiencies, timeliness and any other benefits, since all can be reduced to a monetary value for comparative purposes (note: a human soul can never be adequately quantified in terms of a dollar value, but engineering and practical experience make this risk-to-life assessment in terms of a monetary value, a necessary and common practice). The baseline comparison is the vertically launched, all-rocket transportation, which is the historical approach. Total cost is inclusive of materials, manufacturing, inspection, testing, operations and end-of-life expenses. Synonymous terms are *Project Life Cycle Costs*, *Final Program Cost*, *Total Cost of Ownership*, and *Cradle-to-Grave Analysis*. We primarily concern ourselves with ETO transportation to LEO and for human travel. Although other applications are possible, they usually follow the same advantage/disadvantage trends closely. In order to suggest air launch is worthy of actual implementation, it must show a cost benefit significantly greater than the best existing alternative.

There are five physical differences (velocity, acceleration, altitude, mass fraction, atmospheric effects) that appear to have a significant impact on cost and, specifically, the exponential cost of increasing the safety of launch systems. Each will be addressed in terms of its final impact on total cost, as a difference between the existing baseline and an air launched rocket scenario. This will be a qualitative comparison and will apply to all air launch approaches. Presently, the detailed care and exceptional control applied to every part of a rocket from raw materials to final launch operations is exceedingly labor intensive, requires exceptionally skilled and trained workers, is time consuming, and incurs substantial total costs. To improve the reliability and launch safety, more inspection and testing is demanded. However, each new item will have less and less effect on risk reduction, while the work force will grow at an ever-increasing rate. This is primarily due to the "logistical support train" that accompanies every hands-on engineer and technician and every new test or procedure. There will be requirements for review boards, management supervision, accounting staff, new training, documentation, personnel offices, safety support, and many other items that are all proportionally based to the number of people involved in the program. Needless to say, the total cost exponentially inflates as the attempt at increasing the launch risk from ~99% to ~99.9% is pursued. Air launch has many of the same systems and operations, but its inherent advantages can reverse this divergent cost-to-safety trend.

A. Velocity

A vertically launched rocket has zero velocity at lift-off and no practical means to gain any from sources other than the rocket itself. Sled launch, magnetic tracks/towers and the like are overly complicated to integrate into a rocket and its costly infrastructure. Also, they could only provide trivial increases in velocity since acceleration limits must be kept below the human tolerance restrictions (nominally ~3 to ~5 Gs). Air launching a rocket at even a few hundred miles per hour is advantageous. Forward velocity has two impacts on total costs. First, there is a very minor technical performance advantage in that the velocity is added by 'airbreathing' hydrocarbon-fuel at an equivalent Specific Impulse (I_{sp}) upwards of ~6,000 seconds. But this in itself is negligible to the total cost. Dynamic gains are found in the survivability of the payload should a catastrophic rocket failure occur. Starting with Figure 1 and the fact that the rocket is traveling at a fair fraction of the speed of sound after the initial aircraft climb, it can be shown that the energy intensity of a blast will follow Eq. (1). When the initial shockwave interacts with the payload capsule, the payload's unrestricted motion (again away from the explosion event) will be pushed forward dissipating additional energy at the rate of the distance to the third power. Complicated shock formations setup about the craft's body and a further portion of the energy is absorbed into the vehicle, continually diminishing the net shock that is fatal to life or hardware. The vertical rocket approach can only offer one mitigating solution to the lack of velocity at engine ignition, that is an expensive and dangerous tractor rocket or 'escape tower'.

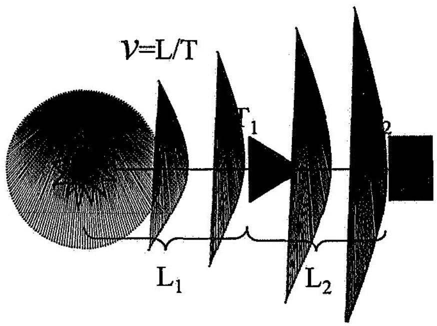

Figure 1: Velocity impact

$$\Delta E \propto \frac{V_1}{V_2} = \frac{\frac{4}{3}\pi R_1^{\,3}}{\frac{4}{3}\pi R_2^{\,3}} = \frac{L}{(L + \frac{L}{c_{fv}})} = \frac{c_{fv}}{1 + c_{fv}} \tag{1}$$

To illustrate Eq (1), a simplifying assumption that the explosive propagation will be on the order of the speed of sound is made. We then see that even at Mach 0.5 ($c_{fv} = 0.5/1.0$), the explosive shockwave is one-third the intensity and, at a more realistic Mach 0.85, the blast is diminished ~84% of the energy intensity that would have hit a "fixed" payload capsule on a vertical launch. The shock of an idealized hydrogen and oxygen detonation or a solid rocket rupture can be several times greater in propagation speed, but we assume here that solid rockets are completely inappropriate for air launch (discussed in later sections). Catastrophic liquid fueled rocket accidents realistically occur with the majority of the propellants not well mixed. Additionally, the blast in both rocket types would be of less intensity along the rocket axis direction. Although more accurate analyses will quantify the precise benefits, the purpose here is to illustrate that velocity itself has potential merit at a very fundamental level. In addition, velocity has a supplementary value. It allows time for emergency response systems or human reaction to implement abort procedures. It might eliminate the need of an escape tower with its extremely high accelerations (as much as 10 Gs which can be more than the effect of the explosion in some cases), or at least significantly reduce its complexity and power requirements. The line between tractor rocket firing to save life and the risk in using the system can make the decision to implement it too close to ensure its effectiveness.

B. Acceleration

A conventional vertical rocket starting at zero velocity is limited to minimally acceptable payload acceleration (~10 G for humans). However, practical application reduces this value at least by half, and for comfort, to about one third. However, the nature of the rocket equation would impose a similar limitation and in fact causes a significant variation in acceleration rate (a steady acceleration being more desirable). The rocket gets lighter as it burns fuel and the acceleration increases, since rocket engines generally are constant thrust devices (i.e., they optimize performance at one thrust level). Constant thrust and increasing acceleration is the nature of rockets, particularly boosters. Boosters require high thrust because the rocket is heaviest on liftoff, and to move off the launch pad at all, a Thrust-to-Weight (T/W) ratio of better than unity is necessary. In fact, higher thrust is important (i.e., T/W much greater than 1) since low thrust means the rocket spends a greater percentage of its time at the highest gravity level. The added propellant to overcome gravity increases the vehicle size and total cost of the system, as well as creating a further mismatch of T/W at higher altitudes. Solid 'strap-on' rocket motors are often used to supplement the lack of thrust at the launch pad because they provide high thrust and burn out quickly, creating a step function in the otherwise smooth exponential acceleration curve. There are tremendous costs for the initial rocket purchase, and further costs buried within the cascade of rocket/payload integration and safety activities. Another often-missed costly feature of a solid rocket is its on/off nature. It has to work the first time, as there is no prior testing, and once ignited, it and all other systems must function flawlessly to avoid catastrophic failure. Hydrocarbon (kerosene) is the liquid rocket booster fuel of choice, because it has high thrust (at the cost of lower Isp). As it is often assumed that at least two stages are necessary to effectively achieve orbit from Earth[4], the common thought has been this second booster system adds no supplementary cost. However, a separate engine development, test and maintenance program does impact the bottom-line, and significantly so, since this is the largest stage. These engines have such poor performance as upper stages that a common engine development program is not likely or fails to significantly reduce total cost, as the systems are tuned so differently to accommodate the necessary thrust profile. The correction to this is the all-liquid hydrogen (LH_2) Oxygen (LOX) vehicle as exemplified by the Delta IV[5]. This only switches the problem back to one of low thrust at takeoff and a non-optimized acceleration over a large portion of the flight. Again, the selection makes no genuine impact on total cost!

So, how does air launching a rocket change the pros and cons inherent in rocket design? First, it nearly eradicates the worst penalty for low T/W, which is the gravity losses. Any need for solid rocket motors is eliminated along with their unsafe and expensive handling issues or a completely unique hydrocarbon engine design. It also makes the first and second stage flight more equal in the acceleration profile and can help reduce the flight's maximum dynamic pressure. The air launch rocket will tend to be smaller and lighter, thus mitigating the wide T/W range seen from ignition to booster separation. With a proper selection of engine size, engines per stage and T/W, the system can use the same LH2/LOX engine in both stages and truly save on a single engine program throughout the system's life cycle (other significant factors will be covered in later sections).

C. Altitude

Like, the previous two fundamental factors, a rather small altitude change inherent in air launching a rocket is marginal in its direct performance impact, but there is a larger influence on risk, system design and total program cost. A 10-kilometer separation altitude is only 1/20 of the potential energy needed for a modest 200-kilometer orbit insertion (the energy required for tangential acceleration being far greater than the potential energy to make altitude). In rocketry, every small bit is helpful, although this alone would not suffice to pay for the complexity and integration of a carrier aircraft. Altitude 'buys time' for emergency and abort scenarios. Remember that safety or risk reduction for the crew/payload is only achieved at extraordinary expense because the driving goal is near perfection on a sophisticated system, bordering on zero engineering tolerances to keep the system mass low. Air launch opens an entirely new concept of achieving high odds of crew survivability or intact payload recovery. It saves the human cost, the cost of payload replacement, and avoids the inevitable disruption or stand-down of the entire spaceflight workforce. It should be noted that no program ever includes this cost or risk in its preliminary design decisions. Furthermore, the disruption of schedule for the entire industry would be minor should a single flight failure end in a planned recovery of the "payload" and a relatively quick reflight.

The Earth's surface is the critical factor in rocket launch design and payload abort/recovery. At launch, a vertical rocket is usually bolted to the launch pad until nominal engine performance is established. The system is most vulnerable a few feet off the pad where it has little forward velocity, all of its explosive propellant, and the 'hard' ground near by. Therefore, the moment before final release (or ignition of solid rocket motors, which cannot be turned off) is the true moment for system reliability determination. With altitude, there are seconds to minutes to assess and take action on flight anomalies. Perhaps time to continue a launch, which otherwise has to be canceled in a flash decision (e.g., include plans to bring backup-systems on, reset/recalibrate a sensor, change control settings and the like rather than prematurely declaring a "crit 1" failure point).

The other more technical implication of zero altitude is the mechanical vibration loads placed on the rocket, due to direct reflection of its own exhaust plume. Although this rumble is the "signature label" of man's conquering space, it is a significant engineering challenge and ultimately a considerable expense. All systems on the rocket and the payload must endure this stress. Vibration testing is a significant factor to budget and schedule on any launch. It adds weight and demands redundancy on everything done from the propellant fluid dynamics to sensor wiring clips, anti-chafing materials and techniques, and harness connector approaches. The systems engineering implications are far greater than for "max dynamic pressure," a value that can be controlled by engine throttling or other system trades.

At the launch pad, operations and facilities are daunting just for the exhaust flame deflectors and trench; a system not intended to protect the concrete launch base (consider rocket engines must contain the explosion with little mass for the duration of the flight, yet the massive pad structure has only to endure the relatively cool plume effects for a fraction of the time). Its primary purpose is acoustic attenuation and damping of the thunderous vibration! For the Space Shuttle, a peak flow of ~900,000 gallons of water a minute (~3,407,000 liters/minute) is used along with a nylon water-bag system in the solid rocket motor holes[6]. The cost and maintenance of such a system is nontrivial and it has to work or the flight is scrubbed. Air launch provides enough distance to eliminate the reflected vibrations (considered insignificant above ~300 meters). Furthermore, without being restrained (i.e., bolted down) the direct vibration effects are dampened through air pressure assisted by the inherent velocity of the vehicle in the free stream and do not concentrate strain at particular points. The results are reduced infrastructure, easier design requirements for maximum dynamic pressure and acoustic vibration levels; opportunity for innovative anomaly, abort and recovery procedures; and a lowering of risk, with a consequential reduction in total cost.

D. Mass Fractions

Rocket system success often boils down to mass fraction. It shows up in the rocket equation and is the only "tweakable" value in the equation to improve performance (gravity being a fixed constant for the Earth and Isp already near its best theoretical limit in existing systems at ~450 seconds). Before evaluating the mass fraction itself, air launch has a unique effect on the only other term in the equation, the change in velocity, or ΔV, required for getting to orbit. Normally, it is considered fixed at ~9 to ~9.2 kilometers per second as gravity and other realistic parameters that make up the value are essentially constant among rocket flights (theoretical ΔV is ~7.5 kilometer per second). But altitude and atmospheric effects combine to increase the minimum orbital goal to ~8+ kilometers per second. This is mentioned here because of the very important effect it has on mass fraction[7]. As seen in Figure 2, this small ΔV change brings the mass fraction off the very steepest part of the curve and the benefits of air launch makes the range of structural mass fraction almost irrelevant as indicated by the small arrow in the figure. This gives program managers and engineers a little "breathing room" if they do not hit the planned structural mass margin and must add a small amount of propellant to close the design. It also affords real margin for safety and risk mitigation for the rocket. A revised derivation of the equation in Figure 2 which includes two similar factors for rocket mass is given in the Appendix. One scales with the gross takeoff weight, such as wings and landing gear and the other scales with dry mass, such as control surfaces or reaction control propellants.

Air launch generally does not eliminate the need for rocket staging. The merit of rocket staging can be understood by examining the updated "Mass Multiplier" equation in the Appendix. A "Single-Stage-To-Orbit" (SSTO) rocket has proved elusive for many reasons, but air launching, by and large, does not improve the mass margin to achieve a "reusable SSTO" (typically envisioned as a fly back return) even with the elimination of takeoff wheel mass, heavy altitude-compensating engines, and reduced ΔV requirements. Only when unrealistic air launch conditions are assumed (~Mach 15 at 50+ km) does it make the "rocket" small enough for an attractive SSTO with reasonable payload capability. Other approaches along these lines include LOX collection[8]; a good example being *Alchemist*[9]. However, these vehicle systems are more like a twin hypersonic configuration (Two-Stage-To-Orbit) rather than an air 'launched' rocket and require much better mass factions than are typically achievable today. It is left up to others to speculate if this area of the ETO trade space is viable in the far future, but it is deemed outside the air launch trade space presented here.

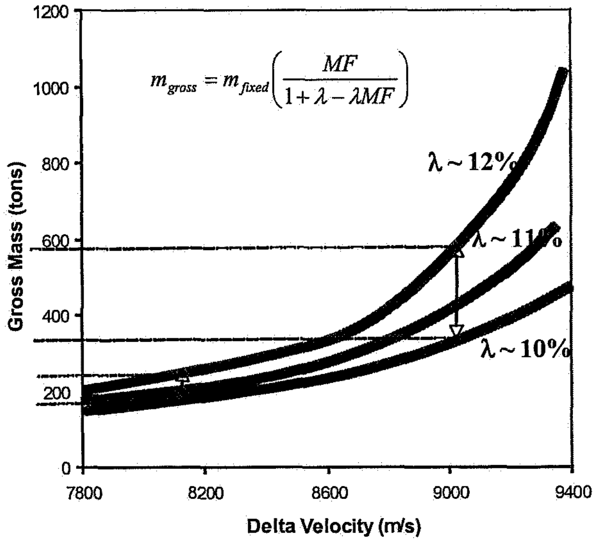

Figure 2: Structural mass fraction

E. Atmospheric Effect

The Earth's atmosphere has a profound effect on rocket operation, performance and ultimate cost. The high air pressure of a sea-level-launched rocket dominates the engine design by forcing designers to high chamber pressures to overcome the inherent backpressure and avoid nozzle flow separation[10]. Chamber pressure correlates directly to reliability and cost of the engine. Rocket nozzles are shortened to function at liftoff, but at the sacrifice of Isp at higher altitudes. Altitude compensating engines and extending bell housing have been tried but with little practical benefit[11]. They are more expensive, and often heavier or less reliable. Designing a rocket engine for ~10 km or higher altitude allows the engine to operate better than 90% of its vacuum Isp with a correspondingly higher overall flight trajectory Isp, the real performance parameter of interest in comparing ETO systems. At the same time, it permits lowering the chamber pressure and enables utilization of the more reliable, lower mass, and less costly expander-cycle engine. The expander has lower turbine temperatures and overall lower demands on engine materials. Traditionally used for upper stages, the air launched expander engine adds the advantage of a single engine development, test and production program for a two-stage rocket.

The atmospheric density also impacts the total drag the rocket must overcome during flight and the maximum dynamic pressure the structure experiences. Obviously, negating all drag losses incurred by a conventional sea-level launched rocket, at the beginning of its flight (~0.075 km/s ΔV), is helpful but hardly noteworthy. Equation (2)

$$F_{Drag} = \frac{1}{2}\rho C_D A v^2 \tag{2}$$

models the drag force and has three terms, which are helped by air launching. Assuming subsonic aircraft operations, velocity is low at the start of the rocket's accelerating ascent, but the term is squared making it relevant. The lower velocity at the beginning avoids additional drag losses within the last, comparatively viscous section of the atmosphere. The velocity must be made up with a slightly longer acceleration period at the top end of the flight where the atmosphere is minimal, thus, adding only a trivial amount of drag and pressure loss there. Atmospheric density decreases by about two thirds and atmospheric pressure, aided by a temperature drop, falls ~75% at launch altitude, as it exponentially decreases during the rest of the trajectory. Air launch affects the area term, A, in Eq (2) since additive effects of other parameters tend to reduce the size of the rocket, and in turn, reduce the vehicle's cross-sectional area. This iterative effect is a common trend in systems engineering. What is unusual with air launch is that the effects converge toward a better solution instead of the typical spiral growth of the rocket seen in studies as the effort is made to close the design.

III. Fundamental Air Launch Approaches

This section is a synopsis of the academic review of air launch presented at the Naval Postgraduate School within the space launch systems class. A complete review of all past air launch concepts is a textbook in itself, and is omitted here for the sake of brevity. Two points are noted concerning past studies or actual operational systems. The first is that all past proposed air launch systems specifically violate what should be the most fundamental premises, upon which are based the rules defined in the next section. Second, they all started from some non-optimal preexisting circumstance or assumption. This can take the form of an 'available' solid rocket, carrier airframe or propulsion methodology that prejudicially compromises the trade space. With the exception of the White Knight[12], no new carrier craft has been designed or flown specifically with the air launch mission as an objective. And that example (Figure 3) shines the light of 'engineering' on how differently the design can be in order to optimize the overall system!

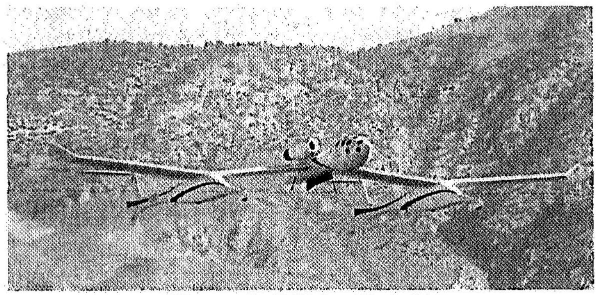

Figure 3: White Knight

Air launch can be conducted from a variety of platforms whose most distinguishing difference is velocity. The trade space can be illustrated as in Figure 4 where it is bounded by four basic categories. Conventional and non-rocket applications are self-explanatory. The Unconventional propulsion eliminates the concepts that have fundamental physics questions or bear a resemblance to science fiction rather than a system that can be operational in the range of two to twenty years. The last boundary is the pure SSTO concepts, which may use some aspects of

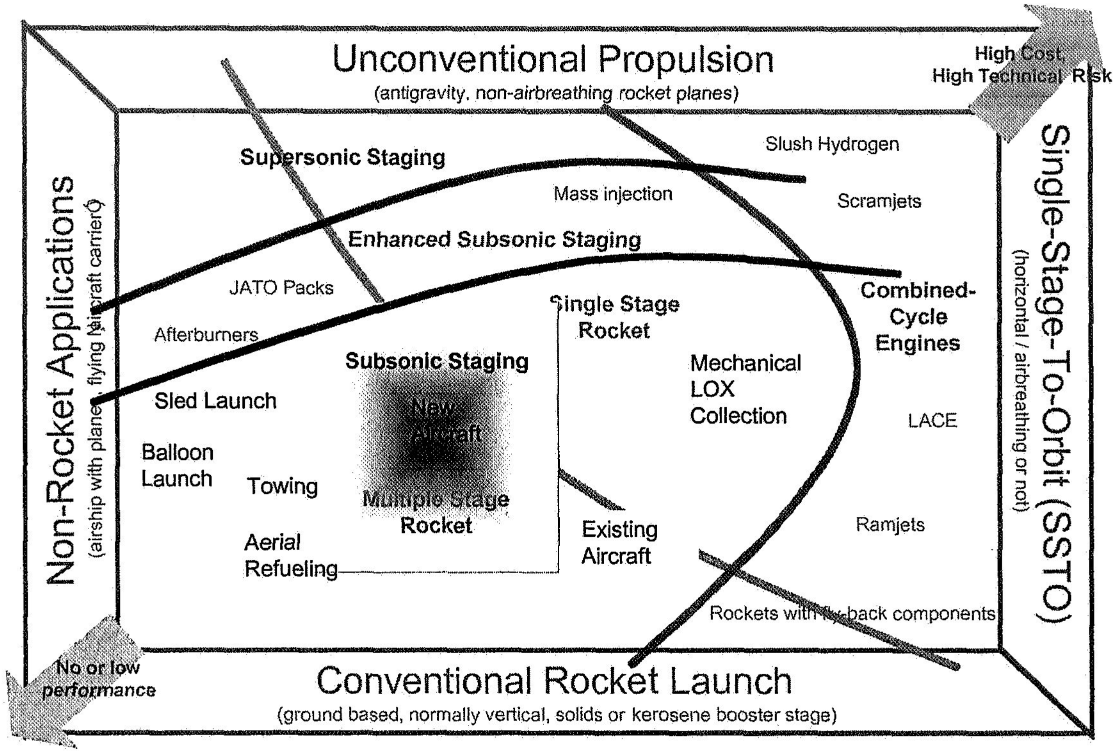

Figure 4: Trade space

air breathing propulsion. Further excluded, on the right-hand side of Figure 4, is the well-researched field of combined cycles, best known as Rocket-Based Combined Cycle (RBCC) propulsion. Table 1 highlights the many variants that can be constructed from the basic engine cycles and the key options available. Again, this area has been well studied, yet has not produced a consensus of what is the 'best system,' much less a practical vehicle.

The trade space this paper addresses, the highlighted region in Figure 4, is subsonic separation of a two-stage rocket, air launched utilizing a new aircraft, designed and built to perform the air launch function as well as other tasks. Supersonic operations have been eliminated, as they are not economically viable. The military, after 50+ years of development, has not fielded a supersonic aircraft with a "low" lifecycle cost: even models produced in high numbers. Certainly the retirement of the Concord, a commercial supersonic aircraft with no follow-on system even in design, indicates the expensive nature of such crafts. Supersonic flow fields are extremely dangerous to attempt separation as revealed in the SR-71 drone (D-21) accident conclusions.[13] The air-launched payload-to-orbit capability of a well-optimized subsonic carrier plane is easily equivalent to that of a Mach 3 or 4 carrier, a performance range that exceeds the best jet aircraft engineered today. Cost is always cited for the retirement of the Blackbird fleet[14], despite its apparent wartime usefulness, yet the 50 year old B-52, with a lesser strategic mission, is not only flying today, but is scheduled to operate for another 20 years![15] The complete case for excluding supersonic operation is beyond the scope of this paper, but the key topics would include the physics and reversing phenomena of flows above and below Mach 1; structural thermal expansion; engine temperatures; shock interactions; and the fact that the rocket still imparts the bulk of the orbital energy. These engineering considerations drive the total expense far above the expected savings for a marginal (if any) benefit. Likewise, enhanced subsonic staging appears to offer less performance advantage and complicates the subsonic operations, while adding significant total lifetime cost.

There are other options surrounding the trade space selected, which have their own advantages and disadvantages. Some are opportunities to enhance the Crossbow trade space. Aerial hydrocarbon refueling is an established technique which permits long transits to optimized launch locations and increased rocket mass (obtained by carrying the minimum jet fuel required for takeoff). It does add the expense of a separate refueling aircraft, which could be minimal if sponsored by the military as training for its existing tanker crews. Tank fill or top-off cryogenic propellant (inevitably the oxidizer LOX) requires more advanced mid-air refueling operations or a mechanical liquefaction/separation system to be developed, but offer similar gains. Balloon launch and towed launch are attempts at simplicity. They eliminate the tricky separation maneuver, but both have major drawbacks. The balloon has no forward velocity, more difficult trajectory targeting and does not scale well for large rockets. The towing choice requires the rocket incorporate heavy wheels, wings sized for takeoff, and structures designed for high tension as well as compressive aerodynamic loads. In the Appendix, the term ϕ becomes very important as the structural mass proportional to the gross mass grows for the towed rocket. A careful economic analysis could quantify the relative total cost associated with each trade and highlight their safety implications. However, the fundamental fact remains that the rocket generates the majority of the ascent ΔV and anything that impacts its design or performance in all probability will not produce a favorable cost effect. Because of the exponential nature of the rocket equation, the rocket mass fraction drives the rocket to larger sizes, so very limited rocket size, such as for the balloon launch, can fall short of expectations, except perhaps in the case of mini-satellites. Too large a rocket and it becomes uneconomical, due to the exponential increase in manufacturing, shipping and operations costs, once the diameter exceeds nominal human/infrastructure dimensions. The large payload capability is often underutilized and actual operation costs creep higher, due to schedule impacts, integration of multiple and non-optimized payloads, insurance costs, low flight rates, and many other 'hidden' losses. A noteworthy hidden cost example is flying a new technology with an expensive payload or a crewed vehicle. The technology's flight hardware must be brought to the same safety specifications and reliability levels as the primary payload, which can quickly overtax such a development program's budget. Often the orbit insertion for the secondary is non-optimum and again leads to poor performance or expensive compensating measures. The most common result is the technology simply not getting flown and remains forever unused. This costs the space industry and society not only the potential savings of the new technology, but also the lost investment of its development. It is these many indirect effects that make space so expensive for very large rockets. Hopefully, a comprehensive economic analysis can quantify these costs that are never considered in launch system trades.

Table 1: Combined-cycle alternatives

Common Engine Cycles	Typical Combination Options
Turbofan	Single or Two Stages
Turbojet	Common vs. Separate Ducting
Afterburners	Transition Timing (discrete or continuous)
Strut Rocket	Variable Inlets (single or multi-wall, shock wave, louvers or doors)
Ramjet	Launch Assist (catapult, maglev, air launched)
Scramjet	Fuels for Each Mode (liquid or slush hydrogen, various hydrocarbons)
Pulsed Detonation Engines	Oxidizers (when & what is used, augmentation)
Liquid Air Cycle Engine (LACE)	Thermal Cooling Schemes
Rocket Assist	Tank Configurations (shapes)
Integrated Body	Control and Stabilization Schemes

IV. Rules for Effective Air Launch

The study has led to certain conditions or rules that appear to be necessary for a substantial benefit to be obtained. Although there are many possible ways to develop the system, and several smaller niche applications, the long-term viability will only be obtained by observance of these often commonsense rules. Alternate development paths might include smaller prototype carrier aircraft that are only used for testing and flight validation and not long-term operations. Perhaps a half-scale vehicle is deployed to demonstrate and build confidence in the aerodynamics of separation. These seeming 'rule violations' can be small steps to the overall program development. With the future vision laid out for commercial aviation in the last section, one would expect several of these 'intermediate' steps along the way. An example alternate niche application is the air launch of a simple 'pop-up' space vehicle not intended to make orbit such as SpaceShipOne & the White Knight carrier aircraft.[16] Also, if a half-scale demonstrator is constructed, it could become the basis of a mini-satellite or dedicated CubeStat[17] rocket launch system. The base vehicle might be considered a 'sunk cost' by the government for research purposes, but then serve as the platform for a modified sounding rocket for ballistic trajectories or low altitude orbit insertion.

There are four categories into which the rules have been organized. They are economic/budgetary constraints, nominal performance values, the rocket/carrier technical approach, and the overall systems engineering or integration. The rule is stated and supported through technical data, logical scrutiny and general engineering knowledge of the propulsion systems within the trade space. However, each can only be fully addressed through its own in-depth study and technical documentation. Rules are set in italics for clarity.

A. Economics

Air launch has been discussed primarily on the basis of total cost advantage. The initial rule recognizes that the carrier aircraft cannot be considered “an even swap” for the booster rocket. The rocket community, rightly, will not embrace a vehicle that is as expensive as today’s booster rockets, but has less performance and requires major changes to the whole rocket design process. Therefore, the system must be very low cost in all stages of development and operation. *The carrier aircraft must produce substantial launch cost reductions.* As discussed earlier, that is the key reason why supersonic and rocket assisted aircraft are not competitive options. In pursuit of cost reduction, the first approaches have been to use an existing aircraft to realize the large cost differential that is required. In fact, buying a used plane or one ‘donated’ by the Government, such as the SR-71 or B-52 ‘given’ to NASA with this intent, commonly is perceived as the solution. However, it is not. Existing planes require modifications that can easily be as expensive as building a new vehicle and there are always compromises in performance or operations that create embedded costs, especially over years of operations. The cost of a new plane might be ~\$300M (considering a new 747 is ~\$200M stripped). This cost is on the order of several all-rocket launches. Consequently the ‘rocket’ must be affected in some financially positive ways. These may include: reduced ground crews; elimination of the launch tower; more economical rocket manufacturing; no rocket shipping and erection costs; no cranes if the rocket is underside mounted; simplified inspection and payload processing; reduced payload insurance rates, assuming multiple abort and recovery procedures; and elimination of pyrotechnics and solid propellants. These many deviations from current practice could make a sizeable total cost reduction.

Another mistake would be to dedicated the carrier to rocket launches alone. *The carrier aircraft must have a continual utilization demand that is profitable.* Today’s spaceflight demand simply cannot support daily flights, even if the cost per kilogram to orbit is reduced. The need for satellites is on the order of 10 to 25 a year and human spaceflight, although desirable, could not support much more. Even at the unrealistically low cost of \$2000/kg, an 90kg person with 180kg of life-support and baggage would cost over 1/2 million dollars per flight just to reach orbit! Therefore, even if all the world’s space traffic was done by a sole air launch carrier - rather doubtful - 50 flights a year is running the plane a few hours once a week. The airline industry has struggled financially for many years; well before the present fuel and security environment, and they have been operating commercially “mass-produced” aircraft several times a day almost continuously! Pegasus launches are actually among the most expensive because of the need to amortize the carrier plane’s yearly operation expense over a few flights per year[18]. In the far future, space flight rates may be higher, but any specially designed plane, if only produced for launching rockets, will be very expensive to build and maintain. For example, three planes averaging two flights per day with just five passengers is over 10,000 people a year into space. That pace is not reasonable to expect. At a believable 250 people per year, the planes would sit idle over 97% of the time and cost some \$300,000 per flight assuming a 20-year service life, but not including maintenance, fuel, insurance, or loan interest. One must conclude that the planes must be capable of other paying or advantageous service!

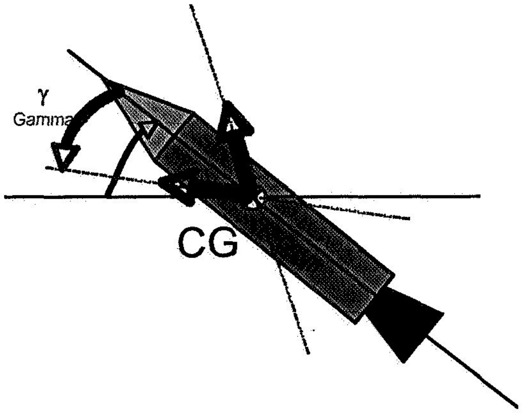

Figure 5: Off-nominal flight path angle

B. Performance Parameters

The separation angle, Gamma, is the single most important parameter to match for air launching a rocket. The flight path angle, or direction the Center of Gravity (CG) is moving, must be along the idealized trajectory path. That path will vary for each launch mission and its computational determination is non-trivial. Figure 5 shows the error that can occur as the rocket may be oriented along the planned trajectory but the actual vector at the CG is misaligned. At an altitude of ~10 km, the minimum the angle should be from the local horizontal is ~30 to 45 degrees (thin black arrow in the Figure). If the CG vector is aligned but the rocket body is not orientated along the trajectory line, little energy needs to be expended for the correction (e.g., gyro motion). Conversely, the energy to correct a gamma angle misalignment is very high and adds the penalty of rocket steering looses.

The altitude and velocity at release are secondary factors to increasing air launch performance, but must not be so low that no favorable impact is made upon the rocket. It is in altering the design approach of the rocket that noteworthy gains lie. Air launch will have few benefits and zero, or negative, change in total launch cost if the rocket is released at 3 or 4 kilometers. A 10 kilometer altitude release is considered the minimum to effect substantial change to the rocket and its costs. The release maneuver and any rocket steering cannot be permitted to null the altitude gained. Allowing a separation-drop to provide a safe rocket start distance from the carrier aircraft will typically cause this detrimental altitude loss to occur. If such is needed and determined practical, then the release point should be correspondingly higher to compensate. Moreover, a flawed design scenario would ensure were a solid rocket motor to be used as the first stage. As previously mentioned, this is not appropriate in the first place since solids are best used to compensate for low T/W at sea level. Besides solids are more hazardous because they can detonate and cause severe blast overpressures; and grain flaws are more likely to result from a rough ride off a runway than from slow and expensive launch pad assembly. This would lead to ever-larger separation distance requirements placed on the carrier aircraft for safety. A freefall drop of 5 or 10 seconds not only lowers the altitude, but also burns off much of the forward velocity and adds negative vertical velocity, all of which must be overcome by eroding the rocket's performance. Steering and control during this time is difficult and requires adding wings, parachutes or other subsystems. Additionally, rocket nozzle steering losses are worse for a solid rocket motor, if there is any significant control at all. It is easy to see how this can look to a rocket engineer as a 'total wash' or even a negative, to the existing launch methodology.

C. Technical Approach

The technical approach is discussed in three sub-categories:

- Carrier aircraft design
- Rocket design
- Separation maneuver

Again in the interest of brevity, the conclusions of years of study are presented with only limited details here.

The carrier aircraft should be a subsonic heavy cargo plane, optimized for the air launch mission. Defense of subsonic operation has already been made. Added to this is the practicality of today's aircraft jet engines. The high-bypass turbofan jet engine is the culmination of billions of dollars of research and 50 years of design & manufacturing perfection worldwide. The turbofan is highly reliable, low maintenance, efficient, quiet and has an excellent power to weight ratio. Considering they are produced in large quantities, as well as having widely available and relatively inexpensive spare parts (compared to rocket turbo pumps for example), use of these power plants should be considered. Similarly, the materials and assembly of commercial jet aircraft are also well established and superior to rockets in cost per payload mass.

There must be a boundary limit for the aircraft size or the tendency will be to grow it uncontrollably and carry an ever-bigger rocket. That leads to "great performance numbers" but "too expensive to buy even a single launch". Also, there are practical issues with larger rockets such as payload manifesting, launch windows, schedule slips and increased costs at every level of building, testing, and operations. *The carrier aircraft is to be limited to existing runway restrictions.* This rule helps cap the vehicle mass and corresponding expenses, but it will also lead to assurance of alternate launch sites and provide incentive for future flight rate growth. The alternate runways lower the risk of schedule slip due to weather delays or site interruptions; the risk of cost growth, since the existence of multiple sites affords competition for the rocket launches; and improves payload/trajectory access (i.e., picking up the payload in the 'sponsoring' governmental territory and hitting ideal orbital trajectories). No doubt the initial flights would originate at a set location like the Kennedy Space Center's runway, but the ability to go other places for abort scenarios is of high safety value in itself

The more versatile the aircraft, the better it will be for a long-term investment. *The rocket must be carried along the vehicle's centerline and from underneath with as little restriction as possible.* This allows easy servicing and inspection, fast mating connections, balanced aircraft flight dynamics, positive separation upon release, and all-horizontal integration and structural support. It fosters other benefits such as future "spiral development" designs for the rocket system, which might include first stage fly-back wings, a lifting body configuration or a hypersonic ramjet booster. The biggest advantage is that it opens up the aircraft to perform a plethora of other non-air launch tasks. These would include carrying outsized commercial cargo items, such as bridge components for example; larger hypersonic research vehicles; forest firefighting water; multiple ISO-standard intercontinental freight containers or IATA-standard cargo containers; defense equipment or special ordinance; and disaster aid, either by air drop or conventional runway delivery.

Aircraft operations and costs should be of concern even for an expensive operation such as launching a rocket to orbit. It also is very important in performing the other tasks just mentioned. Therefore a final aircraft rule should address these values. *A new aircraft should be competitive with the next generation of cargo (and preferably passenger) aircraft performance in terms of fuel efficiency, noise reduction, flight safety, ease of maintenance, and security.* Keeping to existing runway, taxiway and terminal volume and weight limits will help ensure that this commercial nature is not lost in the rush to get the rocket launch mission accomplished.

The rocket has a number of familiar rules that emerge to keep it from becoming too specialized and thus cost ineffective. *The rocket shall be limited to existing manufacturing dimensions and processes that are cost effective.* This has been previously discussed and two to five meters in diameter and 25 to 75 meters in length is suggested as the practical range (i.e. Delta II-class to Delta IV size). *A two-stage all cryogenic hydrogen/oxygen vehicle is most effective for air launching to orbit.* Isp is still the key element in rocket performance and LOX/LH2 is simply the best solution. Considering that air launching eliminates the need for low-performance booster operations, this choice becomes a natural consequence of the engineering trades. *The initial approach to air launched rockets should include an expendable rocket system.* There will be a number of operational and design lessons to be learned and expendables lend themselves to the initial learning curve. Modifications can be made as the flight rate increases to improve or correct anomalies in this new form of rocket launch. Recoverable or reusable stages or major components can easily be phased in when desired and cost effective.

The design of the rocket structure and subsystems must be optimized for horizontal integration, mounting and air launching. The tanks and structures, particularly the mounting points, need to be designed for handling and specialized loads. This is no different than what is presently done for existing Russian rockets and is not a seriously difficult change for U.S. systems. In fact, the Boeing Delta IV plant in Decatur, Alabama, is essentially an all-horizontal operation today. *The first and second stages should be composed of common rocket engines.* This is a direct consequence of cost minimization. The rocket can be designed and optimized to split the ΔV between the stages. Engine throttling and multiple engine configurations can make this vital expenditure reduction measure possible.

The separation maneuver is the third technical category that must be considered. It is the intersection of the first two components, the rocket and the aircraft. *Separation should be done safely, yet not effectively null the primary advantages of air launching.* This was also previously covered, but the two most important impacts are restated. The separation has to ensure that gamma angle is not compromised and that the launching altitude still has a profound effect on the rocket's overall design/optimization. *The separation maneuver should permit a wide range of abort operations and maximize the full recovery of the rocket during incidental rocket malfunction.* Separation methods that expose the rocket to early free flight without a process to recover at least the payload for an immediate relaunch attempt are not going to be cost effective in the long run. They will either put extreme pressure toward rocket 'perfection' or be costly through lost payload, schedule slips, insurance premiums and lost customer confidence. *The separation should use little or no consumables or pyrotechnics.* The Space Shuttle uses small separation rockets and explosive bolts for each separation. They are reliable and lightweight but raise overall operation costs, add safety risk, and are complex. Electromechanical systems take more upfront design and test effort, but can be advantageous over the long-term. They support the likelihood of a fast turnaround and short relaunch preparation time. There are savings in procurement, shipping, installation and storage of these expendable and hazardous subsystems. It also is imperative for any alternate commercial tasks when not air launching a rocket.

D. Systems Engineering

The systems engineering benefits and rules coincide with program management and operations. The first general tenet deals with the aircraft's strongest feature, its mass margin compared to a rocket. *Offload as much mass as possible to the carrier plane.* This might include heavier mechanical connections or support arms rather than making the rocket itself a little stronger to carry the load. Fire suppression systems, cryogenic coolers, extra propellant, power supplies, and tracking and guidance systems might all reside only on the carrier aircraft. Recovering cryogenic boil-off instead of adding more rocket tank insulation is another direct mass-savings example. *The system should be evaluated in terms of multiple launches with fast adaptations, planned options, and early operational experience changes expected.* The systems engineering of the entire launch process must be expected to mature and the changes should be easily and inexpensively integrated into the plane and or rocket hardware. Similarly, a well-engineered program will expect a continual progression of rocket concepts and more flexible alternate aircraft duties. *The carrier payload capacity should accommodate a robust spiral rocket development* *program over the course of its full service life.* This ensures the aircraft will have a high utilization factor and be cost effective, whether it is a single unique system or a production line model sold to a variety of customers. The flexibility to accommodate wings on a future rocket will allow the non-launch payloads also to be size and shape independent, and thus more economically viable. The ultimate in systems engineering integration is the separation maneuver and the design philosophy or balance between the two vehicles. *The carrier aircraft must execute what it does best and the rocket must accomplish what it does best, while not affecting each other.* This requires the aircraft to handle all the takeoff and early abort functions. It should also make the final turning maneuver and not get in the way of the rocket's trajectory or reduce the rocket's speed or altitude. The rocket must operate as a highly efficient, low-cost upper stage. It should not require the plane to support its performance with excessive speed or altitude that would require costly modifications or reduce the plane's inherent mass-margin advantage. *The separation maneuver is a joint function.* With both vehicles optimized toward their strengths, the turn-up and separation operation must be done in a unified manner. The flight planning must account for the thrust loss of turbofan engines at high altitude and the lack of 'aerodynamics' of a traditional rocket stage. Minimization of rocket ΔV losses, safety of the aircraft, a surety of rocket engine start, positive separation, collision avoidance and maximization of abort options are all requirements that must be met.

V. Defining the Crossbow Trade Space

Crossbow was originally an acronym for Cargo ROcket Space System BOx Wing (CRoSSBoW). It was first cited in the literature in 2005[19], but the term was initially used early in 2003 within NASA. It has become the name for a specific trade space that has high promise for a safe, reliable, and cost effective space transportation approach. Crossbow encompasses the basic rules discussed in the previous section. It also includes some more specific details that appear to be of great value. It is where a preliminary design team might start to develop a baseline system configuration. By no means is Crossbow a set design, nor does it claim rigorous experimental testing or computational modeling as basis for its graphic image as in Figure 6. The final skin shape, particularly of the carrier aircraft, is expected to be dynamically different after computational analysis is made. Known design-driving factors include separation aerodynamics, controllability of the aircraft without a payload or pod, structural stability and landing gear loading (i.e., impact upon landing fully laden). Even the final Gross Liftoff Weight (GLOW), number of turbofan engines, and whether it is piloted from the aircraft, the rocket, or the ground are all variables open for investigation.

Figure 6: CRoSSBow

The operational sequence does include several ideas that appear to be key to attaining the cost and safety goals necessary for routine space travel. Crossbow is to be operated from existing runways and must balance its wheel bearing capacity with the vehicle GLOW. The plane's structure also must provide a wide underside clearance, incorporate wing fuel, and give adequate support to the heavy payload. The design approach is to use a box wing configuration[20] that inherently gives strength against bending moments. The box wing was originally conceived as a method to afford aerodynamically efficient, narrow-camber wings. That feature is still preserved in the Crossbow trade space. The wing design evokes the use of air dams along the wings or at the tips. The tail section and control surfaces are not specified, but broad clearance and the need for additional structural rigidity and lift surface are suggested in the high wing form. Actual aerodynamic control requirements, especially without a payload, may alter the present shape significantly.

The rocket in its first version is a two-stage rocket derived from Delta II or Delta IV tank dimensions. The Boeing Delta rocket is ideal since its manufacturing is not only extraordinarily economical, but also very adaptable to air launching. It is horizontally assembled and of a reasonable matching size to a large subsonic aircraft. The factory has ample capacity to produce numbers that make Crossbow, even as a single carrier test bed, a very competitive launch system. It is suggested that the rocket engines be an expander cycle derivative, such as the Pratt & Whitney RLX. Present wisdom puts three engines on the first stage and a single engine on the second. All rocket subsystems are conventional in nature with the exception of the mounting points. The rocket will operate in flight exactly like any other rocket, with no special alterations to materials, methodologies, or operations. In fact, the rocket is expected to achieve greater reliability and safety margins just by operating in a less demanding launch environment.

The unique feature Crossbow presently posseses is its joint turn-up maneuver before separation. Although the thought of starting a rocket while attached to an aircraft appears unsafe, it is exactly for safety reasons that the idea was proposed. All ground launched liquid systems are brought to nominal operating conditions before launch is committed. Engine reliability is directly connected to the first few moments at start up. If that transient period is well monitored and no initial degradation is observed, the risk of "engine out" during ascent is very low. That is the basis for the bimese configuration so popular at NASA for many years. Fear of air-starting a high pressure, staged-combustion engine, like the SSME, was considered out of the question. The expander engines can be deeply throttled so a low power start of one engine is possible, but only with the air launch scenario. Systems then can be checked and release of the rocket from the plane completed with minimum risk. Perhaps full engine start or multiple engine start will be feasible. Nevertheless, the minimum of one engine operation at release guarantees a safe and steady control of the rocket, power to dump fuel in an abort, and operational systems to start the remaining engines and begin orbital accent. Safety is increased when the abort options using carrier plane fly-back is available to the last reasonable moment. Dropping the rocket in a free fall before any system is functionally checked in operation is high risk. Crossbow also includes video and diagnostics monitoring of the rocket, umbilical power for start (avoiding yet another battery system to fail as well adding weight to the rocket), and fire suppression systems on the plane.

Powered separation aids in the difficult trades between forcing the plane to somehow make up for its low thrust at launch altitude (half that at sea level), the high penalty of delivering the rocket at low gamma, and the fatally expensive modification of the rocket to include wings. The extremely high thrust generated by the rocket engine is more than enough to make up for the altitude-hampered turbofans. The low position of the rocket engine with respect to the combine vehicle's centerline will tend to naturally pitch up the system to a high gamma. Little rocket fuel is wasted as the pitch up occurs with the engine startup diagnostics. The entire operation is slow and naturally smooth. Heating of the aircraft is minimal due to the transparent LOX/LH2 plume (i.e., little radiant heat transfer) and the cold boundary layer airstreams along the fuselage. Positive separation of the two vehicles is ensured. The rocket has very little lift and will accelerate rapidly forward. The carrier plane will be nominally powered, but have tremendous lift as its mass is suddenly diminished. The plane lifts upward while the rocket accelerates forward. The two never cross or incur risk in recrossing paths (more aircraft stability control analysis must be done to determine the plane's best path, but a banking turn tactic is suggested).

VI. Future Vision

The air launch methodology and the trade space defined here are aimed at creating a major difference to ETO operations and total cost. The future of space transportation would be very different if the Government were to embrace a large carrier aircraft for space launch. Maximum rocket performance can be achieved in a payload capacity that is ideal for human access to space. But it is the direct effect on Earth that may have the most importance. Changes to the military and then commercial air cargo might be worth the investment alone for a new heavy aircraft with some unique capabilities. Yet it is in the exciting long-term change the concept could effect on the airline industry and air travel that makes it most intriguing.

A. Space Transportation

Predicting the future of technology is problematic and never accurate in detail. Air launch appears to possess a bright future for space travel, even if not embraced by the aerospace industry as a whole. Very heavy vertical launch vehicles may continue to be used. Early on, large rockets may be needed to establish NASA's lunar infrastructure or the eventual Mars manned missions. Once commercial space operations are established, larger orbital components may need to be launched as well. Undoubtedly, all these will be cargo missions, much as we use trains and supertankers to move massive amounts of materials and goods today. "Commuter traffic" to space needs a level higher in safety and flexibility. That is where air launching will be firmly in place in the future. Since the carrier aircraft can be automated or controlled by the rocket crew, the safety to the aircraft is not as critical during that very slim chance of a catastrophic mishap that could destroy the plane. How many cargo missions might be done using air launched vehicles is uncertain, but the flexibility and reliability may make it a significant amount. How well space components can be packaged for launch and the use of in-situ materials will impact the future cargo throughput value.

NASA might take the lead and encourage the fledgling commercial air launch ventures to go further. A modest carrier size might be developed to verify the concept, or an existing aircraft sufficiently modified to carry a rocket. The eventual trend will be to bigger rockets, carrying more payloads of greater mass, for less cost. It will also be driven toward more runways, with greater flexibility for launch times, locations, payload types and customers.

Schedule slips will be a thing of the past and rapid cargo changes/manifesting will be easily accommodated to attract more customers. Aborts and vehicle subsystems failures will be reduced to mere irritants from the lost time to fly back and land. Insurance premiums are expected to be lower as the aborts return the precious cargo back intact and only fuel is lost.

Military interest may also spur Crossbow type launches because it provides immediate space access. The system is inherently flexible, providing rapid target or trajectory changes. It is relative invulnerable to attack, having launch site mobility. Weather avoidance, variable payloads and missions and potential low cost alone are attractive for defense applications. Changes or spiral development of the rocket system can continue for both military and civil space. Reusable components or stages can be tried while not losing any existing operational capability. A Crossbow-based future has exciting opportunities for space and the business of ETO transportation.

B. Changing Aviation

Presently the vision for future aviation, both commercial and military, is uncertain and full of paradox. The long-term vision from NASA has been the drive to smaller, more numerous and more flexible aircraft; almost replacing the car for city-to-city transit.[21] However, fuel will continue to be expensive and small aircraft are not fuel efficient per passenger-mile even accounting for some gains in direct transport from and to the traveler's desired locations. A large pod-hauler system could be a compromise in gaining aerodynamic efficiency as well as greater traveler accommodation. Transportation from the center of a city is proposed to be done in small neighborhood facilities similar to a train or bus station. A pod could be moved city-to-city by high-speed, electro-magnetically levitated rail or to a remote airfield between metropolitan areas. The airfield facility is lower cost since the large land area it requires is not on prime city real estate. Noise pollution and secure access is easier to manage there. The pod becomes a sealed unit that is mixed with other pods and waits at the end of a runway. The carrier aircraft can land and exchange one or more pods without taxiing to the terminal. Time on the ground is limited by the refueling rate, perhaps unnecessary for a large aircraft with adequate fuel capacity. A single turn is made to the runway and the plane immediately makes its takeoff run. One airport can service whole regions depending on the speed of the pods and total passenger numbers expected each day. The airlines keep the economic advantage of a hub system and let much of the more expensive "spoke" legs be done by high-speed electric rail. The rail system is advantageous to local cities as it can replace inefficient car, bus, and train traffic over the medium city-to-city distances. To the passenger it is all one-system whether flying or not. There is convenience and simplicity since once taking a seat (with all bags in hand) a passenger is set for the entirety of the transit. It also ensures security and lower cost as the pod/people can be scanned as they board one time. They are moved around in a computer-directed (thus random) order based on traffic flows, etc. and there is no possible access to pilots or controls. The harm that can be done is actually limited to a few people in a single pod and the pod can be diverted away from doing more harm if terrorists are onboard. Air safety can include the pods being independently ejected with parachute and air bag recovery in case of an accident or unintentional release. The result would be a step up in safety not possible in today's aircraft designs and one that leads to a drop in air travel fatalities.

This grand vision is a far-term reality, nevertheless a very attractive one. It is a vision that can be achieved in small steps, perhaps by first developing the pods for military transport or commercial cargo; or by investing in small pod-rail systems for urban areas; or by building the first plane for space applications, but maintaining economic viability for other tasks. This is followed by slowly phasing in pod-hauler planes in conventional airports and qualifying them for passenger travel. The rest will come as a result of the piece-parts being available.

VII. Conclusion

Air launched rocket concepts have historically been single point designs usually done by a distinct group or advocate. There has been little independent academic research or classroom knowledge from which to evaluate the approach in terms of quantifying benefits over existing vertical rocket launch at sea level. This paper establishes a logical basis for air launch of rockets and provides a framework of hypotheses for future investigations. There were five key factors found inherent in air-launched rockets: velocity, acceleration, altitude, mass fraction, and the atmosphere. Each was shown to have a direct impact on total cost and risk. This study has concluded that a high capacity carrier plane is essential to minimizing payload cost to orbit when air launching. The cap on the plane size is the existing runway system limitation. This fixes the rocket size at one large enough to carry a human payload to a circular orbit. The rocket performance requires a two-stage vehicle, both being optimized upper stages. The use of LOX/LH2 propellants, low-pressure expander cycle type engines and common engines on both stages are considered obligatory technical approaches. While the plane and rocket size and shape are still unoptimized parameters, the Crossbow-style separation was considered necessary to overcome the mission risk with early separation, the thrust augmentation of the plane (at no cost), and the performance losses.

Air launch appears to have ample effect on total costs of space access, with far reaching risk reduction and payload safety. Rules were developed for maximum advantage in an air launch system for both the rocket and the carrier aircraft. There are guidelines for the separation process, which has influence on both vehicles. Finally, a specific methodology for air launch is suggested through the Crossbow trade space. Crossbow is not a point design or an exclusive pod-hauler airframe. The distinctive feature is the operation of the aircraft and rocket together for a brief, but important, turning maneuver before actual separation. This avoids shortening the abort options and adding power and other subsystems to the rocket side, while it augments the turbofan's low thrust at high altitude which otherwise prevents the aircraft from performing the critical pull up maneuver. The combination is expected to produce the best overall cost and safety performance, which includes all risks from hardware development to ensuring future new customers are available to maximize system capacity.

Appendix

Derivation of the Mass Multiplier Equation

The impetus for this derivation is the desire to get a "feel" for the gross weight of a launch system without going to all the effort of building a "weights and sizing" spreadsheet and having a number of mass-estimating relationships. Like every approximation, rigorous accuracy is often sacrificed for simplicity, but the hope is that this derivation will enable a designer to get some quick 'kinesthetic' feels for a launch system.

To begin, the mass of a launch system can be broken down into three simple components, payload mass, propellant mass, and structural mass with the structure mass fraction defined by its dependence on the value of the propellant, system GLOW, or dry mass.

$$m_{gross} = m_{payload} + m_{prop} + m_{PS} + m_{DMS} + m_{GMS} \tag{3}$$

The structural mass of the rocket includes such things as tanks, engines, thrust structure, avionics, etc. Furthermore, if the rocket is meant to be reusable, the vehicle will probably include such things as wings, landing gear, thermal protection systems, and a host of other subsystems designed so that the system is recoverable and serviceable for reuse again. Therefore, another goal of the derivation is to have a "switch" that can be thrown on or off, based on whether or not the system is reusable. If reusable, the assumption is that the 'payload' is the dry mass & lands with the vehicle each time. For a SSTO, the astronauts and their life support are built-in and little 'cargo' mass is 'trucked' into orbit. Conversely, pulling the payload out of the dry mass is more closely associated with a cargo vehicle carrying a satellite for example. In an earlier derivation[22], the assumption was made that all the structural mass would scale with the propellant load. That is not such a bad assumption for the tanks and feedlines and so forth, but it wasn't a very good assumption for wings and landing gear and such things. Typically, in a weights-and-sizing spreadsheet the following relations naturally hold:

- Landing gear mass—landed mass
- Wing mass—landed mass
- TPS mass—atmospheric entry mass
- Control surface mass—atmospheric entry mass
- OMS/RCS mass—orbital insertion mass
- Tank mass—propellant mass
- Engine mass—gross takeoff mass*takeoff thrust/weight

If we make the assumption that orbital insertion mass equals atmospheric entry mass, which equals landed mass, which is equivalent to dry mass, as in Eq (4), things simplify quite a bit. Now, this isn't too bad of an assumption since the only mass that really changes is the OMS/RCS propellant expended, propellant residuals, and so forth. However, for a large SSTO-type vehicle where the propellant residuals are on the order of the payload mass, this isn't as easily justified.

$$\mathrm{m}_{\mathrm{insertion}} = \mathrm{m}_{\mathrm{entry}} = \mathrm{m}_{\mathrm{landed}} = \mathrm{m}_{\mathrm{dry}} \tag{4}$$

Next, we define three non-dimensional parameters, in Eq (5) to (7), to relate each of the three classes of masses (i.e., mass that is proportional to propellant or dry mass or gross mass) to masses that we know, or will know.

$$\lambda = \frac{m_{propellant-sensitive}}{m_{propellant}} \tag{5}$$

$$\varepsilon = \frac{m_{dry-mass-sensitive}}{m_{dry}} \tag{6}$$

$$\phi = \frac{m_{gross-mass-sensitive}}{m_{gross}} \tag{7}$$

Therefore, we are assuming that propellant-sensitive mass (such as tanks, feedlines, and tank insulation) scales linearly with the mass of the propellant. We also assume that the dry-mass-sensitive masses (wings, gear, TPS) scale with the dry mass. We also assume that the gross-mass-sensitive masses (engines, thrust structure) scale with the gross mass of the vehicle. Equations (5), (6) and (7) can be rewritten in the form:

$$\lambda m_{prop} = m_{PS} \qquad \varepsilon m_{dry} = m_{DMS} \qquad \phi m_{gross} = m_{GMS} \tag{8}$$

Out of these terms we can rewrite the expression in Eq (3). Note that dry mass is calculated by subtracting the propellant mass from the gross mass. Sometimes, the payload is also subtracted from the gross mass. This happens when the "switch" term is used. It allows us to include the payload in the dry mass or not. This "switch" term is 1 if the dry mass does NOT include the payload, and 0 if the dry mass DOES include the 'payload'. This will give us a convenient way to see the effect that landing with the payload has on the rest of the vehicle.

$$m_{gross} = m_{payload} + m_{prop} + \lambda m_{prop} + \varepsilon\left(m_{gross} - m_{prop} - f m_{payload}\right) + \phi m_{gross} \tag{9}$$

By grouping terms, we end up with three types of masses: payload, propellant, and gross mass.

$$m_{gross}\left(1 - \varepsilon - \phi\right) = m_{payload}\left(1 - f\varepsilon\right) + m_{prop}\left(1 + \lambda - \varepsilon\right) \tag{10}$$

Now the rocket equation, Eq (11), comes into play. It will give us a relation between the gross mass of the vehicle and the propellant mass for a particular ΔV and engine Isp. The ΔV comes from an ascent trajectory generated from a computational program (e.g., POST). It should be the "ideal ΔV", which will include ΔV losses from gravity, drag, aero, engine-pressure, and steering. The Isp should be the ideal vacuum Isp of the engine, because pressure losses typically will be included as a 'hit' on the ideal ΔV value within the code.

$$MF = e^{\left(\frac{\Delta V}{g^* Isp}\right)} = \frac{m_{initial}}{m_{final}} = \frac{m_{gross}}{m_{gross} - m_{prop}} \qquad \frac{m_{prop}}{m_{gross}} = \frac{MF - 1}{MF} \tag{11}$$

With this relation between the gross mass and the propellant mass (Eq (11) derived from the rocket equation), Eq (10) can be rewritten with the only mass terms being for payload and gross mass.

$$m_{gross}\left(1 - \varepsilon - \phi\right) = m_{payload}\left(1 - f\varepsilon\right) + m_{gross}\left(\frac{MF - 1}{MF}\right)\left(1 + \lambda - \varepsilon\right) \tag{12}$$

A little algebraic manipulation of Eq (12) is required to generate the final form of Eq (14)…

$$m_{gross}\left((1-\varepsilon-\phi)-\left(\frac{MF-1}{MF}\right)(1+\lambda-\varepsilon)\right)=m_{payload}(1-f\varepsilon)$$

$$m_{gross}\left(\frac{(MF-\varepsilon MF-\phi MF)-(MF-1)(1+\lambda-\varepsilon)}{MF}\right)=m_{payload}(1-f\varepsilon)$$

$$m_{gross}\left(\frac{MF-\varepsilon MF-\phi MF-MF-\lambda MF+\varepsilon MF+1+\lambda-\varepsilon}{MF}\right)=m_{payload}(1-f\varepsilon)$$

$$m_{gross}\left(\frac{1-\lambda MF+\lambda-\varepsilon-\phi MF}{MF}\right)=m_{payload}(1-f\varepsilon) \tag{13}$$

…and out pops the final expression:

$$m_{gross}=m_{payload}\left(\frac{MF(1-f\varepsilon)}{1-\lambda(MF-1)-\varepsilon-\phi MF}\right) \tag{14}$$

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