AIAA 2003-5244

ANALYSIS OF PARALLEL BURN, NO-CROSSFEED TSTO RLV ARCHITECTURES AND COMPARISON TO PARALLEL BURN WITH CROSSFEED AND SERIES BURN ARCHITECTURES

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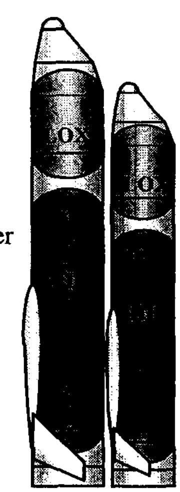
ABSTRACT

Three dominant Two Stage To Orbit (TSTO) class architectures were studied: Series Burn (SB), Parallel Burn with crossfeed (PBw/cf), and Parallel Burn, no-crossfeed (PBncf). The study goal was to determine what factors uniquely affect PBncf architectures, how each of these factors interact, and to determine from a performance perspective whether a PBncf vehicle could be competitive with a PBw/cf or a SB vehicle using equivalent technology and assumptions. In all cases, performance was evaluated on a relative basis for a fixed payload and mission by comparing gross and dry vehicle masses of a closed vehicle. Propellant combinations studied were LOX: LH2 propelled booster and orbiter (HH) and LOX: Kerosene booster with LOX: LH2 orbiter (KH). The study observations were: 1) A PBncf orbiter should be throttled as deeply as possible after launch until the staging point. 2) A PBncf TSTO architecture is feasible for systems that stage at mach 7. 2a) HH architectures can achieve a mass growth relative to PBw/cf of <20%. 2b) KH architectures can achieve a mass growth relative to Series Burn of <20%. 3) Center of gravity (CG) control will be a major issue for a PBncf vehicle, due to the low orbiter specific thrust to weight ratio and to the position of the orbiter required to align the nozzle heights at liftoff. 4) Thrust to weight ratios of 1.3 at liftoff and between 1.0 and 0.9 when staging at mach 7 appear to be close to ideal for PBncf vehicles. 5) Performance for HH vehicles was better when staged at mach 7 instead of mach 5. The study suggests possible methods to maximize performance of PBncf vehicle architectures in order to meet mission design requirements.

NOMENCLATURE

HH	=	Hydrogen fueled booster, Hydrogen fueled Orbiter
KH	=	Kerosene fueled booster, Hydrogen fueled Orbiter
MPC	=	Main Propellant Crossfeed
PB	=	Parallel Burn
PBncf	=	Parallel Burn, no-crossfeed
PBw/cf	=	Parallel Burn with Crossfeed
RLV	=	Reusable Launch Vehicle
SB	=	Series Burn
TSTO	=	Two Stage To Orbit
HHC5	=	This is the standard vehicle description method used in the study. (Booster Fuel)(Orbiter Fuel)(Propellant Method, C=PBw/cf, S=series burn, P=PBncf)(Staging mach number)

Figure 1: Typical HHP7 vehicle architecture



INTRODUCTION

NASA is currently performing launch vehicle and technology trade studies required to develop and deliver the Nation's next generation launch vehicle. This work is currently being done by the Next Generation Launch

Technology (NGLT) program led by the NASA Marshall Space Flight Center (MSFC). This paper describes a set of launch vehicle trades studies conducted for the 2nd Generation Reusable Launch (2Gen RLV) program office (the precursor to the NGLT program).

The need for this study was in creating a set of reference vehicles for the Advanced Concept Department in the Space Transportation Directorate of NASA Marshall Space Flight Center. These reference vehicles were used for required technology trade studies of Two Stage To Orbit (TSTO) second generation launch vehicle architectures. One reason for the technology trade studies was to create a standard of comparison for proposed vehicles, each of which used different technology sets. The two kinds of TSTO RLVs previously studied were series burn (SB) and parallel burn with crossfeed (PBw/cf).

In reviewing the proposed architectures, it became apparent that two proposals held mutually exclusive positions concerning the value and risks of main propellant crossfeed. Main Propellant Crossfeed (MPC) is a propellant feed system, similar to that used by the shuttle and external tank, where fuel and oxidizer from the booster is supplied to the orbiter engines. The booster and orbiter both burn propellant from the booster main tanks until separation, when the orbiter switches to its own (still full) tanks, and continues to orbital insertion. It became obvious that NASA needed a way to objectively consider each side's arguments, without bias due to competition for NASA contracts. Thus, this study was undertaken with the goal of determining what factors uniquely affect Parallel Burn, no-crossfeed (PBncf) architectures, how each of these factors interact, and to determine from a performance perspective whether a PBncf vehicle could be competitive with a PBw/cf or SB vehicle using equivalent technologies and assumptions.

STUDY METHODOLOGY

TSTO RLV Types

There are three major types of TSTO RLVs. They are: Series Burn (SB), Parallel Burn with crossfeed (PBw/cf), and Parallel Burn, no-crossfeed (PBncf).

Series Burn RLVs

In Series Burn RLVs, the booster engines are started on the ground. When the booster consumes all its propellant, the orbiter separates, starts its engines, and accelerates to orbital insertion, while the empty booster returns to the launch site. There are two unique issues with SB RLVs. The first is whether the orbiter should be stacked vertically or horizontally on the booster. In this study all vehicles used a horizontally stacked configuration for ease of comparisons. The second, often debated issue, is the risk from malfunctions during air start of the orbiter engines. The answer to this second issue has a deciding impact on the relative value SB versus PBw/cf or PBncf.

Parallel Burn with crossfeed

A TSTO parallel burn with crossfeed vehicle must be horizontally stacked (side mounted) in order to align the booster and orbiter engines and avoid thrust plume interactions. PBw/cf ascent events differ from SB in that both the orbiter and booster engines are lit and both draw propellant from the booster tanks. During the boost phase the orbiter draws its propellant from the booster main tanks across connecting pipes. Crossfeeding propellant avoids the need for air-starting the orbiter engines and allows the lightest possible dry mass in cases where the orbiter and booster use the same propellants, but adds the complexity of the crossfeed system. The technical feasibility and reliability of a bipropellant booster-to-orbiter main propellant crossfeed system has recently been a topic of significant debate among second generation RLV contractors. The major issue is the design difficulty and cost risk inherent in making a system that is doubly or triply redundant with a reliability of 99.9% or higher.

Parallel Burn, no-crossfeed

The Parallel Burn, no-crossfeed architecture (see Figure 1) avoids both air-start and crossfeed at the cost of a larger booster and orbiter. In a PBncf vehicle, both the orbiter and booster engines are lit and the orbiter uses its own propellant during the boost phase. Thus, when the booster runs dry and separates from the orbiter, the orbiter has already used 25% to 35% of its ascent propellant. This induces a weight penalty in the orbiter in order to carry additional propellant, which causes a further weight penalty in the booster to achieve the same staging point. In addition, the CG control problem is far worse for a PBncf vehicle than for a SB vehicle because the aft ends of the booster and orbiter must be aligned to avoid engine plume damage to the booster, and the orbiter specific thrust-to-weight is very low. One way to reduce the orbiter propellant consumption during the first stage is to throttle down the orbiter engines as much as possible. Another possibility is to use smaller or fewer engines. Throttling the orbiter engines soon after liftoff minimizes CG control problems due to a low orbiter liftoff thrust, but may result in an unnecessarily high orbiter thrust after staging. Reducing the number or size of engines size may cause CG control problems and drift at launch. This study assessed the overall size penalty caused by the orbiter's additional propellant usage and attempted to quantify the performance benefits, drawbacks, and potential risks of a parallel burn system without crossfeed.

Parallel Burn Analogies to the Space Shuttle

Expert opinions vary significantly on the reliability of both air-startable engines and TSTO crossfeed systems. Air-start has been previously demonstrated in ELVs, but not in an RLV, and thus a reusable air-startable engine is still only theoretical. Proponents of MPC TSTO vehicles often point to the shuttle as an existing vehicle with a propellant crossfeed system that has been used and studied extensively. Opponents then point out that the crossfeed pipes of a TSTO RLV would have to be on the order of twice the diameter of those used by the shuttle while still using two fault tolerant systems. It can also be pointed out that if the shuttle and ET are considered as a single stage, then the shuttle system can be seen as a PBncf system, with the SRMs as the first stage. Unfortunately, all of these analyses and analogies are heavily dependant on what assumptions are made, and are often biased.

Reference Mission and Ground Rules

In comparing a set of disparate vehicle architectures, it is essential to have a method of comparing their relative merits that introduces as little bias as possible. Each vehicle was closed with respect to performance for an identical mission, which was considered to be representative of missions that might be undertaken by a successfully built TSTO RLV. The mission was to lift a payload of 35,000 lb to the International Space Station by reaching a 50×248 nmi orbit at an inclination of 51.6°. The required payload envelope was a cylinder of 15 ft diameter ×55 ft long. The payload was carried in an external payload bay mounted to the back of the orbiter. Launch and landing were both assumed to be at KSC. The orbiter was required to rendezvous with the ISS, but not to physically dock with it. Early studies found that booster staging mach number had a significant effect on the net size of the vehicle, with higher staging mach resulting in smaller vehicles. Cases were run with boosters staging at either mach 5.0 or 7.0. No higher staging mach numbers were selected due to booster flyback range complications. The performance figures of merit (FOMs) used for comparisons were: dry mass of the booster and orbiter, gross liftoff mass (GLOM) of the vehicle system, and booster and orbiter surface areas and dimensions. The ground rules and assumptions used in this study are listed in the appendix.

Sizing a TSTO Vehicle

Sizing of a TSTO vehicle concept usually starts with establishing the insertion orbit and payload mass for the reference mission, the main propellant types, and the main engine Isp. The reference mission orbit determines the actual delta velocity (ΔV) required. The ideal required delta velocity includes velocity losses, and thus is higher than the actual ΔV. Losses to ΔV are caused by gravity, drag, steering, and atmospheric thrust reduction. For a typical TSTO 2nd generation RLV on a mission to the International Space Station, actual required ΔV is about 25500 ft/s. Losses to ΔV usually total about 5000 ft/s, giving a required ideal ΔV of about 30500 ft/s. For a TSTO vehicle, the ideal ΔV must be split between the orbiter and booster. The proportion of the ideal ΔV used for the booster and orbiter is determined by the desired staging velocity. For expendable TSTO vehicles, the booster often has two-thirds of the ΔV, but in RLVs the booster is usually intended to return to the launch site, which puts a limit on how far down range staging can be. The higher the staging velocity, the farther down range the booster will be when it stages. For this reason, fly-back boosters are rarely designed to stage at velocities higher than mach 8. For the vehicles in this study, all boosters were intended to fly back to the launch site under their own power and the staging velocity was set at either mach 5 or mach 7. This resulted in the boosters having approximately one third of the total ideal ΔV.

Performance Models Used

Performance analysis used iterative looping of three different software models. The weights and sizing (W&S) model, INTROS, was iterated with a structural model, LVA, and a trajectory model, POST. Aerodynamic data for POST was supplied by APAS.

INTROS: Weight and Sizing

The weights and sizing model was an Excel/Visual Basic for Applications based program called INTROS, developed by Emory Lynn at NASA/Marshall Space Flight Center, Advanced Concepts Department. INTROS was developed to perform conceptual and preliminary sizing of launch vehicles and systems trade and parameter sensitivity studies. The program can be run on PC or Macintosh platforms. Launch vehicles can be designed for ascent or in-space application. Propulsion systems can be liquid rocket engine, solid rocket motor, hybrid rocket motor, or combined air-breathing /rocket engine. Stages can be expendable, partially recoverable or fully recoverable. Mass properties, which include masses and optional centers of gravity, are based on a large architectural breakdown structure of systems, subsystems, propellants and other fluids. Bookkeeping for mass properties can be established, as applicable, for prelaunch, launch, main engine cutoff, on-orbit maneuvers, deorbit and landing. Geometry is modeled for each launch vehicle stage body, and wings and other airfoils, if applicable. The program has several methods for scaling the size and performance capability of each launch vehicle stage in order to match design reference mission requirements..

LVA: Structural Analysis

Launch Vehicle Analysis (LVA) is an expert system launch vehicle structural analysis computer program written in Visual Basic for IBM PC compatible computer systems. It handles cylindrical cross-section vehicles in both in-line and side-mount multistage configurations. Starting from a textual descriptive input file, the program does a pre-launch and flight loads analysis and translates it into a structural weight estimate. It must be emphasized that LVA accomplishes this without reverting to Mass Estimating Relationships (MERs). LVA uses proven direct solution techniques as provided by the NASA Astronautics Structures Manual and the McDonnell Douglas Isogrid Design Handbook to do analysis and generate the weight estimates. LVA's structural analysis capability has been verified by numerous methods including finite element analysis. LVA generally takes less than one minute to perform an iterative loads and structural analysis, even on legacy PC equipment.

LVA's outputs include a detailed structural weight statement including sizing parameters, a to-scale dimensioned drawing, a calculated loads graph, and a to-scale 3D rotate-able configuration illustration.

POST3D: Trajectory

POST3D (Program to Optimize Simulated Trajectories) is a FORTRAN 77 based legacy code developed by NASA Langley for detailed trajectory simulations. Quoting from the introduction in the Utilization Manual: "POST is a generalized point mass, discrete parameter targeting and optimization program. POST provides the capability to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate planet. POST has been used successfully to solve a wide variety of atmospheric ascent and reentry problems, as well as exoatmospheric orbital transfer problems. The generality of the program is evidenced by its N-phase simulation capability which features generalized planet and vehicle models. This flexible simulation capability is augmented by an efficient discrete parameter optimization capability that includes equality and inequality constraints."

APAS: Aerodynamics

APAS (Aerodynamic Preliminary Analysis System) is a FORTRAN 77 based legacy code originally developed by North American Aircraft Operations, Rockwell International Corporation and NASA Langley for aerodynamic analysis. Quoting from the summary in the User's Manual: "An aerodynamic analysis system based on potential theory at subsonic/supersonic speeds and impact type finite element solutions at hypersonic conditions is described. Three-dimensional configurations having multiple non-planar surfaces of arbitrary planform and bodies of non circular contour may be analyzed. Static, rotary, and control longitudinal and lateral-directional characteristics may be generated."

Performance Closure Process Overview

1st Order Sizing

1st order sizing is used to set up the first iteration of performance and to guess at the size of the vehicle by estimating the propellant requirements. The first step is to establish the mission and payload requirements. The mission defines the required orbital parameters and should also define or provide some indication of how much ΔV must be provided by the main propulsion system (MPS) and orbital maneuvering system (OMS). The payload mass can then be combined with an educated guess about the payload fraction, expected engine I_{sp}, number of stages, and the ideal rocket equation to provide a first iteration guess about the mass of each stage. For a TSTO RLV with a flyback booster, the orbiter will usually provide approximately 2/3rd of the total ideal delta velocity, while the booster will provide the remainder. In this case the useful form of the ideal rocket equation is propellant mass fraction (PMF) = $[1 - \exp(-\Delta V_{ideal}/g_0 * I_{sp})]$. PMF is the mass of propellant for the stage, divided by the total mass of the stage, and represents the fraction of the stage mass that is propellant. For a TSTO case using this method, the PMF of the orbiter includes the payload, and the PMF of the booster includes both the orbiter and payload. If the payload is carried in an external container, as was done in this study, then include the container mass in the payload mass. Ballpark first guess payload fractions are 0.025 to 0.040 for the orbiter and 0.25 to 0.40 for the booster. Higher payload fractions represent better performance. Divide the payload by the orbiter's payload fraction to get the first iteration mass of the orbiter. Divide the orbiter plus payload mass by the booster payload fraction to get the first iteration mass of the booster. Multiply the mass of the orbiter and booster by their respective PMF values to obtain the mass of propellants required by each stage. A fuel/oxidizer fraction can be applied to the propellant masses to yield fuel and oxidizer masses.

2nd Order Sizing

Choosing a vehicle configuration (wing-body TSTO RLV with booster flyback) and fuel and oxidizer combination (LOX: Kerosene or LOX: LH2) provides enough information to choose a fuel/oxidizer ratio, calculate propellant volumes, and decide on the shapes and locations of propellant tanks (domed cylinders, LOX forward). This information establishes the rough size and layout of the vehicle system and constitutes the beginning of 2nd order sizing. With an approximation of the vehicle size and shape available, component and section volumes and surface areas can be estimated. Next, structural materials must be chosen, such as graphite-epoxy for wings and unpressurized structures and aluminum-lithium for the tanks. Mass estimating relationships (MERs) are then formulated to yield a structural mass based on the unit mass and volume or area of each component. Engines are then chosen for each stage based on a desired T/W and the 0^{th} order stage mass estimates. If an existing engine is chosen, the number of engines must vary with the size of the vehicle to maintain the desired T/W. If a new engine will be developed, then the engine is "rubberized" and both the number and thrust of the engines can be varied to obtain the desired stage T/W. The thrust, Isp and specific T/W of an engine have an enormous effect on the performance of a launch vehicle, and should be considered early in its design. All known subsystems are then filled in and their masses accounted for by MERs, such as tanks, nose cone, intertanks, wings, landing gear, crew accommodations, avionics, batteries, engines, propellants, etc. The result of most MERs depends in some way on the mass, volume, or surface area of the vehicle or stage, and thus depends indirectly on every other MER. The simultaneous solution of all the MERs in a model yields an approximate net mass of the vehicle. Once an approximate mass of the vehicle is available, the size and shape of the vehicle can be refined to yield the desired Propellant Mass Fraction and available ΔV. Trajectory simulations are performed based on the masses, areas, and engine performance from the first iteration of sizing. With the vehicle at roughly the correct size after the first one or two trajectory iterations, the Weight & Sizing model should be iterated with a Structures model until an iteration closes to within 10% of the mass of the previous iteration, when sized for the correct ΔV from trajectory. Structural analysis is used to provide area or volume specific structural unit masses for each structural section of the vehicle and thus the structural MERs are valid as long as the vehicle scale and load paths are close to what was simulated in the structural model. The goal of the trajectory simulations is to refine the required ΔV estimate used to size the vehicle. Successive iterations are performed between Weight & Sizing, Structures, and Trajectory models until (a) the orbiter and booster dry mass are both within 10% of the last Structures iteration, (b) the available and required ΔVs are equal, (c) the desired mission requirements are met. At this point the vehicle is considered "closed" by the performance models and 2^{nd} order sizing is complete.

CASE DESCRIPTIONS

17 cases were studied, 14 of which are presented in this document. Cases 1, 2, and 3 are HH vehicles that stage at mach 5. Cases 4 through 11 are HH vehicles that stage at mach 7. Cases 12, 13, and 14 are KH vehicles that stage at mach 7.

Case 1 – HHC5
Mach 5 HH comparison case
This case was used for comparison to cases 3 and 4. Structural analysis was provided by LVA. The engines were rubberized with T/Ws of 1.3 at liftoff and 1.17 at staging. 1.17 was chosen to compare with case 3, which was intended to match a case generated at Langley Research Center. LOX: LH2 booster and orbiter with crossfeed. Staged at mach 5.04. Orbiter used 6 engines throttled to 104% pre-staging and 104% post-staging.

Case 2 – HHP5-104
This is the unthrottled mach 5 PBncf case. It was based on Case 1 and used identical assumptions except for the removal of crossfeed systems and related changes.

Case 3 – HHP5-90/65
This is the throttled mach 5 PBncf case. The orbiter engines were at 90% throttle from ignition to 9000 ft, then throttled down to 65% until staging. Throttling was done to minimize pre-staging propellant usage and was limited by nozzle flow separation below 9000 ft. After staging the engines were throttled up to 104% until Main Engine Cut Off (MECO). All other throttled mach 5 PBncf cases follow this same throttle schedule.

Case 4 – HHC7
Mach 7 HH comparison case
This is the mach 7 staging version of Case 1. Identical to Case 1 except that: (a) the propellant loadings were optimized for mach 7 staging, and (b) additional TPS was added to the booster. This was the comparison case for all mach 7 HH vehicles. Structural analysis was provided by LVA. The engines were rubberized with T/Ws of 1.3 at liftoff and 1.17 at staging. LOX: LH2 booster and orbiter with crossfeed. Staged at mach 7.01. Orbiter used 6 engines throttled to 104% pre-staging and 104% post-staging.

Case 5 – HHP7-104
This is the unthrottled mach 7 HH PBncf case. It was based on Case 4 and used identical assumptions except for the removal of crossfeed systems and related changes.

Case 6 – HHP7-90/65
This is the throttled mach 7 HH PBncf case. Identical assumptions to Case 5 except for the orbiter throttling. The orbiter engines were at 90% throttle from ignition to 9000 ft, then throttled down to 65% until staging. Throttling was done to minimize pre-staging propellant usage and was limited by nozzle flow separation below 9000 ft. After staging the engines were throttled up to 104% until MECO. All other throttled mach 7 HH PBncf cases follow this same throttle schedule.

Case 7 – HHP7-90/65-tw14/117
Variant of case 6, HHP7-90/65, with the booster engine size increased to yield a liftoff T/W of 1.4. The orbiter staging T/W was held constant at 1.17. No other assumptions were changed from case 6.

Case 8 - HHP7-90/65-tw12/117
Variant of case 6, HHP7-90/65, with the booster engine size decreased to yield a liftoff T/W of 1.2. The orbiter staging T/W was held constant at 1.17. No other assumptions were changed from case 6.

Case 9 – HHP7-90/65-tw13/10
Variant of case 6, HHP7-90/65, with the orbiter engine size decreased to yield a staging T/W of 1.00. The booster liftoff T/W was held constant at 1.30. No other assumptions were changed from case 6.

Case 10 – HHP7-90/65-tw13/09
Variant of case 6, HHP7-90/65, with the orbiter engine size decreased to yield a staging T/W of 0.90. The booster liftoff T/W was held constant at 1.30. No other assumptions were changed from case 6.

Case 11 – HHS7
This is the series burn version of case 4, created as a comparison to cases 12, 13, and 14. No assumptions were changed except for those resulting from the change to series burn.

Case 12 – KHS7
Mach 7 KH comparison case
This case was used for comparison to cases 9, 11, 13, and 14. Structural analysis was provided by LVA. The engines were rubberized with T/Ws of 1.3 at liftoff and 1.00 at staging. LOX: Kerosene booster and LOX: LH2 orbiter. Staged at mach 7.00. Structural analysis from LVA. Orbiter used 3 engines, air started after staging, then throttled to 104%.

Case 13 – KHP7-104
This is the unthrottled mach 7 KH PBncf case. It was based on Case 12 and used identical assumptions except for the ground start of orbiter engines and related changes to convert it to a PBncf architecture.

Case 14 – KHP7-90/65
This is the throttled mach 7 KH PBncf case. Identical assumptions to Case 13 except for the orbiter throttling. The orbiter engines were at 90% throttle from ignition to 9000 ft, then throttled down to 65% until staging. Throttling was done to minimize pre-staging propellant usage and was limited by nozzle flow separation below 9000 ft. After staging the engines were throttled up to 104% until MECO. All other throttled mach 7 HH PBncf cases follow this same throttle schedule.

RESULTS

Refer to Table 1, Table 2, and Table 3 at the end of the document

OBSERVATIONS

1. A PBncf orbiter should be throttled as much as possible during the 1st stage of ascent.

Evidence: This can be seen by comparing cases 2 and 3 (HHPJ5-104 and HHPJ5-90/65), comparing cases 5 and 6 (HHPJ7-104 and HHPJ7-90/65) and by comparing cases 13 and 14 (KHPJ7-104 and KHPJ-90/65). In each of these comparisons, the throttled case ("-90/65") has lower a Gross and Dry mass than the unthrottled case.

2. A PBncf TSTO architecture is feasible for systems that stage at mach 7. HH architectures can achieve a mass growth relative to PBw/cf of <20%. KH architectures can achieve a mass growth relative to Series Burn of <20%.

Evidence: For all of the PBncf vehicles that were staged at M7 and whose orbiters were throttled during the booster phase, mass growth relative to the comparison case was less than 20%.

3. CG control will be a major issue for a PBncf vehicle, due to the low orbiter specific T/W and to the position of the orbiter CG required to align the nozzle heights at liftoff.

Evidence: In comparing the PBw/cf to the PBncf cases it can be seen that at liftoff the difference between the orbiter specific T/W and the booster specific T/W is much greater in the PBncf cases. In addition, the PBncf orbiters are relatively larger compared to their boosters than the PBw/cf cases. These two factors together will create a larger thrust moment at liftoff in the PBncf vehicles and thus require higher gimbal angles to achieve CG control. The higher gimbal angles will in turn cause more drift on the launch pad, which could cause other problems.

4. T/Ws of 1.3 at liftoff and between 1.0 and 0.9 at mach 7 staging appear to be close to ideal.

Evidence: This can be seen from the T/W studies. Compare cases 6, 7, and 8 for the liftoff T/W study and cases 6, 9, and 10 for the staging T/W study.

5. Performance for all vehicles studied is better when staged at mach 7 instead of mach 5.

Evidence: This can be seen by comparing cases 1 and 4, cases 2 and 5, and cases 3 and 6. The vehicle size decreases substantially for all the mach 7 cases.

DISCUSSION

Issues with the Parallel Burn, no crossfeed architecture

The major complication in dealing with PBncf vehicles is that PBncf orbiters consume one quarter to one third of their ascent propellant before reaching the staging point. This causes a mass penalty in that additional propellant must be added to compensate for this inefficiency, which necessitates larger tanks and thus a larger orbiter. The booster must also then grow a bit to accommodate larger engines to allow the vehicle as a whole to achieve the desired liftoff T/W. The orbiter's propellant usage during the boost phase can be minimized by either using smaller engines, or by throttling the orbiter engines as deeply as possible during the boost phase. Using some combination of these methods will allow the lowest possible orbiter boost phase propellant consumption.

However, there are potential disadvantages to both methods which must be considered. Small orbiter engines limit the acceleration that is possible after staging and may increase ΔV losses due to a long ascent time. Higher losses increases ΔV_{ideal} and must be countered with a higher orbiter PMF and larger orbiter, and thus also a larger booster to carry the orbiter. The other problem of small orbiter engines is that because the booster and orbiter engines must be horizontally aligned to avoid plume infringement, allowing the orbiter specific T/W to drop significantly below the booster specific T/W will create a CG control problem. The problem must then be countered with thrust vectoring gimbal angles in the range of 8 to 16 degrees, resulting in significant launch pad drift in the direction of the orbiter. The CG control problem will become more severe as the flight continues and the booster uses all of its propellant. This will cause the vehicle CG to move upward toward the orbiter. The most severe problems are likely to occur as the vehicle passes through maximum dynamic pressure. At that time the vehicle should be at 0 degrees angle-of-attack to minimize wing loads. A PBncf vehicle that cannot maintain 0° angle of attack through max Q will suffer a substantial structural mass penalty due to related wing loads.

Use of throttling of the orbiter engines allows better CG control at launch if the orbiter engines are kept at near nominal throttle for the first 30 seconds or so of flight. The orbiter engines can then be deep throttled until staging to conserve orbiter propellant. The possible penalty of deep throttling the engines is the impact on reliability of additional throttling events, due to the possibility of engine failure while throttling. It may be possible that the reliability penalty is greater than the gain from ground-starting the orbiter engines (instead of air-starting), thus defeating the entire purpose of PBncf.

The Need for Structural Analysis

Early on in the Two Stage to Orbit (TSTO) program, the weight estimates for the vehicles were based on Space Transportation System (STS) External Tank (ET) MERs. The logic was based on the fact that the TSTO vehicles looked and appeared to function similar to the Space Shuttle. Although there were some similarities in appearance, the actual relationship between the two programs were very different indeed. The STS is a masterpiece of modern aerospace engineering. The LOX forward design of the ET placed the combined center of gravity (CG) of the system high enough that flight control problems could be avoided. The addition of the axial thrust component of the Solid Rocket Boosters (SRBs) just aft of the LOX tank helps cancel out the enormous load input from that tank and the liquid oxygen contained within. This results in a highly efficient and optimized design. However, MERs from the ET that have been applied to the TSTO have resulted in a grossly underestimated structural weight. This occurs because deviations from the ET design quickly decrease the accuracy of the ET MERs. These underestimated structural weights are compounded when they are wrapped with the necessary propellant loadings. This results in an overall system weight that is a mere fraction of a realistic value and a subsequent far too optimistic appearance of feasibility for the program.

One of the main problem areas with the TSTO program is the combined CG of the two vehicles. This problem occurs whether the two vehicles are of similar size or not, but can be mitigated in serial burn concepts by placing the orbiter forward in the configuration. The CG problem's relationships to flight loads and structural weight are two fold. The large engine gimbal angles required for flight result in a significant lateral component to the thrust vector. This in turn results in a substantial increase in aerodynamic loads. This also translates into a large increase in point loads and moments that must be passed between the two vehicles. The two vehicles must be able to structurally accommodate the increased loads, leading to a considerable structural weight increase that cannot be foretold by ET MERs. It is therefore necessary to do a complete loads and structural analysis on a TSTO vehicle in order to obtain an accurate weight forecast for the system.

CONCLUSION

From this study's results it is apparent that an optimized reusable TSTO Parallel Burn, no-crossfeed vehicle can potentially be competitive with the performance of an optimized Parallel Burn with crossfeed or Series Burn RLV. However, PBncf does have its own risks and shortcomings which may be just as difficult to overcome as air-start or crossfeed. Each of the three major TSTO RLV architectures has its own unique technology hurtle. Parallel Burn with crossfeed requires a highly reliable main propellant crossfeed system, Series Burn requires air-startable orbiter main engines, and Parallel Burn, no-crossfeed requires both an engine that can be throttled to lower than 60% and resolution of issues related to CG control and non-zero angle of attack ascent through max Q. Provided that the vehicles are optimized for the lowest possible dry mass and that the vehicle stages at mach 7 or higher, it is the author's opinion that non-performance related disciplines, such as Cost, Operations, Safety, or Reliability must provide the deciding vote between these three vehicle architectures, but that they must do so with full awareness of the benefits and risks of each approach.

ACKNOWLEDGEMENTS

The authors wish to thank the following individuals for their support and assistance.

At NASA, MSFC, Advanced Concepts Division: Mr. Emory Lynn, Mr. David Mercier, Mr. Jim Hays, Mr. Reginald Alexander, Mr. Ed Threet, and Mr. Hugh Brady.

At NASA, Langley Research Center: Mr. Roger Lepsch.

At International Space Systems, Inc.: Mr. Troy Stanley, Mr. Jerry Wittenstein, and Mr. John Hatfield.

APPENDIX: GROUND RULES AND ASSUMPTIONS

Ground Rules and Assumptions for All Vehicles

DRM: 35000 lb (plus 17420 lb payload carrier) to a 50x248 nmi orbit at 51.6°, circularized at 248 nmi. OMS/RCS propellant was also allotted for ISS approach and deorbit.

All boosters used either LOX: LH2 or LOX: Kerosene propellants. All orbiters used LOX: LH2 propellants.

Engines were assumed to be new, rubberized to yield a set thrust-to-weight ratio (T/W) regardless of the size of the vehicle, and had Isp, and engine T/W similar to either the SSME block II (for LOX: LH2 engines), or the RD-180 (for LOX: Kerosene engines).

All orbiters used SSME block II engines. After staging, engines were throttled to 104%

All LOX: LH2 boosters used 8 SSME block II engines at 104% throttle.

All LOX: Kerosene boosters used 8 RD-180s at 100% throttle.

Booster engines were throttled to less than nominal to allow for max g and for max Q (throttle bucket).

All orbiters were side-mounted to the booster.

All orbiters and boosters used a wing-body architecture.

The payload container was externally mounted to the back of the orbiter.

Best guess 2012 technologies

Al-Li reusable tanks and GrEp unpressurized structure

15% mass margin (optimistic)

Maximum Mission Duration from Launch to Landing = 9 days + 2 day contingency

Vehicle Weight Contingency (also called Mass Margin) = 15%

LVA Structural Analysis Computer Model used for structural analysis of all vehicles

Axial Acceleration on Ascent and Descent Limited to 3 g, Descent Normal Acceleration limited to 3 g

Max Dynamic Pressure Limited to 650 psf

ETO Flight Performance Reserves = 320 ft/sec

OMS Propellant Margin = 44 ft/sec for ISS missions; 12 ft/sec for LEO missions

RCS Propellant Margin = 30% reserves added

All boosters used jet-back propulsion after staging via F-119 engines.

Booster Flyback Propellant Margin = 25% reserves added

No detailed abort scenario was investigated for any case.

Ground Rules and Assumptions for Series Burn Vehicles

Air start of orbiter engines at staging

Orbiter Engines Rubberized for T/W of 1.00 at Staging

Orbiter engines at 104% throttle from staging to MECO, unless throttled for max g

Ground Rules and Assumptions for Parallel Burn with crossfeed Vehicles

Uses crossfeed of LOX and LH2 from booster to orbiter

Orbiter Engines Rubberized for T/W of 1.17 at Staging

Orbiter engines at 104% throttle from liftoff to MECO, unless throttled for max g

<u>Ground Rules and Assumptions for Parallel Burn, no crossfeed Vehicles</u>

Does not use crossfeed

Ground start of orbiter engines

Orbiter Engines Rubberized for T/W of 1.00 at Staging

Orbiter engines at 90% throttle from liftoff to 9000ft, 65% throttle from 9000ft to staging, and 104% throttle from staging to MECO, unless throttled for max g

[shaded box] = divergence from comparison case
Comparison cases are in italics

	Vehicle Summary - W&S	HH M5 staging		
	Case #	1	2	3
	Case Name	HHC5	HHP5-104	HHP5-90/95
1	Architecture	HHC5	HHP5	HHP5
2	Staging Mach	5.04	5.00	5.00
3	Crossfeed used?	y	n	n
4	Booster Propellants	LOX/LH2	LOX/LH2	LOX/LH2
5	Booster Throttle Settings (%)	104%	104%	104%
6	Orbiter Propellants	LOX/LH2	LOX/LH2	LOX/LH2
7	Orbiter 1st stg Throttle Settings (%)	104%	104%	90/95%
8	Orbiter 2nd stg Throttle Settings (%)	104%	104%	104%
9	Liftoff T/W	1.30	1.30	1.30
10	Staging T/W (at vac)	1.17	1.17	1.17
11	For PBnof: % of Orb prop used during stg 1	n/a	31.9%	25.4%
12				
13	Total Dry	1.00	1.81	1.39
14	GLOM	1.00	1.87	1.41
15	Aref (B+O)	1.00	1.74	1.36
16	Total Ascent Prop	1.00	1.91	1.42
17				
18	Booster GLOM	1.00	1.34	1.15
19	booster useable propellant	1.00	1.29	1.12
20	booster burnout weight	1.00	1.55	1.29
21	booster dry weight	1.00	1.59	1.33
22	booster theoretical wing area	1.00	1.60	1.33
23	booster engine thrust(vac) at 100% pwr level	1.00	1.84	1.51
24	booster engine exit area (each)	1.00	1.84	1.51
25	Booster # of engines	1.00	1.00	1.00
26				
27	Orbiter GLOM	1.00	2.69	1.60
28	orbiter useable propellant	1.00	2.85	1.80
29	orbiter burnout weight	1.00	2.08	1.47
30	orbiter dry weight	1.00	2.10	1.46
31	orbiter theoretical wing area	1.00	1.89	1.36
32	orbiter engine thrust(vac) at 100% pwr level	1.00	1.95	1.42
33	orbiter engine exit area	1.00	1.95	1.41
34	orbiter # of engines	1.00	1.00	1.00
35				
36	booster length	1.00	1.09	1.04
37	booster diameter	1.00	1.09	1.04
38	booster wingspan	1.00	1.24	1.13
39				
40	orbiter length	1.00	1.42	1.24
41	orbiter diameter	1.00	1.42	1.24
42	orbiter wingspan	1.00	1.39	1.19
43				
44	Dry weight vs Case 1	n/a	81.3%	39.4%
45	GLOM vs Case 1	n/a	87.2%	40.9%
46	Booster dry weight vs Case 1	n/a	59.4%	32.7%
47	Orbiter dry weight vs Case 1	n/a	110.3%	46.1%
48				
49	Orbiter LO T/W	0.974	0.706	0.661
50	Booster LO T/W	1.532	2.104	2.005
51	Liftoff T/W difference	0.558	1.397	1.344

	Vehicle Summary - W&S	HH M7 staging							
	Case #	4	5	6	7	8	9	10	11
	Case Name	HHC7	HHP7-104	HHP7-90/95	HHP7-tw14/117	HHP7-tw12/117	HHP7-tw13/10	HHP7-tw13/08	HHS7
1	Architecture	HHC7	HHP7	HHP7	HHP7	HHP7	HHP7	HHP7	HHS7
2	Staging Mach	7.01	7.00	7.00	7.00	7.00	7.00	7.00	7.00
3	Crossfeed used?	y	n	n	n	n	n	n	n
4	Booster Propellants	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2
5	Booster Throttle Settings (%)	104%	104%	104%	104%	104%	104%	104%	104%
6	Orbiter Propellants	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2
7	Orbiter 1st stg Throttle Settings (%)	104%	104%	90/95%	90/95%	90/95%	90/95%	90/95%	0%
8	Orbiter 2nd stg Throttle Settings (%)	104%	104%	104%	104%	104%	104%	104%	104%
9	Liftoff T/W	1.30	1.30	1.30	1.40	1.20	1.30	1.30	1.30
10	Staging T/W (at vac)	1.17	1.17	1.17	1.17	1.17	1.00	0.80	1.00
11	For PBnof: % of Orb prop used during stg 1	n/a	36.9%	29.1%	27.6%	31.3%	25.8%	23.6%	n/a
12									
13	Total Dry	0.96	1.17	1.09	1.10	1.13	1.03	1.03	0.96
14	GLOM	0.90	1.17	1.07	1.06	1.15	1.01	1.01	0.87
15	Aref (B+O)	0.96	1.16	1.09	1.10	1.12	1.03	1.04	0.87
16	Total Ascent Prop	0.89	1.17	1.08	1.04	1.15	1.01	1.01	0.84
17									
18	Booster GLOM	1.06	1.07	1.08	1.06	1.16	1.05	1.04	1.05
19	booster useable propellant	1.05	1.03	1.06	1.02	1.14	1.02	1.04	1.01
20	booster burnout weight	1.10	1.22	1.21	1.23	1.25	1.16	1.18	1.21
21	booster dry weight	1.07	1.19	1.17	1.20	1.20	1.13	1.18	1.17
22	booster theoretical wing area	1.08	1.21	1.19	1.22	1.22	1.15	1.17	1.19
23	booster engine thrust(vac) at 100% pwr level	1.00	1.26	1.24	1.38	1.21	1.21	1.24	1.24
24	booster engine exit area (each)	1.00	1.28	1.24	1.32	1.21	1.21	1.24	1.24
25	Booster # of engines	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
26									
27	Orbiter GLOM	0.67	1.34	1.03	1.03	1.16	0.97	0.94	0.60
28	orbiter useable propellant	0.64	1.39	1.09	1.05	1.18	0.98	0.96	0.57
29	orbiter burnout weight	0.78	1.13	0.98	0.97	1.03	0.89	0.87	0.68
30	orbiter dry weight	0.78	1.13	0.98	0.97	1.03	0.89	0.87	0.68
31	orbiter theoretical wing area	0.82	1.11	0.98	0.97	1.02	0.91	0.88	0.73
32	orbiter engine thrust(vac) at 100% pwr level	0.68	0.94	0.82	0.81	0.98	0.86	0.89	0.82
33	orbiter engine exit area	0.68	0.84	0.82	0.81	0.98	0.86	0.89	0.52
34	orbiter # of engines	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
35									
36	booster length	1.02	1.01	1.01	1.01	1.04	1.00	1.01	1.00
37	booster diameter	1.02	1.01	1.01	1.01	1.04	1.00	1.01	1.00
38	booster wingspan	1.02	1.08	1.07	1.08	1.08	1.05	1.08	1.07
39									
40	orbiter length	0.86	1.12	1.03	1.02	1.08	0.99	0.98	0.83
41	orbiter diameter	0.86	1.12	1.03	1.02	1.08	0.99	0.99	0.83
42	orbiter wingspan	0.83	1.08	1.00	0.99	1.02	0.96	0.95	0.86
43									
44	Dry weight vs Case 1	-4.8%	16.6%	8.9%	10.2%	12.6%	2.9%	3.1%	-4.0%
45	GLOM vs Case 1	-9.6%	17.4%	7.2%	5.0%	15.2%	1.3%	1.5%	-13.2%
46	Booster dry weight vs Case 1	7.1%	19.1%	17.3%	20.4%	19.7%	13.2%	18.1%	17.4%
47	Orbiter dry weight vs Case 1	-22.0%	13.4%	-2.3%	-3.3%	2.9%	-10.8%	-12.7%	-32.2%
48									
49	Orbiter LO T/W	0.966	0.681	0.649	0.661	0.633	0.576	0.530	0.000
50	Booster LO T/W	1.446	1.832	1.758	1.812	1.601	1.774	1.783	1.812
51	Liftoff T/W difference	0.480	1.151	1.109	1.251	0.969	1.198	1.253	1.812

	Vehicle Summary - W&S	KH M7 staging		
	Case #	12	13	14
	Case Name	KHS7	KHP7-104	KHP7-90/95
1	Architecture	KHS7	KHP7	KHP7
2	Staging Mach	7.00	7.00	7.00
3	Crossfeed used?	n/a	n/a	n/a
4	Booster Propellants	LOX/RP	LOX/RP	LOX/RP
5	Booster Throttle Settings (%)	100%	100%	100%
6	Orbiter Propellants	LOX/LH2	LOX/LH2	LOX/LH2
7	Orbiter 1st stg Throttle Settings (%)	0%	104%	90/95%
8	Orbiter 2nd stg Throttle Settings (%)	104%	104%	104%
9	Liftoff T/W	1.30	1.30	1.30
10	Staging T/W (at vac)	1.00	1.00	1.00
11	For PBnof: % of Orb prop used during stg 1	n/a	33.0%	25.8%
12				
13	Total Dry	0.84	0.96	0.87
14	GLOM	1.06	1.25	1.13
15	Aref (B+O)	0.73	0.89	0.81
16	Total Ascent Prop	1.11	1.32	1.19
17				
18	Booster GLOM	1.36	1.30	1.27
19	booster useable propellant	1.44	1.38	1.36
20	booster burnout weight	0.89	0.94	0.91
21	booster dry weight	0.85	0.92	0.88
22	booster theoretical wing area	0.81	0.79	0.76
23	booster engine thrust(vac) at 100% pwr level	1.40	1.35	1.28
24	booster engine exit area (each)	0.58	0.56	0.53
25	Booster # of engines	1.00	1.00	1.00
26				
27	Orbiter GLOM	0.66	1.20	0.95
28	orbiter useable propellant	0.61	1.21	0.94
29	orbiter burnout weight	0.72	1.01	0.85
30	orbiter dry weight	0.71	1.01	0.84
31	orbiter theoretical wing area	0.64	1.01	0.87
32	orbiter engine thrust(vac) at 100% pwr level	1.10	1.47	1.26
33	orbiter engine exit area	0.86	1.47	1.26
34	orbiter # of engines	0.50	0.50	0.50
35				
36	booster length	0.81	0.80	0.80
37	booster diameter	0.80	0.79	0.78
38	booster wingspan	0.89	0.88	0.87
39				
40	orbiter length	0.88	1.07	0.98
41	orbiter diameter	0.86	1.07	0.98
42	orbiter wingspan	0.80	1.01	0.94
43				
44	Dry weight vs Case 1	-16.3%	-4.3%	-13.4%
45	GLOM vs Case 1	6.5%	24.5%	12.8%
46	Booster dry weight vs Case 1	-8.7%	-8.4%	-11.8%
47	Orbiter dry weight vs Case 1	-29.1%	1.0%	-15.5%
48				
49	Orbiter LO T/W	0.000	0.596	0.562
50	Booster LO T/W	1.581	1.589	1.538
51	Liftoff T/W difference	1.581	0.991	0.976

Table 1: Summary of TSTO Vehicle Trade Study Results