Air Launch: Examining Performance Potential of Various Configurations and Growth Options

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The Advanced Concepts Office at NASA's George C. Marshall Space Flight Center conducted a high-level analysis of various air launch vehicle configurations, objectively determining maximum launch vehicle payload while considering carrier aircraft capabilities and given dimensional constraints. With the renewed interest in aerial launch of low-earth orbit payloads, referenced by programs such as Stratolaunch and Spaceship2, there exists a need to qualify the boundaries of the trade space, identify performance envelopes, and understand advantages and limiting factors of designing for maximum payload capability. Using the NASA/DARPA Horizontal Launch Study (HLS) Point Design 2 (PD-2) as a point-of-departure configuration, two independent design actions were undertaken. Both designs utilized a Boeing 747-400F as the carrier aircraft, LOX/RP-1 first stage and LOX/LH2 second stage. Each design was sized to meet dimensional and mass constraints while optimizing propellant loads and stage delta V (ΔV) splits. All concepts, when fully loaded, exceeded the allowable Gross Takeoff Weight (GTOW) of the aircraft platform. This excess mass was evaluated as propellant/fuel offload available for a potential in-flight propellant loading scenario. Results indicate many advantages such as payload delivery of approximately 47,000 lbm and significant mission flexibility including variable launch site inclination and launch window. However, in-flight cryogenic fluid transfer and carrier aircraft platform integration are substantial technical hurdles to the realization of such a system configuration.

I. Introduction

Many variations of horizontal air launch concepts have been evaluated in the past and are more recently showing resurgence in commercial applications. This is understandable with the multiple benefits that are offered by horizontal launch. In many ways the vehicle concept of operations can be simplified for faster launch turn-around times along with easier vehicle integration and increased payload delivery flexibility. The 1st stage carrier aircraft provides a very mobile launch platform that can avoid weather, offer an increased number of possible launch orbits, and provide for covert launching capability.

Within this framework the Advanced Concepts Office (ACO) Earth To Orbit (ETO) Team was asked to analyze two separate actions to further the knowledge base on horizontal launch vehicles. Action 1 focused on broadening the Point Design #2 (PD-2) concept which was a recommended design option from the NASA/DARPA Horizontal Launch Study (HLS). That resultant vehicle was a two-stage rocket mated atop a Boeing 747-400 class carrier

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aircraft. The ETO team action was to determine what advantage in-air propellant loading of the rocket would provide in terms of payload delivery. With the ETO team no longer constrained to size a fully loaded vehicle within the Gross Take Off Weight (GTOW) capacity of the carrier aircraft, the tradespace opened up.

Action 2 was assigned following the presented results of Action 1. Utilizing the same interest of in-air propellant loading, the ETO team was requested to find the maximum air-launch vehicle size, limited by the dimensional constraints of the carrier aircraft along with the maximum in flight payload capability and the GTOW capacity. The ETO team needed to determine which of these constraints would be the true limiting factor. As a result, the Action 2 vehicles were called BUD concepts, and adjectival acronym for Big, Ugly, Dry. The initial assumption was to take full advantage of in-air propellant loading and take off with essentially a dry rocket.

II. Action 1: Effect of In-Flight Propellant Loading on Payload Capability of Existing Design

The analysis of Action 1 began with creating a trajectory model of the PD-2 concept which was the 'go-forward' result of the HLS report. By creating a trajectory model from the PD-2 data that the team was given, several ground rules fell out which could be applied in order to compare the new vehicle concepts against. Once Action 1 Ground Rules and Assumptions (GR&A) were established three concept vehicles were evaluated.

A. Ground Rules and Assumptions

From the set of data initially provided for the PD-2 concept, Table 1 summarizes the important ground rules and assumptions that need to be accounted for in the study.

Table 1. Action 1 Ground Rules and Assumptions.

Constraints
• 16.4 ft max stage diameter
• 127 ft max vehicle length
• Max gross takeoff payload = 305,000 lbm
• Max in-flight payload = 1,437,000 lbm • 2.5 * takeoff weight – aircraft weight • Derived from 2.5 g pull-up maneuver requirement 747-400
Aero-surface / Trajectory
• Simulation starts at rocket 1st stage ignition, altitude = 25,243 ft, Mach = 0.7
• Lift and drag coefficients are considered constant for vehicle resizing
• Constant 6.7° angle of attack held from max Q to aero-surface jettison
• Shroud drop at dynamic pressure of 0.1 psf
• Optimized flight path angle at aero-surface jettison to maximize performance
• Due East release from KSC flown to 100 nmi circular orbit
• Aero-surface mass ground-ruled at 12,000 lbm

The approach for all concepts would be to grow the stages to the maximum, allowable length and diameter taking advantage of in-air propellant loading. Also the optimal propellant and ΔV split between the stages would need to be established in order to determine the optimized vehicle configuration with the maximum payload delivery capability.

B. Preliminary Design # 2

PD-2 provided the initial starting point from which the in-air propellant-loading concepts were derived. It is a two-stage vehicle with three Merlin-1C engines in the 1st stage and three RL10A-4-2 engines in the second stage. Dimensionally, the vehicle is 102 ft long with a 12.5 ft diameter. The design constraint for PD-2 is that, fully loaded, it needed to meet or fall under the gross take-off payload capacity of the 747 carrier aircraft at 305,000 lbm. Hence the interest arose in determining if a larger vehicle, which could get around the GTOW limitation, would deliver more payload.

As mentioned, a trajectory reconstruction of the PD-2 was the first step to starting the new design action. This reconstruction was built from a customer-provided mission profile timeline which identified many of the ground rules. A few important differences in the trajectory reconstruction as it was modeled were due to not having detailed aerodynamics of the aero-surface. This resulted in some very broad assumptions being applied to the winged configuration. One of these was to start the trajectory simulation at engine ignition rather than aircraft separation. By matching the mission profile event variables as closely as possible, the ETO team was able to produce a payload which was higher than what PD-2 reported. Trajectory reconstruction resulted in 14,700 lbm of payload as compared to the 12,575 lbm from the HLS report. This discrepancy caused the team to research what additional ground rules the provided mission profile might not have included that had been used in the Horizontal Launch Study.

Once a more detailed set of HLS-specific ground rules was identified, a few key differences revealed themselves. Table 2 details these additional ground rule differences. It is important to note that these dissimilarities were not applied to the vehicles analyzed in Action 1 due to the time at which they were discovered by the team. As a result, the ETO team went forward with Action 1 based on the values in the right hand column of Table 2. Several key differences in the groundruls include the greatly different thrust classifications for the Merlin 1C engines and how to quantify the reserves and residuals. Also, the term 'resultant maximum' is meant to indicate that the values were a fall out of the analysis, while the PD-2 vehicle was designed to a specific constraint.

Table 2. GR&A Differences.

	PD-2	ETO
Weights and Sizing		
Wing Unit Weight	Function of wing surface area and aspect ratio	Wing surface area held constant so weight was constant
Propellant reserves, residuals, and start-up losses	1.8% of ideal propellant mass	Residuals: INTROS MER, function of nominal ΔV propellant FPR: 1.0% Start-up: None (all useable)
Propellant Ullage	2.0% of required propellant volume	2.0%
Wing Platform Area	940 ft^2	940 ft^2 fixed
Propulsion		
Performance	Merlin 1C: specific impulse Merlin 1C: vacuum thrust RL 10 A-4-2: specific impulse RL 10 A-4-2: vacuum thrust	Merlin 1C: -6 sec isp Merlin 1C: -10,400 lbf thrust RL 10 A-4-2: +1 sec isp RL 10 A-4-2: +11 lbf thrust
Trajectory		
Simulation Constraints	Maximum q: Less than 1,000 psf Maximum q-Alpha: Less than 5,000 psf-degrees	Resultant Maximum q: 569 psf Resultant Maximum q-Alpha: 10,909 psf-degrees
Acceleration Constraints	Maximum wing normal factor: Less than 1.5 g Maximum acceleration: Less than 5.0 g	Maximum wing normal factor: 2.7 g Maximum acceleration: 3.7 g
Orbit	Targeted direct injection into 100 nmi circular due east orbit from a latitude of 28.5 degrees	Targeted direct injection into 100 nmi circular orbit with inclination of 29.0 degrees

C. Iteration 1

This was the first cut design that the ETO team evaluated to take advantage of in-air propellant loading. The first trade was to keep the same engine configuration that PD-2 used and simply increase vehicle dimensions to the maximum allowable size. With the new vehicle size it was necessary to redefine the optimal propellant split between stages. This was bounded by maintaining the same diameter for both the first and second stages of the rocket. Without aerodynamics for the aero-surface, the coefficients were assumed to be constant. This assumption was also applied because the ETO team did not have a wing resizing tool to determine how wing geometry would change for the larger size vehicle. The corollary to this constant coefficient assumption was that, going forward, a wing would need to be designed that had similar aerodynamic coefficients to those of the PD-2 configuration.

It became apparent during optimization that the size increase would need to be balanced by thrust increase and the given engine configuration was optimizing toward a smaller diameter solution. The resulting payload for this design was a paltry 5,543 lbm (2.5 t); less than half what PD-2 was capable of delivering. Due to the low resultant payload, partials on this concept were run to determine where improvements could be made; which fed the starting point for Iteration 2. This led to abandoning Iteration 1 for more promising vehicle concepts.

D. Iteration 2

Moving forward from the Iteration 1 vehicle, the team decided to increase thrust for both stages to overcome the low thrust to weight values at each stage ignition. Therefore, the second vehicle concept had a total of four engines in each stage while maintaining the maximum dimensions for the entire vehicle. This concept also incorporated the notion of propellant offload or, in the case of in-air propellant loading, not completely filling the propellant tanks and seeing which stage may want less than its propellant capacity to deliver the most payload to orbit.

It turned out that the 2nd stage optimized to a condition where almost 30% less propellant was needed than could notionally fit in the sized tanks. Flying with this optimized upper-stage propellant, the Iteration 2 vehicle was able to deliver 15,332 lbm (7.0 t) to orbit. As a result of the greater payload delivery than Iteration 1, options for in-air propellant loading were considered. The various options are shown in Figure 1 which features a vehicle schematic, without attached aero-surface, as well as the various in-air propellant-loading options. These account for the carrier take-off weight maximum and the potential propellant allocation for in-air loading. The first is to take-off with less than a full tank of fuel in the carrier aircraft and refuel only the aircraft at loiter altitude. It was later approximated that the amount of aircraft fuel available for offload was 88% (~338k-lbm) assuming 12% (~46k-lbm) was needed for takeoff and loiter evolutions. This assumption was not included in the Action 1 analysis and the quantity of Jet-A offload for Action 1, Iteration 3 is marginally over budget. Option 2 is a split between the aircraft fuel (Jet-A) and the 1st stage rocket fuel (RP-1). Option 3 covers liquid oxygen (LOX) only replenishment and is the only cryogenic fluid option considered.

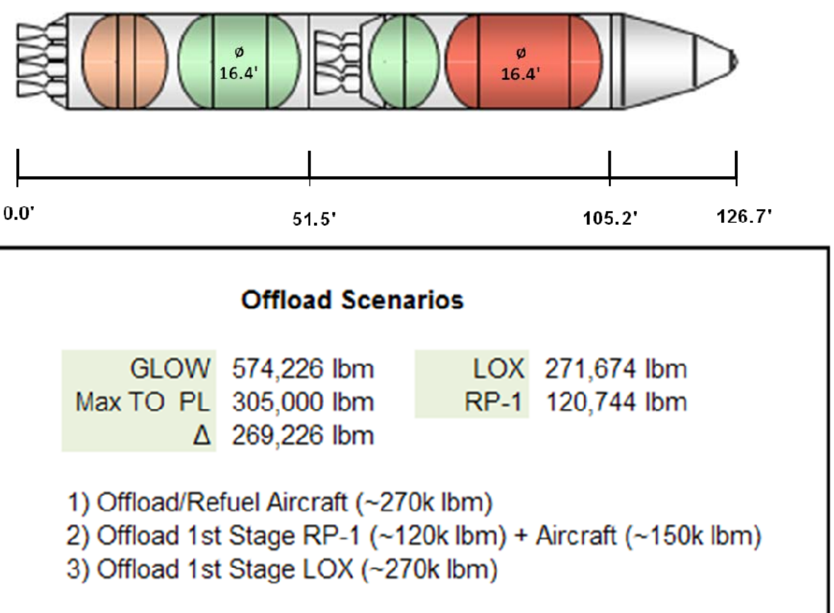


Figure 1. Iteration 2 in-air replenishment options.

E. Iteration 3

Building off the positive results of Iteration 2, and the optimized 2nd stage propellant load, Iteration 3 embarked on the first diameter change in the tradespace. Since maintaining industry standard diameters was a desirable manufacturing trend the 2nd stage was reduced to 12.5 feet. A structural analysis based on flight loads was performed to size the inter stage adaptor to handle the diameter neck down. The decreased diameter of the 2nd stage more efficiently accommodated the 30% reduction in propellant load identified from Iteration 2, and meant that the 1st stage was able to increase in length and thus carry more propellant for ascent which was a payload benefit. Additionally, with a lower weight 2nd stage it was possible to reduce the number of engines from four down to the three employed by PD-2.

There are some drawbacks to the smaller diameter 2nd stage. Most of these focus on interface issues between both the carrier aircraft and the aero-surface. With a constant diameter, the carrier vehicle attach mounts could be located at various stations along the vehicle. When the 2nd stage is a smaller diameter than the first, attach points can now only be located along the 1st stage. This is a similar problem for the aero-surface, it now must only attach to the 1st stage. The drawback is that it may place sizing constraints on the aero-surface such that its leading edge cannot hang over the transition section to the second stage of the rocket. While these concerns are noted, analysis of these issues was outside the scope of this study, again due to the level of aerodynamic analysis detail that would need to be performed on the fully mated configuration.

With all of these design changes Iteration 3 was able to provide 19,940 lbm (9.0 t) of payload to orbit. The configuration, without the aero-surface, is shown in Figure 2 along with the propellant loading scenarios for in-air propellant loading. Once again, multiple options exist for replenishment scenarios: To take-off with the rocket carrying a full propellant load and only refuel the aircraft at altitude, to top off the tank for the carrier aircraft and fill the 1st stage RP-1 only, or fill all the 1st stage LOX and 6k-lbm of additional wet mass, either Jet-A or RP-1.

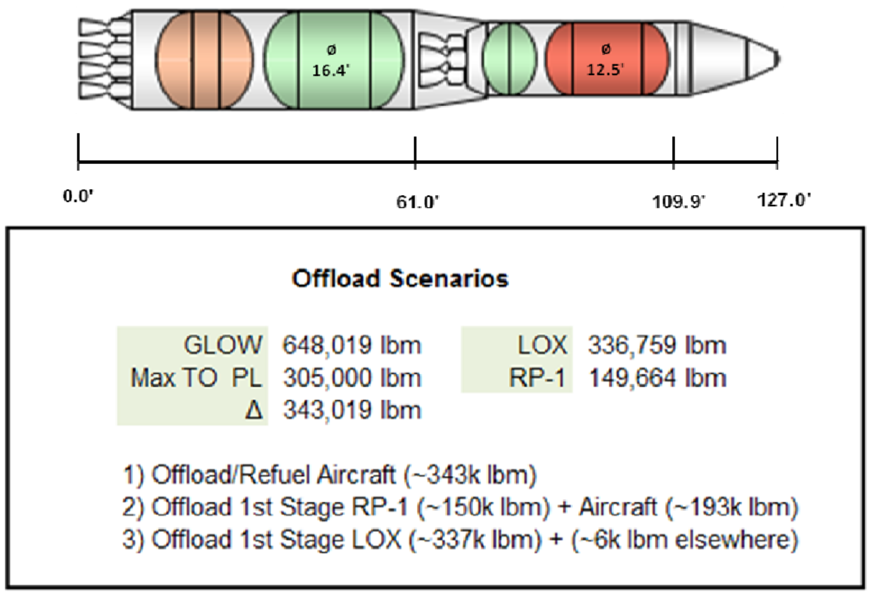
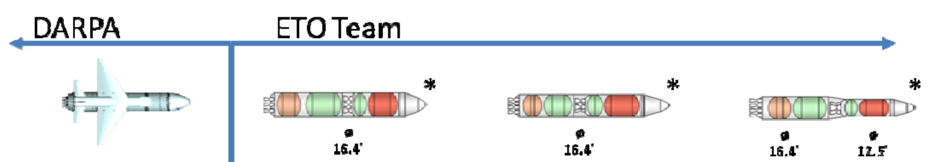


Figure 2. Iteration 3 in-air replenishment options.

F. Action 1 Observations

Figure 3 presents a side by side comparison of all three concepts that the ETO team evaluated as compared to the PD-2 result from the HLS report. Key items to note in the graphic are the length limitation which all three ETO concepts meet, and is the limiting factor of the designs from achieving higher payloads. Along with this, the 'Offload for GTOW' row is the difference of each concepts' 'Total Gross Weight' minus the carrier aircraft take-off constraint which, by design, is the 'Total Gross Weight' of the PD-2 concept.



Metric	PD-2	ACO Iteration 1	ACO Iteration 2	ACO Iteration 3
Payload to LEO	12,575 lbm	5,543 lbm	15,332 lbm	19,940 lbm
Total Gross Weight	305,000 lbs	400,452 lbs	574,226 lbs	648,019 lbs
Total Length	102 ft	127 ft	127 ft	127 ft
Maximum Diameter	12.5 ft	16.4 ft	16.4 ft	16.4 ft / 12.5 ft
# Engine First/Second	3 Merlin / 3 RL-10	3 Merlin / 3 RL-10	4 Merlin / 4 RL-10	4 Merlin / 3 RL-10
Offload for GTOW	N/A	95,452 lbm	269,223 lbm	343,019 lbm

* aero-surface not shown

Figure 3. Action 1 Results.

The ETO team made several observations while analyzing the Action 1 vehicles. Increasing the size of the vehicle to accommodate more propellant without a subsequent increase in the number of engines has no benefit. The thrust-to-weight for each stage of the larger vehicle drops too low, which leads to an increase in gravity losses through the trajectory. Designs featuring four engines in each stage that maintained constant diameters optimized with 2nd stage propellant offload. This was the leading indicator that the 1st stage wanted more propellant and the 2nd stage needed to be smaller. In fact, the Iteration 3 vehicle wants even more propellant and could deliver more payload if the ground-ruled maximum dimensions could be exceeded.

There were also various alternatives on how best to perform in-air propellant loading. Since no specific approach was ground-ruled, it was up to the ETO team to establish a high level of 'what ifs'. As a result, three alternatives were considered; the first, an all aircraft approach in which the rocket was fully loaded on the ground and the carrier aircraft took off with less than a full tank of fuel. Once reaching a cruising altitude the carrier aircraft would be topped off and continue on to the rocket release point. The second was an option where all cryogenic fluids were loaded on the ground and the 1st stage RP was loaded in the air. This did not cover all scenarios, however, because removing only the RP mass was not enough to get under the take-off weight constraint. Since this was a non-cryogenic in-air fueling option the only other non-cryogenic fluid was the carrier aircraft fuel. The final LOX only option was greatly debated in terms of feasibility and technology readiness level. It was considered necessary because it was such a large fluid mass and would prove the greatest benefit of only requiring a single fluid be loaded in the air. So while the option and advantage is clear, there is high risk due to immature existing capability. It's important to point out that only 1st stage in-air propellant-loading options were considered, as well as the avoidance of filling the hydrogen tank. The hydrogen issue was similar to LOX in terms of the cryogenic temperatures, yet more extreme due to the lower temperatures of the liquid hydrogen (LH2). Also, due to density, the hydrogen mass in all concepts was one of the lightest masses to deal with. So an in-air propellant-loading scenario in this case would require filling both the hydrogen as well as some other propellant. The reason for focusing on 1st stage replenishment only is similar to the hydrogen issue. If all the propellant in the 2nd stage needed to be filled, both LH2 and LOX, the gross mass of the rocket would still exceed the take-off mass capability of the carrier aircraft. So either the aircraft would need fuel offload or that mass would come out of the 1st stage propellants. This would then require three different fluids to be filled at altitude.

A final note is that the Iteration 2 vehicle performance is very similar to that for the ETO trajectory reconstruction performance for PD-2. This means that, accounting for differences in ground rules, the delta mass between the Iteration 2 payload and the payload of the ETO reconstruction run is the same payload delta that can be applied to the reported PD-2 vehicle if the ETO design changes were implemented. Unless more design work is done to properly size the aero-surface and attach interfaces for the Iteration 3 vehicle with the smaller diameter 2nd stage, within the given ground rules, the best approach may be to proceed with the PD-2 design. The operational concept for this option does not require an in-air replenishment evolution and no redesign work would be necessary.

III. Action 2: Determination of Maximum Constrained Air-Launch Vehicle Size

Upon completing the previously reported Action 1 concept analyses, an additional effort commenced to study significant growth of a similar air-launch configuration. As the following GR&A indicate, the dimensional boundaries of growth were increased as a result of some first-order calculations for allowable, exterior payload on a 747-400 class airframe. Not only were larger dimensional boundaries specified, but alternate, higher-powered engine options were also examined. As with Action 1, the objective of the Action 2 analysis was to determine the maximum launch vehicle payload, while considering aircraft capabilities and given dimensional constraints. Any excess GTOW was assumed to be launch vehicle propellant and/or aircraft fuel offload, to be supplied from an in-flight propellant loading evolution.

A. Ground Rules and Assumptions

Table 3: Action 2 GR&A.

Launch Vehicle	
Configuration	Two-stage, liquid propellant
First stage propellant	LOX/RP-1
First stage engines	Merlin 1-C or RD-180
Second stage propellant	LOX/LH2
Second stage engines	RL-10A-4-2 or J-2X-285
Diameter (max)	Unconstrained, constant along vehicle length
Length (max, integrated)	180 ft.
Payload shroud density	< 9.0 lbm/ft^3
Carrier Aircraft	
Platform	747-400 class
Max gross takeoff payload	305,000 lbm
Max in-flight payload	1,437,000 lbm
Required Jet-A for take-off / loiter	46,122 lbm (12% of load)
Trajectory	
Launch site	KSC
Release	Due East
Orbit	100 nmi circular
Launch altitude	25,243 ft
Launch Mach #	0.7
Shroud drop criteria	Q = 0.1 psf
AoA	8° constant from max Q to aero surface jettison
Aero Surface	
• Linearly-scaled reference area/mass from DARPA/NASA HLS PD-2 aero surface (940 ft^2)	
• Optimized flight path angle at aero surface jettison to maximize performance based on PD-2	

B. BUD 1

The goal of this analysis (Action 2, Growth Option 1 – 'BUD 1') was to size the concept for optimal payload performance, propellant load, and propellant split between 1st and 2nd stages while remaining within the assumed, given geometrical and payload constraints of the carrier aircraft. Building upon the results of Action 1, this exercise sought to explore the extreme boundaries of air launch potential with a ground-ruled increase in allowable launch vehicle dimensions. Additional design objectives were also considered. These were, if possible:

- specify fully loaded propellant tanks due to uncertainty in partial load levels, especially if factoring-in boil off during climb and loiter
- specify constant diameter tanks to mitigate additional attach mechanism complexity
- utilize an industry standard diameter to take advantage of manufacturing capital.

Engine selection was based upon establishing a 'linear' growth potential comparison from PD-2 and Action 1 concepts. Additionally, it was always the intention to specify RP-fueled engines due to the favorable density, which translates into more compact tankage, and to take advantage of the established practice of aerial loading of kerosene-type fuel. This is a substantial benefit due to existing tanker and logistic resources. The vehicle optimization strategy was to add engines and enlarge geometric dimensions until loaded launch vehicle mass equaled maximum carrier aircraft in-flight payload capability. Furthermore, enough 1st stage propellant and carrier aircraft fuel had to be available for offload in order to lower total mass to accommodate the aircraft GTOW constraint.

Figure 4 illustrates results of the aforementioned design optimization routine. Assuming offload and in-flight propellant loading is possible, the payload to 100 nmi circular orbit is 46,640 lbm (21.2 t). The 1st stage utilizes 10 Merlin 1-C engines while the second stage is fitted with 10 RL-10A-4-2 engines. This number of (these particular) engines yield the maximum performance capability within the given mass limitations and adding engines has a negative impact. Due to several factors, such as the length constraint and the amount of propellant required to fulfill 1st stage ΔV requirement, the goal of specifying an industry standard tank diameter was unachievable. At the given

20 ft (6.01 m) the 2nd stage oxidizer tank is dome-to-dome and requires a small offload in order to maintain the proper mixture ratio.

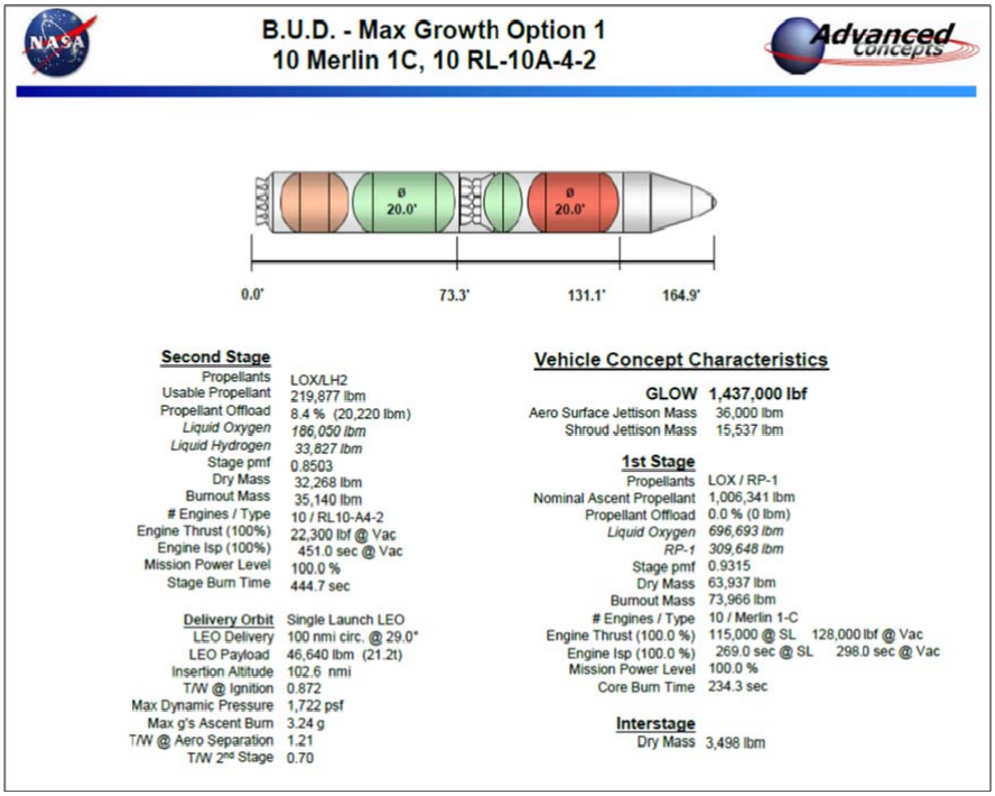


Figure 4. BUD 1 Results.

Table 4. BUD 1 Replenishment Options

Launch Vehicle GLOM	**1,437,000 lbm**	LOX (1st Stage)	**696,693 lbm**
Max 747 Takeoff Payload	**305,000 lbm**	RP-1 (1st Stage)	**309,648 lbm**
Required Offload	**1,132,000 lbm**	Jet A-1 (747-400F)	**338,228 lbm**
		Available Offload	**1,344,569 lbm**

The ultimate driving factor for this configuration was the ground-ruled 1.47 M-lbm in-flight payload capability of the 747-400F. Table 4 gives the replenishment options. With a launch vehicle GLOM of 1.437 M-lbm and a maximum carrier aircraft takeoff payload capability of 305 k-lbm, the required mass/propellant load reduction is the delta of 1.132 M-lbm. It is assumed that both 1st stage tanks are available for complete offload, as well as the carrier aircraft fuel not needed for takeoff and loiter; therefore, the required offload is achievable. The optimization analysis suggests that higher performance can be achieved by specifying a larger core in concert with a smaller 2nd stage. With a dome-to-dome oxidizer tank at the current diameter, one way to achieve more performance would be to neck down the 2nd stage which would violate this study's ground rules. The other side effect of such a strategy would be to necessitate hammerhead of the payload shroud or a significant increase in shroud cylinder length, in order to maintain a more reasonable payload density.

One noteworthy, and potentially hazardous, situation was discovered while examining a plot of altitude vs. time. As Figure 5 illustrates, BUD 1 descends approximately 10,000 ft after release prior to establishing a positive climb rate. Such a drastic loss of altitude in the given time frame would require the 747 crew to perform aggressive maneuvers to mitigate re-contact. This altitude loss is due to low lift coefficients, a direct result of the applied method of aerodynamic scaling, and could potentially be mitigated by future aerodynamic analysis. Varying release conditions (i.e., altitude, release angle of attack, flight path angle) may also reduce this effect.

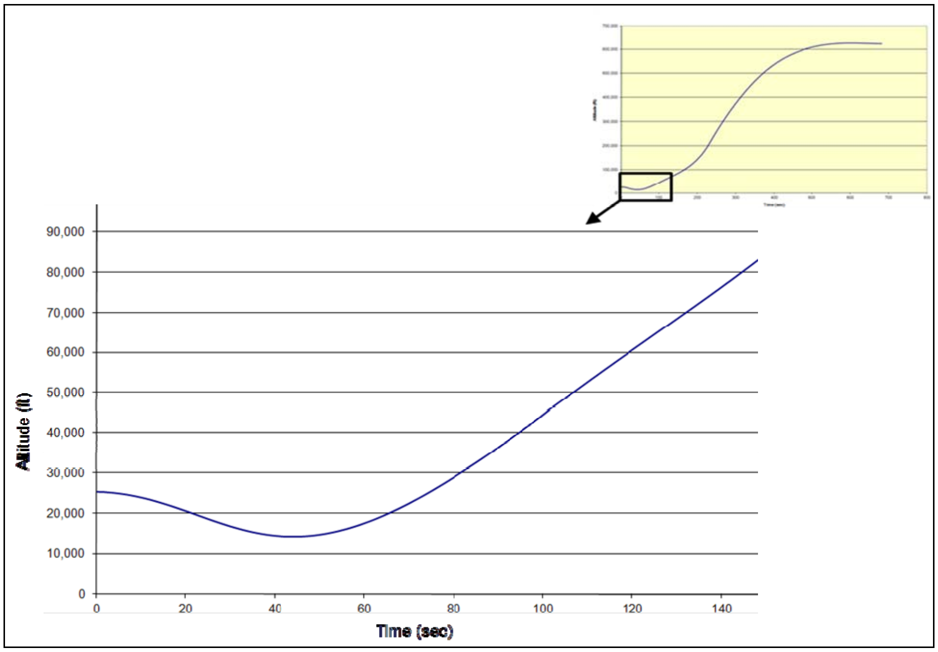


Figure 5. BUD 1 Altitude Profile.

C. BUD 2

While the number of technical challenges to hurdle with such an architecture is high, one of the complexity issues identified was the number of propulsion elements needed to maximize performance. As indicated in the previous section, the launch vehicle requires ten Merlin 1-C engines on the 1st stage and ten RL-10 engines on the second stage, when designing for maximum performance and to fully take advantage of the in-air propellant-loading scenario posed. Therefore, the design team substituted these twenty elements with one RD-180 on the core and one J-2X-285 on the second stage. The swap did trade some performance for relative-simplicity, as Table 5 indicates.

Table 5. Alternate Engine Options.

First Stage	(1) RD-180 vs. (10) Merlin 1-C	~346,000 lbf less vacuum thrust
		~36 sec more vacuum specific impulse
Second Stage	(1) J-2X-285 vs. (10) RL-10A-4-2	~62,000 lbf more vacuum thrust
		~16 sec less vacuum specific impulse

Other than the engine swaps, the ground rules and design objectives from BUD 1 remain; specifically, the goal was to size for optimal propellant load/split while remaining within geometrical constraints, specifying fully loaded propellant tanks (at operational-design capacity) and utilizing an industry standard diameter if possible. As figure 6 indicates, the resultant payload of 64,515 lbm (15.7 t) is several tons less than BUD 1; however, there were many positive notes gleaned in doing the comparison. First and foremost is the complexity reduction measure of specifying two propulsion elements rather than twenty. While the performance impact is not negligible, perhaps a reduction in system complexity, capital inventory, failure probability, and integration schedule is a worthy trade. Additionally, optimization using this particular engine arrangement allowed for the achievement of two other objectives: specify industry standard tank diameter and specify fully loaded propellant tanks when at design capacity. The diameter optimized well at 5.4 m (18.0 ft) and the 2nd stage LOX tank, while dome-to-dome, did not require any offload in order to maintain mixture ratio. As with previous concepts, performance trends pointed towards a vehicle with a larger core and a smaller 2nd stage. In order to fit within the GR&A this is the optimal solution; however, it is suggested that necking down the 2nd stage and requiring more ΔV from the 1st stage would produce higher payload capacity but may fall out of given carrier aircraft capabilities.

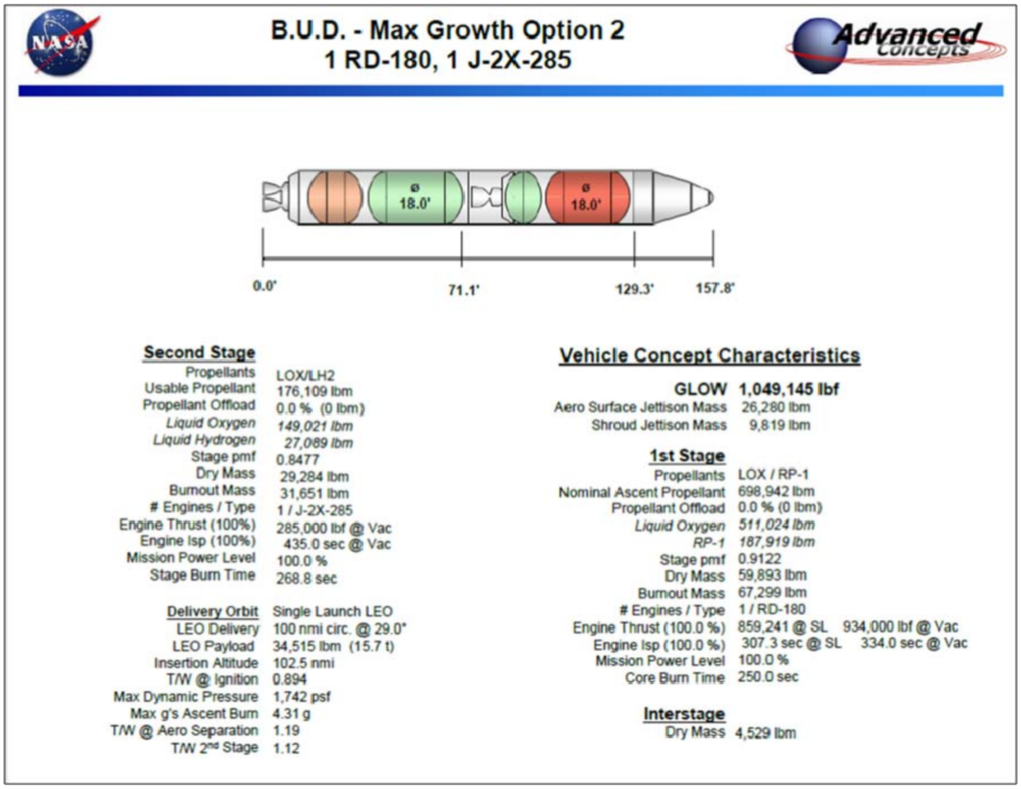


Figure 6. BUD 2 Results.

The required replenishment options are presented in Table 6 which indicates more than sufficient, available propellant and jet fuel mass. For this iteration, carrier aircraft in-flight payload capability (launch vehicle GLOM in other words) was not the limiting condition, as allowable mass was strictly dictated by engine performance and system capability. Changing the configuration in any way other than increasing core propellant load and decreasing 2nd stage propellant load, would be detrimental to performance.

Table 6. BUD 2 Replenishment Options

Launch Vehicle GLOM	1,049,145 lbm	LOX (1st Stage)	511,024 lbm
Max 747 Takeoff Payload	305,000 lbm	RP-1 (1st Stage)	187,919 lbm
Required Offload	744,145 lbm	Jet A-1 (747-400F)	338,228 lbm
		Available Offload	1,037,171 lbm

D. Action 2 Comparison

In order to fully utilize the given, allowable in-flight payload mass of the carrier aircraft, the launch vehicle capability from Action 1 had to increase. The only way to do this was to relax the dimensional constraints and explore the extreme boundaries of this architecture's potential. Figure 7 illustrates the payload capability of BUD 1&2 vehicles referenced against the landscape of similarly capable vehicles. While this is an attractive space to occupy, existing, legacy systems bound and intersect BUD vehicle's performance envelope.

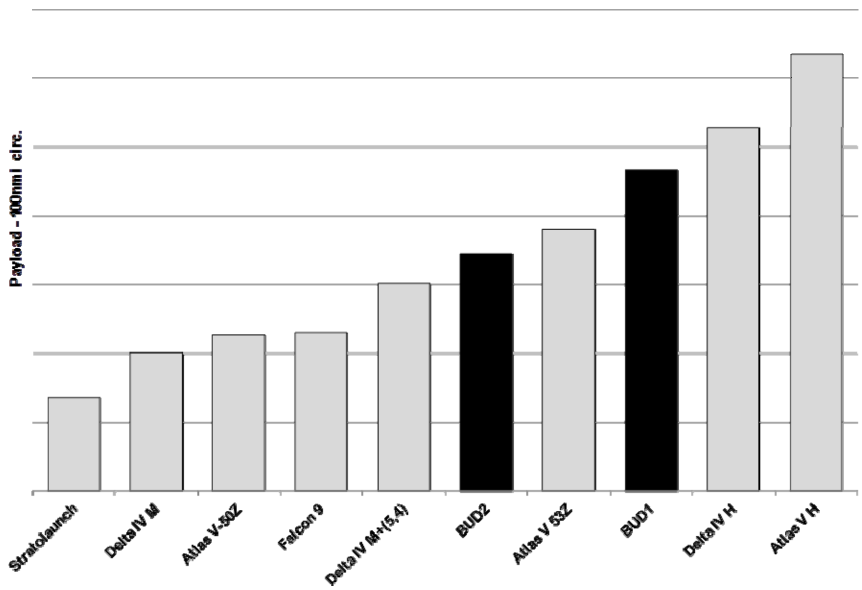


Figure 7. Payload Comparison.

Not only do existing systems capture the relative payload order-of-magnitude, but do not pose near as severe a technological challenge as a concept such as BUD vehicles. There are significant feasibility concerns and technical challenges associated with such a massive air launch vehicle as well as the fundamental concept of aerial loading of rocket propellants. In order to suffice these requirements, in-flight transfer of LOX would be required for the 1st stage of both BUD 1 and BUD 2. This may be the most insurmountable technical challenge. Not only would cryogenic oxidizer transfer be required, but also a very large amount of RP-1; specifically, the entire fuel tank for each concept studied (180k-300k lbm) would need filling, which is a logistical challenge. Furthermore, the impact of 'piggybacking' such a massive vehicle will have some impact on aerial loading operations; potentially rendering it an unusable evolution. Other technical challenges are discussed in section IV; still, the performance potential is high compared to existing and future ground and air launch concepts.

IV. Conclusion

The fundamental requirement of this study was to evaluate what the potential outer bounds of an air launch configuration, baselined on the NASA/DARPA HLS vehicle, would necessitate. Within the given ground rules, specifically aircraft carrying capability and dimensional constraints, the objective was achieved. There are many benefits with an air-launch configuration, most notably offering a mobile launch pad with potential for faster mission turnaround, higher number of achievable orbits with a broad range of launch opportunities, weather avoidance, and covert launch. An interesting thought was to utilize a 'dual-use' kerosene product, which would suffice launch vehicle and carrier aircraft requirements. Having a common fuel would enable simultaneous filling of the aircraft and rocket propellant tanks, or at least mitigate stand-alone RP-1 or Jet A/A-1 replenishment equipment.

Coincidental with the advantages come many technical challenges and items to consider. For the sake of readability these are presented as a list with applicable discussion.

Aerodynamics/controllability: A vehicle with the size and mass of the BUD 1 & 2 concepts is sure to have a significant impact on the controllability and capability of the 747 carrier aircraft. While these have not been quantified and would require individual study, some high-order speculation can derive the major issues: whether or not the aircraft would fly, fly stable, and be controllable. The Action 2 (BUD) vehicles are roughly 160 ft long and up to 20 ft in diameter. If mounting with as little cockpit overhang as possible, scale illustrations indicate that there still exists potential for significant airflow disturbance forward of the plane's vertical stabilizer. Without allowance for a base fairing (e.g., Space Shuttle in-transit), high base drag and turbulent flow aft of the vehicle should be expected. There exists potential for the center-of-gravity (CG) to drastically shift during replenishment operations, which adds to the controllability concerns. Also, there are the unknowns associated with: horizontal slosh mitigation at this scale and the potential need for compartmentalized tanks with multiple domes and feed lines.

Aircraft capability/allowable dimensions assumptions: The maximum in-flight payload was derived from the 2.5 g normal load limit to which the 747 airframe was designed. While this can be used to determine a structural limit load it likely overestimates what the aircraft can carry in sustained, level flight considering load margins, angle-of-attack requirements, combined system drag, and thrust available at the specific flight conditions. In actual 747 operations, this limit load can only be reached in a transient state, such as a pull-up maneuver or when encountering a wind gust. A more accurate carrying capability should be studied and applied, to consider the extra 747 payload mass (launch vehicle) and corresponding level-flight alpha, launch vehicle drag effects, and aero-surface lift generation. Modeling the combined configuration and simulating the static, level-flight conditions, accounting for engine thrust and angle of attack requirements would produce a more realistic carrying capability and more discriminately bound launch vehicle dimensions.

Mounting hardware: Such a large, mated system would require an equally robust mounting method. Mass for this system is likely to be on the scale of tons and was not included in the system mass for this study. Challenges also surface when considering vehicles of multiple diameters, not only for integration onto the carrier platform, but mounting of the aero-surface to the launch vehicle becomes more complex.

Cost: No detailed cost analysis was completed for this study; however, one can assume that there are many high-cost drivers outlined in the given architectures. In addition to the cost of the launch vehicle (especially the high dollar engines specified on BUD 2) there would be a need to upgrade/retrofit/redesign a 747-400F carrier aircraft.

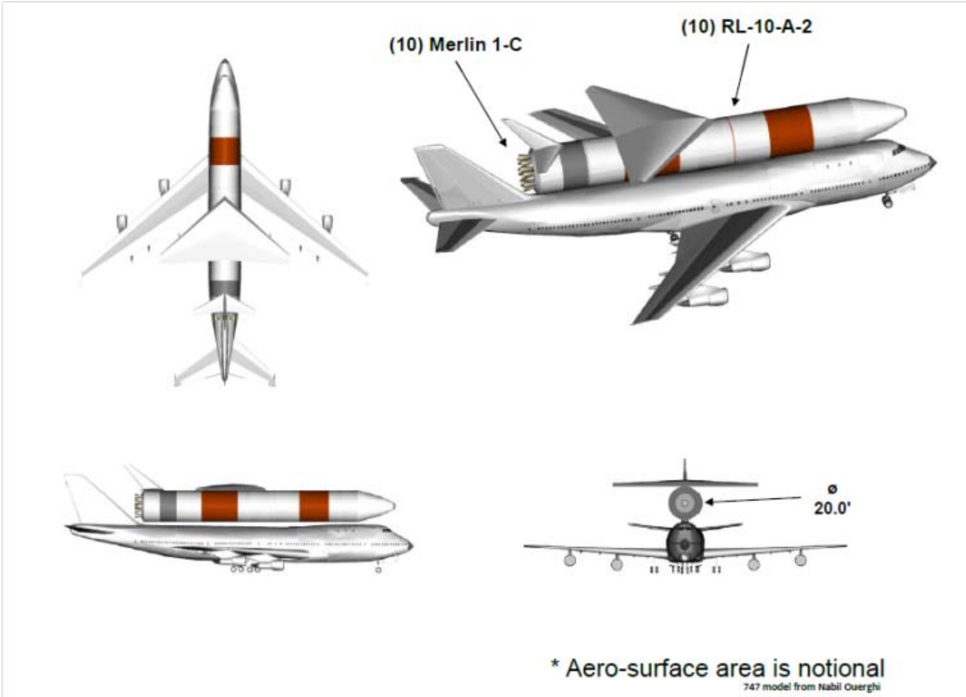
In-flight propellant transfer: The need to design and implement changes to the supply aircraft and replenishment technology at large, would surface. For the Action 2 study, three types of transfer would be required: Jet A, RP-1, and LOX, necessitating a significant hardware and logistical support effort. Designing to a dual-use kerosene product, which would provide both the launcher and aircraft fuel requirement, would ease the burden. But by far the greatest challenge to resolve is still the need to transfer cryogenic oxidizer. Here lies a massive technological development opportunity. Adding to the cryogenic equation are the effects of boil off. Since the LOX is loaded on the ground, it will vent during the takeoff, climb out, replenishment, and loiter evolutions. This was unaccounted in the GR&A.

Various ground rules & assumptions: Upon completion of the study several ground rules were identified as needing update or re-evaluation. The conditions at separation need to be evaluated for feasibility and the altitude, attitude, and Mach number should be optimized for each concept vehicle. These ground rules were gathered from the HLS study and unchanged for comparison purposes; however, trends indicate a tight coupling between LEO capability and initial trajectory conditions. Not only would optimization likely increase performance metrics, but would also become a variable when mitigating issues such as the immediate loss of altitude experienced when simulating the BUD 1 concept.

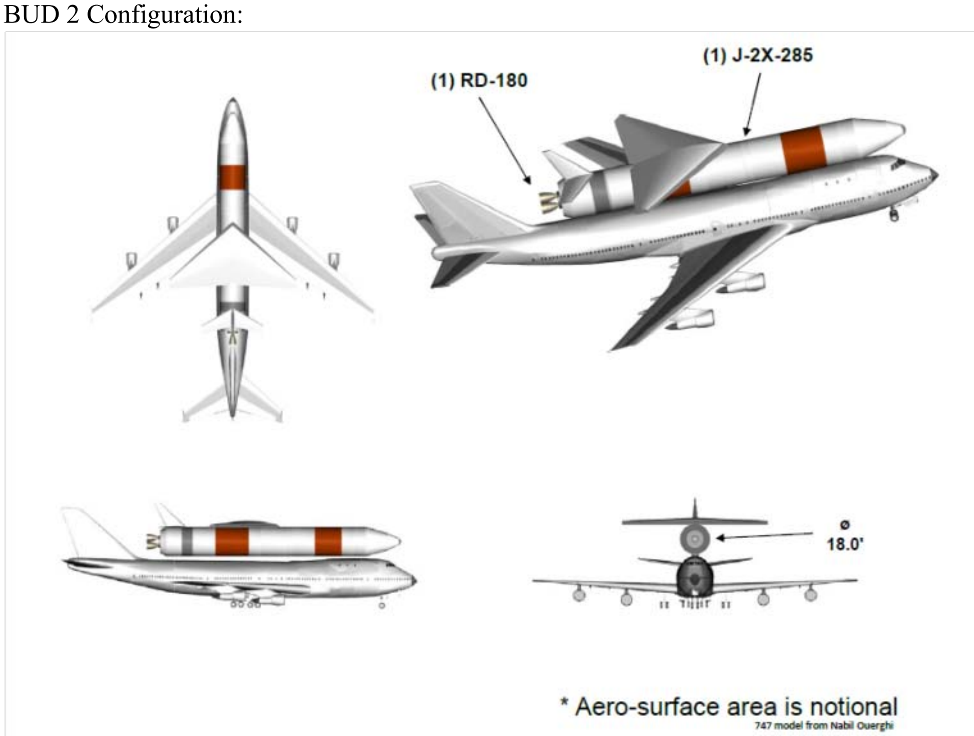
Lift and drag coefficients were considered constant for vehicle resizing; therefore, planform area and mass were linearly scaled from data utilized for HLS. While not an outrageous method to use when formulating first-cut, high-order evaluations, the fundamental need exists to perform a proper aerodynamic analysis and establish more realistic surface area, wing mass, and lift/drag coefficients. Not only would this analysis benefit the realism of the launch vehicle trajectory, but would also complete the data on carrier aircraft capability by establishing a launch vehicle lift vector to sum with that of the carrier aircraft.

Appendix

BUD 1 Configuration:



BUD 2 Configuration:



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