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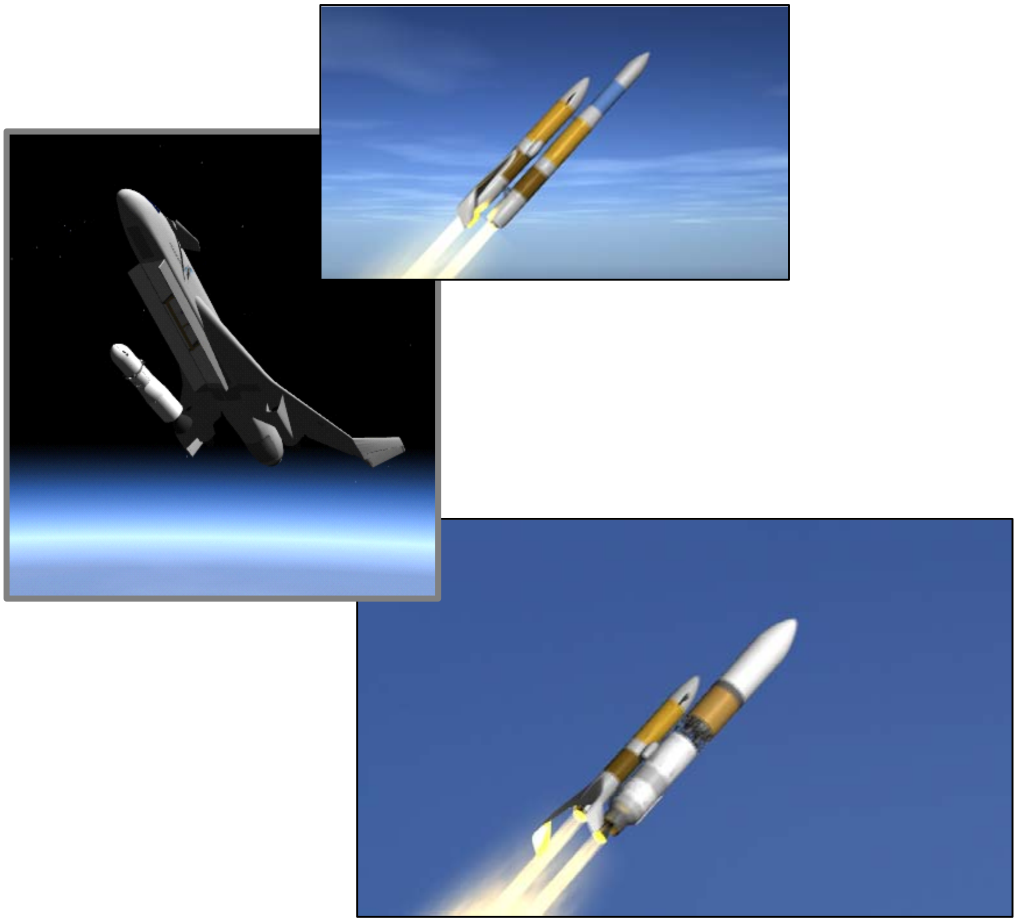

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Abstract

Over the past several years the Department of Defense (DoD) has focused its launch system development activities on designing next generation systems capable of responsive space launch and prompt global strike. These efforts have resulted in the DARPA Force Application and Launch from CONUS (FALCON) program as well the USAF Hybrid Launch Vehicle broad area announcement.

Andrews was a participant in the DARPA FALCON program and has performed numerous internal studies to assess a broad range of launch architectures that are capable of addressing the top level USAF Operationally Responsive Spacelift objectives. In this paper we compare a range of vertical and horizontal hybrid (part reusable / part expendable) launch architectures, assess their respective advantages and drawbacks with respect to the USAF ORS objectives, and make several observations. We examine three classes of vehicles as representative members of the launch families: a small launch vehicle for immediate DoD global strike and small satellite launch needs, a mid-size vehicle with moderate (10-15klb to LEO) payload capacity to compete with existing expendables, and an advanced system capable of heavy lift for NASA exploration missions.

Acronyms

ACES	Air Collection and Enrichment System
AFRL	Air Force Research Laboratory
APU	Auxiliary Power Unit
C/A	Control/Avionics
CONUS	Continental United States
COTS	Commercial Off The Shelf
EMA	ElectroMechanical Actuator
FOD	Foreign Object Damage
GTOW	Gross Takeoff Weight
HHLC	Hybrid Horizontal Launch Concept
Landing I_{sp}	Specific Impulse
JP	Jet Propellant (Jet Fuel)
LEO	Low Earth Orbit
LOX	Liquid Oxygen
LRU	Line Replaceable Unit
MCC	Main Combustion Chamber
MOTS	Military Off The Shelf
MTBO	Mean Time Between Overhaul
PAV	Peregrine Air Vehicle
PLS	Peregrine Launch System
RCS	Reaction Control System
RP-1	Rocket Propellant (Rocket Kerosene)
T_{VAC}	Vacuum Thrust
TVC	Thrust Vector Control
T_{SL}	Sea Level Thrust
USA	Upper Stage Assembly

Introduction

Over the past several years the Department of Defense (DoD) has focused its launch system development activities on designing next generation systems capable of responsive space launch and prompt global strike. These efforts have resulted in the DARPA Force Application and Launch from CONUS (FALCON) program as well the USAF Hybrid Launch Vehicle broad area announcement. The recent USAF Hybrid Launch Vehicle activity (also known as ARES) is a result of the Operationally Responsive Spacelift (ORS) Area of Analysis (AOA), which had the goal of defining both the requirements and preferred space launch architecture for the future Warfighter. The ORS AOA identified critical architecture traits, which are summarized in **Table 1**, and recommended that future efforts focus on hybrid (part reusable / part expendable) launch architectures because they balanced development and operational cost and risk versus fully reusable or expendable approaches.

Table 1. Operationally Responsive Spacelift Attributes.

ORS Attribute	Metric
Turnaround Time	24 – 48 hours
Surge Capability	Several missions per day
Recurring Cost	At least 1/3 of current prices

This paper summarizes conceptual launch system architecture trades performed by Andrews Space (Andrews) to identify and evaluate a range of hybrid launch architectures. The goal of the trades was to identify and quantify launch architecture sensitivities with respect to the ORS Figures of Merit. Specific trade attributes presented in this paper include:

- Operating Mode: Horizontal takeoff and landing (HTHL) versus vertical takeoff horizontal landing (VTHL) – note that vertical takeoff and vertical landing (VTVL) is not presented or evaluated in this paper
- Staging Approach: parallel versus series burn operations between the first and upper stages
- Propellant Selection: All options used liquid oxygen as the oxidizer. Fuel options included RP, liquid hydrogen and methane.

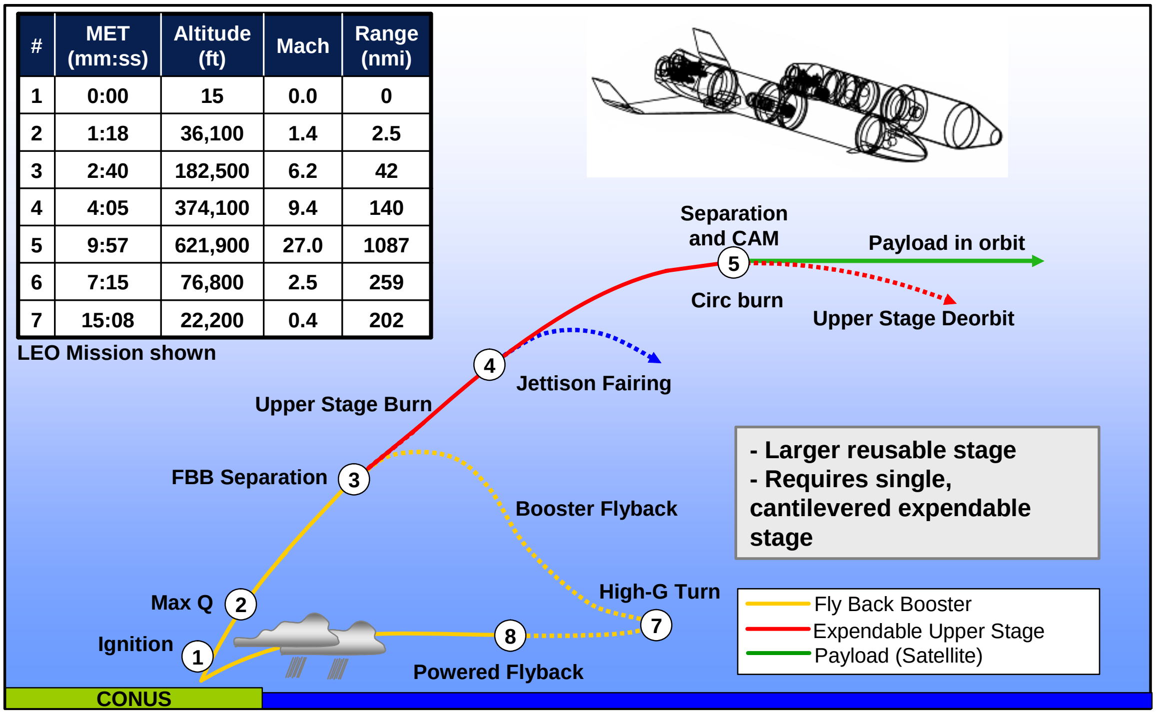
Vertical Launch Options

Multi-stage vertical takeoff hybrid launch vehicles have two ascent operating profiles: parallel burn and series burn. In the parallel burn configuration, the reusable first stage is ignited along with one of the expendable stages. The reusable stage, once it has performed its mission, shuts down its engine and separates from the stack. In series burn configurations, the expendable stage(s) are carried by the first stage to the staging point, where the reusable stage shuts down and the expendable stage is ignited and the two separate.

The optimal approach is driven by specific recovery techniques and ideal staging points, which are in turn, are influenced by stage propellant choice and specific impulse. A range of reusable first stage recovery options have been proposed, including downrange recovery (e.g. Falcon I), boost back (e.g. Kistler first stage), and flyback recovery. Given the ORS surge requirement of several missions per day, downrange recovery and boost back options were ruled out given their requirement for extended turnaround time. As a result, flyback (horizontal landing) first stages were considered exclusively in this paper.

For point design VTHL solutions, the size and complexity of the booster increases with increasing staging Mach number as does the size and weight of the flyback jet engines and the flyback fuel required. This is offset by a corresponding reduction in the size and weight of the 2nd stage. The optimum staging point is determined by factors like the rocket engines available (both thrust and performance), booster planform loading (how high you are willing to push landing speed), and whether the vehicle uses serial or parallel burn.

Figure 1 and **Figure 2** depict reference serial and parallel burn profiles. Extensive performance analyses for each approach indicated that parallel burn reusable first stages, paired with expendable (or mostly expendable) upper stages, tended to stage around Mach 3 for RP based fuels, and only slightly

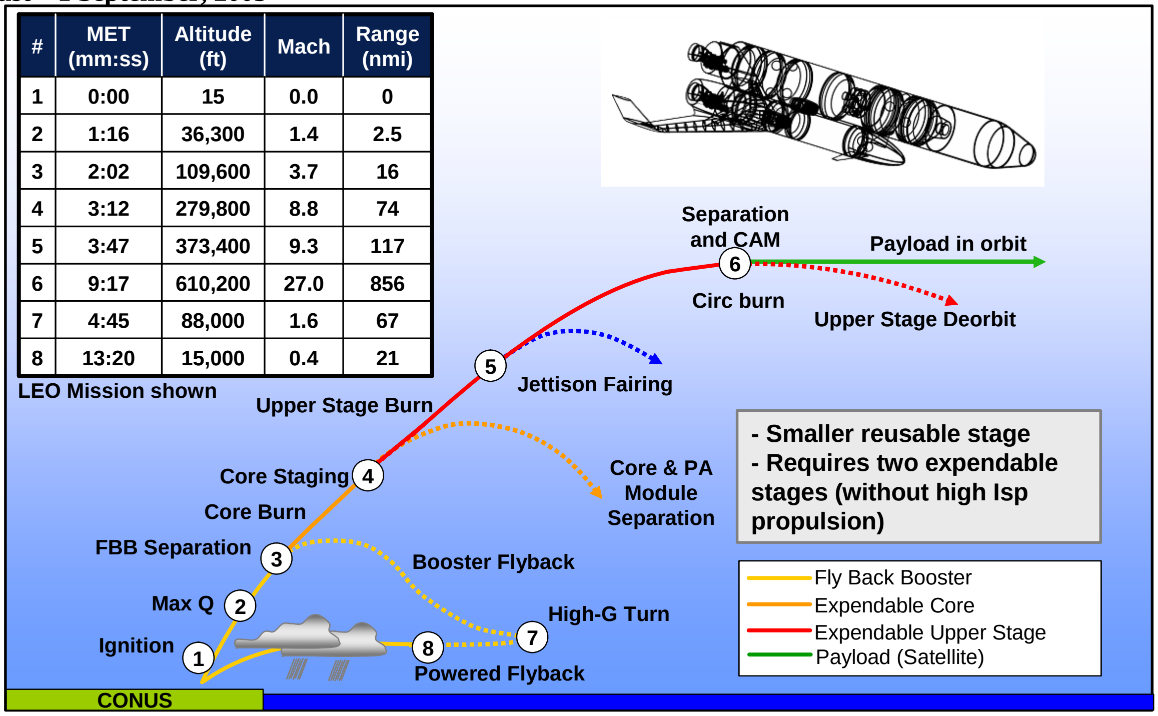


#	MET (mm:ss)	Altitude (ft)	Mach	Range (nmi)
1	0:00	15	0.0	0
2	1:18	36,100	1.4	2.5
3	2:40	182,500	6.2	42
4	4:05	374,100	9.4	140
5	9:57	621,900	27.0	1087
6	7:15	76,800	2.5	259
7	15:08	22,200	0.4	202

LEO Mission shown

- Larger reusable stage
- Requires single, cantilevered expendable stage

Figure 1. Series burn architectures recover the reusable first stage over 200 miles downrange. The example shown uses all RP based fuels.



#	MET (mm:ss)	Altitude (ft)	Mach	Range (nmi)
1	0:00	15	0.0	0
2	1:16	36,300	1.4	2.5
3	2:02	109,600	3.7	16
4	3:12	279,800	8.8	74
5	3:47	373,400	9.3	117
6	9:17	610,200	27.0	856
7	4:45	88,000	1.6	67
8	13:20	15,000	0.4	21

- Smaller reusable stage
- Requires two expendable stages (without high Isp propulsion)

Figure 2. Parallel burn mission profiles stage the reusable element(s) at lower, slower, more benign conditions versus series burn approaches. The example shown uses all RP based fuels.

higher for methane or hydrogen fuels. These relatively low staging mach numbers and subsequently short downrange recovery distances required very little flyback propulsion or propellant. Series burn configurations, by contrast, paired with expendable upper stages, tend to stage between Mach 6 (for RP fuel) and Mach 9+ (for methane or hydrogen fuels). These velocities require more aggressive thermal designs and efficient aero planforms to fly back the 200 to 400+ miles to the launch site.

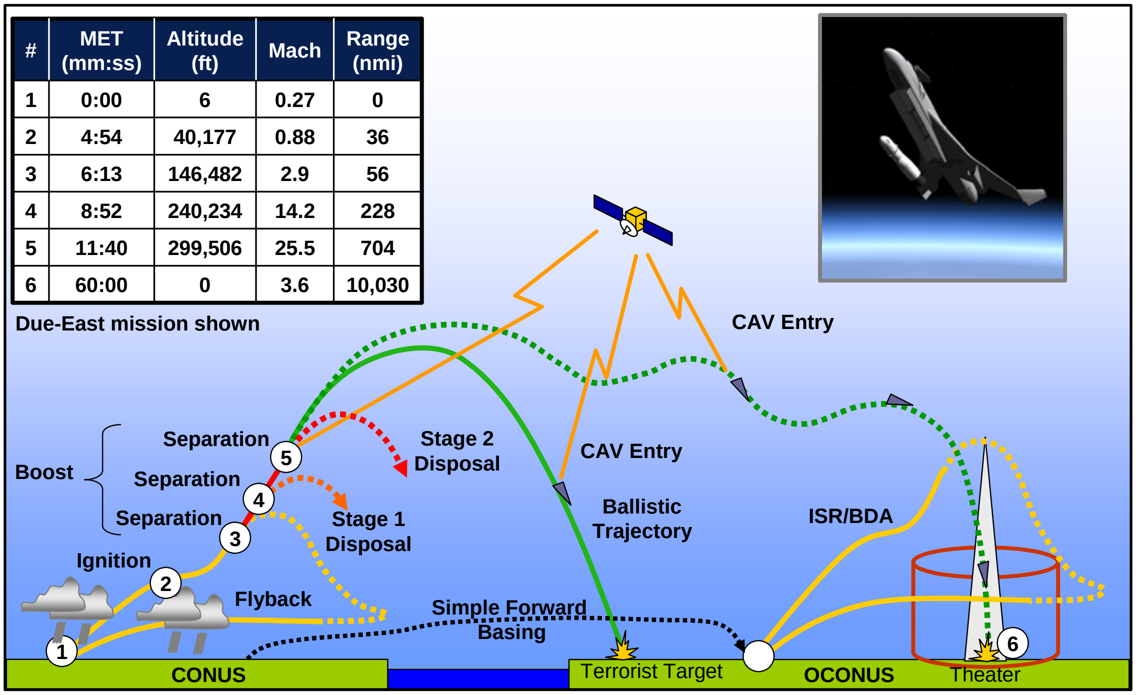
The discussion above focuses on general trends. Specific analyses across a spectrum of payload classes resulted in some secondary effects. Specifically, for small payloads (<5klb) series burn approaches integrate and optimize better and as payloads get heavier (>15klb) parallel burn begins to dominate. For the medium (Delta II) class of payloads, the design choice can be one of personal preference. Table 2 shows a comparison between parallel-burn and series-burn vehicles sized for intermediate (10k – 15klbs) payloads to LEO using existing LOX/Hydrocarbon rocket engines. The parallel-burn system staged at approximately Mach 3.7 at 110,000 feet, while the series-burn system staged at Mach 7 and 219,000 feet. Note that the parallel-burn system relied on a recoverable Propulsion-Avionics Module (PAM) to recover the expensive portions of the 2nd stage (core). This allows it to be cost competitive with the series-burn system in this payload class on a recurring basis. From a non recurring standpoint, the series burn approach has a significantly larger reusable stage and higher staging Mach number (3.7 versus 7), which will require more up front funding to develop and test.

Table 2. VTHL Parallel-Burn configuration versus VTHL Series-Burn using existing engines.

	VTHL Parallel Burn	VTHL Series Burn
Liftoff Weight	602,975 lbm	720,619 lbm
Payload to 100x100x28.5	10.9 klbm	12.4 klbm
1st Stage	Reusable Winged Vehicle	Reusable Winged Vehicle
Engines	1 x AJ26-58 or -59	3 x AJ26-58 or -59
GLOW	166,272 lbm	606,801 lbm
Staging Point	Mach 3.7 @ 110 kft.	Mach 7.0 @ 219 kft
2nd Stage	Partially reusable stage (AJ26 recovered)	Expended Stage
Engines	1 x AJ26-59	2 x Merlin
GLOW	347,204 lbm	113,818 lbm
Staging Point	Mach 8.8 @ 280 kft.	100x100 nmi orbit
3rd Stage	Expended Stage	n/a
Engines	1 x Merlin or RD 0124	
GLOW	89,499 lbm	

Horizontal Launch Options

All hybrid horizontal launch systems (HHLS) are aircraft optimized for subsonic flight and capable of boosting out of the atmosphere under rocket power. HHLS operate within the existing government and commercial infrastructure and all offer the flexibility to provide global strike or space launch capability from existing airport assets. Horizontal launch options have the benefit over vertical launch options of being able to locate their "launch" point to avoid traditional range, weather and overflight constraints. In this manner, they are better suited to address launch on demand needs (e.g. rapid global strike) as well as covert mission requirements. All HHLSs can take off from existing air bases, climb to altitude on turbojet power, then ignite LOX/RP or LOX/LH^2 rocket engines to boost the system to its payload release point of approximately 150 kft at supersonic to low hypersonic Mach numbers.



#	MET (mm:ss)	Altitude (ft)	Mach	Range (nmi)
1	0:00	6	0.27	0
2	4:54	40,177	0.88	36
3	6:13	146,482	2.9	56
4	8:52	240,234	14.2	228
5	11:40	299,506	25.5	704
6	60:00	0	3.6	10,030

CAV / ECAV Launches from CONUS Bases **"In Theater" Operations from forward basing OCONUS**

Figure 3. Typical hybrid horizontal launch system mission profile.

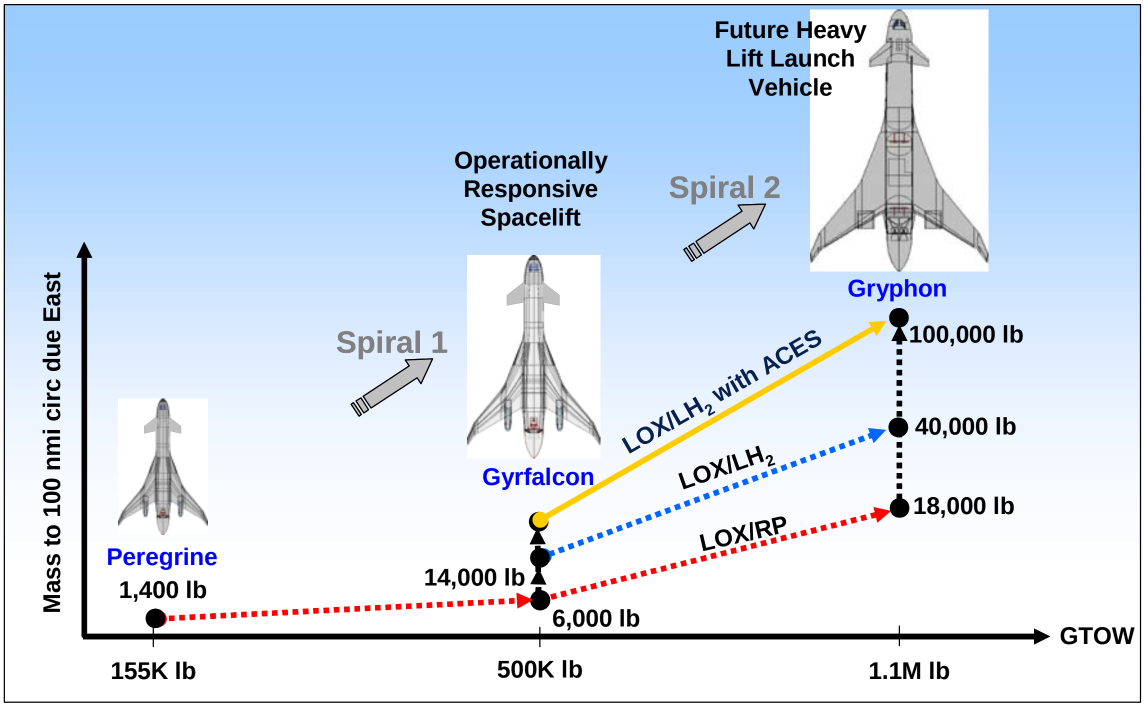


Figure 4. Variation in HHLS sizing and Payload Capability.

	VTHL-Series	VTHL-Parallel	HTHL
Non Recurring Cost	1	2	3
Recurring Cost	3	2	1
Scalability	1	2	3
High Flight Rates	3	3	1
Minimal Ground Infrastructure	3	3	1

Table 3. System selection is highly dependent on FOM weighting (FOM rankings shown).

The drawback of horizontal launch options is that they require large wings and landing gear to support heavy rocket propellants, which in turn drive non-recurring cost. As a result, horizontal launch options prefer higher Isp propellants such as methane and hydrogen, and are much more performance sensitive than their vertical takeoff counterparts. Specifically, HHLS have difficulty scaling up to address intermediate payloads without switching to hydrogen fuels and, for heavy payloads, augmenting with in-flight LOX generation systems (Figure 4).

Observations

System selection is highly dependent on the requirements (payload size, flight rate, recurring cost, non-recurring cost, scalability) and the weighting of the figures of merit (Table 3). From these analyses, we can not draw specific conclusions, but instead infer trends and report them as observations.

Vertical Takeoff Parallel Burn: This approach has the lowest non-recurring cost and is the most scalable (it lends itself to create a modular family architecture). It provides the most flexibility for a moderate (<20 per year) flight rate.

Vertical Takeoff Series Burn: This approach is the most cost effective from a recurring cost perspective for moderate (<20 per year) flight rates optimizes around one or two payload classes.

Horizontal Takeoff: This approach is best suited for high flight rate mission models and smaller payload sizes (e.g. global force projection).

Summary

Operationally Responsive Spacelift requires good interaction between the mission planners and the system developers, advancement of launch system technologies to provide rapid turnaround with high reliability, and finally affordable highly reliable expendable elements. This paper examined three potential HLS configurations and showed the relative figures of merit with each. More interaction with the mission planners is required before an optimum configuration can be chosen.

References

1. Andrews, D.G., Cannon, J. H., and Crocker, A. M., "A Comparison of Horizontal Takeoff RLVs for Next Generation Space Transportation", AIAA Paper 2003-5037, 39th Joint Propulsion Conference, Huntsville AL, July 2003.