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Low Recurring Cost, Partially Reusable Heavy Lift Launch Vehicle

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This paper presents a partially reusable, two-stage-to-orbit launch vehicle concept for delivering 65 metric ton payloads to low Earth orbit. A winged booster and an expendable core stage each use identical main propulsion, thrust structure, and propellant feed systems. For both stages, four 745,000 lbf thrust, RS-68 oxygen/hydrogen rocket engines, presently used on the Delta-IV launch vehicle, are used. The booster, which does not require reentry thermal protection, ascends to a Mach 2.4, 81,000 ft altitude condition, separates from the core stage, and glides back to a runway landing. Sixty-five metric tons in orbit would be enabling to a variety of exploration missions, including very large telescope emplacement missions, robust outer planet missions, and others requiring large payload masses or volumes. Use of a reusable booster, designed for maintainability and affordability, would, in combination with an expendable core using common propulsion, allow for significant reductions in recurring costs compared with a totally expendable vehicle with similar payload capabilities.

I. Introduction

LAUNCH vehicles capable of delivering 65 t (143,000 lb) to low Earth orbit (LEO) would be able to uplift the heavy components required for a variety of exploration missions, including delivery of lunar surface and Earth–sun libration point telescopes, Jupiter outer moon orbiters, Saturn Titan landers and atmospheric probes, commercial platforms, and other missions requiring large payload masses or volumes. A conceptual two-stage-to-orbit (TSTO) launcher, capable of delivering large payloads and in-space transfer stages to a 280 km^2 (150 n mile^2) orbit, was developed with a view to a significant reduction in recurring costs as compared with the shuttle and to several new, totally expendable, heavy-lift launcher concepts currently under consideration. The 65 t capability is about 60% of the capability of the Saturn V, over twice the lift capability of the shuttle, and almost three times the capability of the Delta-IV heavy rocket, which deliver about 110 (242,000), 27.5 (60,600), and 25 t (55,000 lb) to LEO, respectively, when launched due east from Kennedy Space Center into a 28.5 deg inclination. The glideback booster TSTO system consists of an expendable oxygen/hydrogen core stage and a reusable O2/H2 booster. A key feature of this vehicle is common tankage and propulsion systems among the stages; both use identical tankage cylinder diameter and dome geometries, identical aft thrust structure, and identical main propulsion systems (which consist of four Rocketdyne RS-68 engines). In this way, both stages are assembled on the same production line with the most expensive elements and major subassembly being identical.

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II. Rocket System

A simple winged, fully reusable, glideback booster is shown in Fig. 1. Parallel-burn/cross-feed is used from liftoff to separation, so that the core stage is fully loaded with propellant at staging; all boost-phase propellant is contained in the booster tanks. The rocket incorporates aluminum-lithium forward and aft cylindrical propellant tanks, both of which are integral and load bearing. The LO2 tank forms part of the forward fuselage. Shown in Fig. 1 are locations for the forward gear stowage, forward attachment to the core stage, main gear stowage (two places) LO2 and LH2 cross-feed umbilicals aft attach points, liftoff umbilicals (two places), and LH2 tankage which forms part of the fuselage. The booster attach point is at the core stage interstage region. Easy access is provided to subsystems, which are installed in the wing/body fairing forward of the wing carry-through structure. The glideback booster uses wing tip effectors deployed for yaw control and energy management. Each of the gimballed/throttleable engines has slight modifications from standard RS-68 engines for improved reusability and maintainability.

The aft fuselage of each stage contains identical thrust structure, four RS-68 main engines, and their associated feed line and gas pressurant plumbing provisions, the exception being that the aft fuselage of the booster does not require pad attachment provisions, and the aft fuselage of the core stage, although having the same geometry as the booster, would have some detail changes to reduce cost, because the core stage is expended.

The booster stages and returns from a low-energy condition, greatly simplifying its design and operation, and requires no reentry thermal protection system or reaction control system (RCS). This simple booster is designed for ease of maintenance: no toxic propellants or fluids of any type are used; all hydraulic systems and their associated high-pressure fluid lines have been eliminated. The booster uses electromechanical actuators exclusively run by three gas turbine/generators for redundancy (either of the three would provide adequate power for the system). For the portion of the booster trajectory that is above the feasible operating altitude for the power generation gas turbines, the craft would switch to battery power. The objective is to eliminate the problematic and high-maintenance monopropellant auxiliary power unit system such as the hydrazine system used by the shuttle orbiter.

The core stage is shown in Fig. 2; it would incorporate auxiliary thrusters for RCS and precise orbit insertion. These could possibly

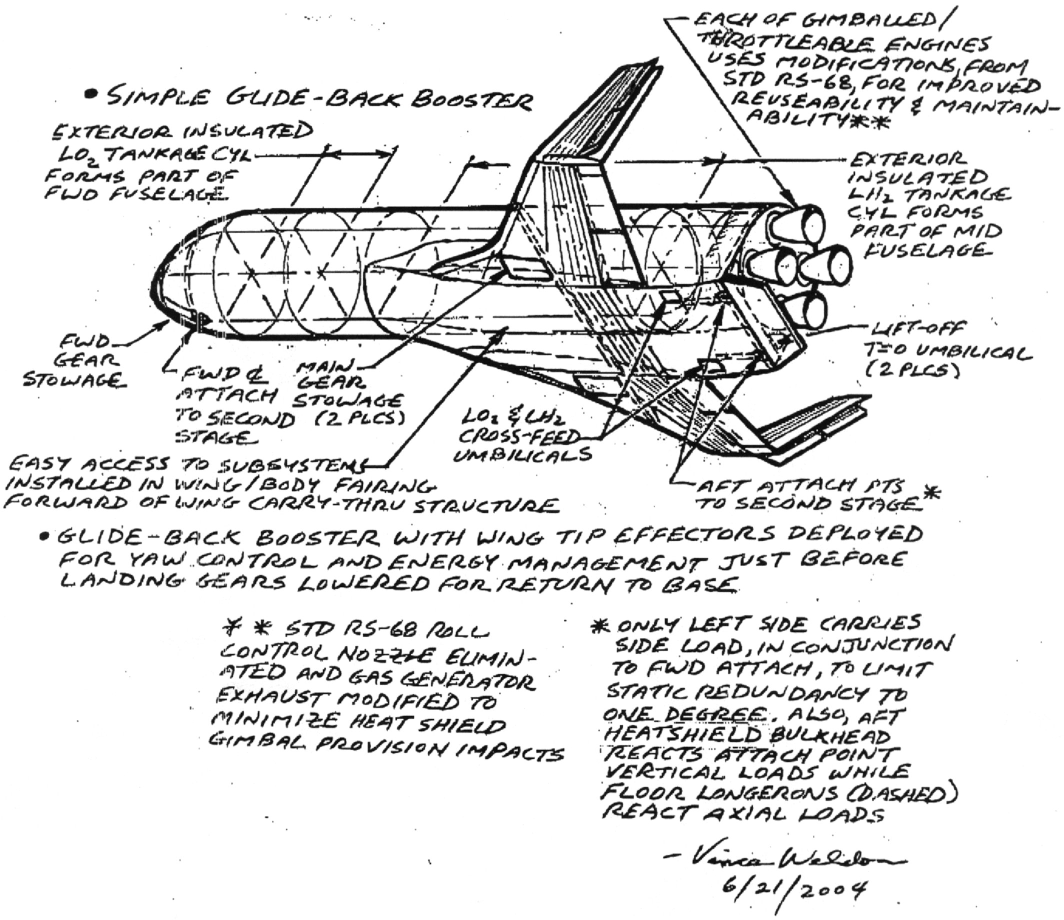

Fig. 1 Mach 2.4 staged, glideback booster.

use residual main propulsion propellants. Much of the internal and nontankage load-bearing interstage structure is composite material. Payload fairing houses a payload of 7.3 m (24 ft) in diameter by 18.3 m (60 ft) in length. The fairing itself is 30 m (99 ft) in length and 7.6 m (28 ft) in diameter. The core stage is 95 m (313 ft) in total length and the booster is 51 m (167 ft) in length. Pad support is provided on the core stage at four points. For information on other TSTO systems see [1,2].

III. RS-68 Engine

The RS-68 is the first new large liquid-fueled rocket engine to be developed in the United States in 25 years. Designed for the Boeing Delta IV family of evolved expendable launch vehicles, the bell-nozzle RS-68 uses a simplified design philosophy resulting in a drastic reduction in parts compared with current cryogenic engines. This design approach results in lower development and production costs. RS-68 thrust is 650,000 lbf at sea level and 745,000 lbf at vacuum, making it the largest liquid oxygen-liquid hydrogen booster in existence. The engine mixture ratio is 6.0, vacuum I_{sp} is 410 s, weight is 14,561 lb, chamber pressure is 1410 psia, and nozzle expansion ratio is 21.5. The standard RS-68 roll control nozzle is eliminated and the gas generator exhaust is modified to minimize heat shield gimbal provision impacts.

IV. Flight Profile

After takeoff, the rocket combination climbs to a 24,695 m (81,000 ft) altitude, Mach 2.4 condition, at which time the booster separates and begins its glideback return. Dynamic pressure Q at staging is 220 psf. Maximum Q is 610 psf at 60 s into the flight. The core's payload fairing is staged at Mach 4.35 and 92,000 m (302,000 ft). The core stage ascends to a 280 km^2 (150 n mile^2), 28.5 deg LEO via direct ascent; it requires no orbital maneuvering system. Flight acceleration is limited to 3.0 g. The RS-68 engines are throttled during ascent to 58%. Vehicle altitude and angle of attack are plotted vs time of flight in Figs. 3 and 4.

V. Performance

The Optimal Trajectory via Implicit Simulation (OTIS) ascent trajectory analysis used preliminary aerodynamics and weights estimates. What is presented is considered to be a concept for which further concept assessment is warranted, rather than a concept which has been fully analyzed at a conceptual study level. Payload to LEO performance, 65 t, is achievable with a single engine out on the core stage during ascent, i.e., the vehicle has enough propulsive margin that it can suffer an engine shutdown anywhere during the flight and still achieve orbit with its full payload. vehicle gross liftoff weight (GLOW) is 1652.9 t (3,644,000 lb). Booster stage propellant and inert mass values are 555.7 t (1,225,000 lb) and 98.0 t (216,000 lb), respectively; core stage propellant and inert mass are 862.3 t (1,901,000 lb) and 63.1 t (139,000 lb), respectively. Faring mass is 9.1 t (20,000 lb). Booster stage propellant mass fraction (PMF) is 0.85; core stage PMF without payload and fairing is 0.93, which compares to 0.96 for the shuttle external tank.

VI. Upgrade to 74 Metric Ton Capability

A brief analysis was also conducted to examine the potential for a performance upgrade of the baseline vehicle. It was determined that it would not be practical to add a centerline engine to the reusable booster stage because it would require about 25% more tankage volume as well as a major redesign to the aft compartment, plus a substantially larger wing [for proper center of gravity (c.g.) placement].

However, it would be relatively inexpensive to add a centerline engine to the expendable core stage. The cylindrical tanks could be

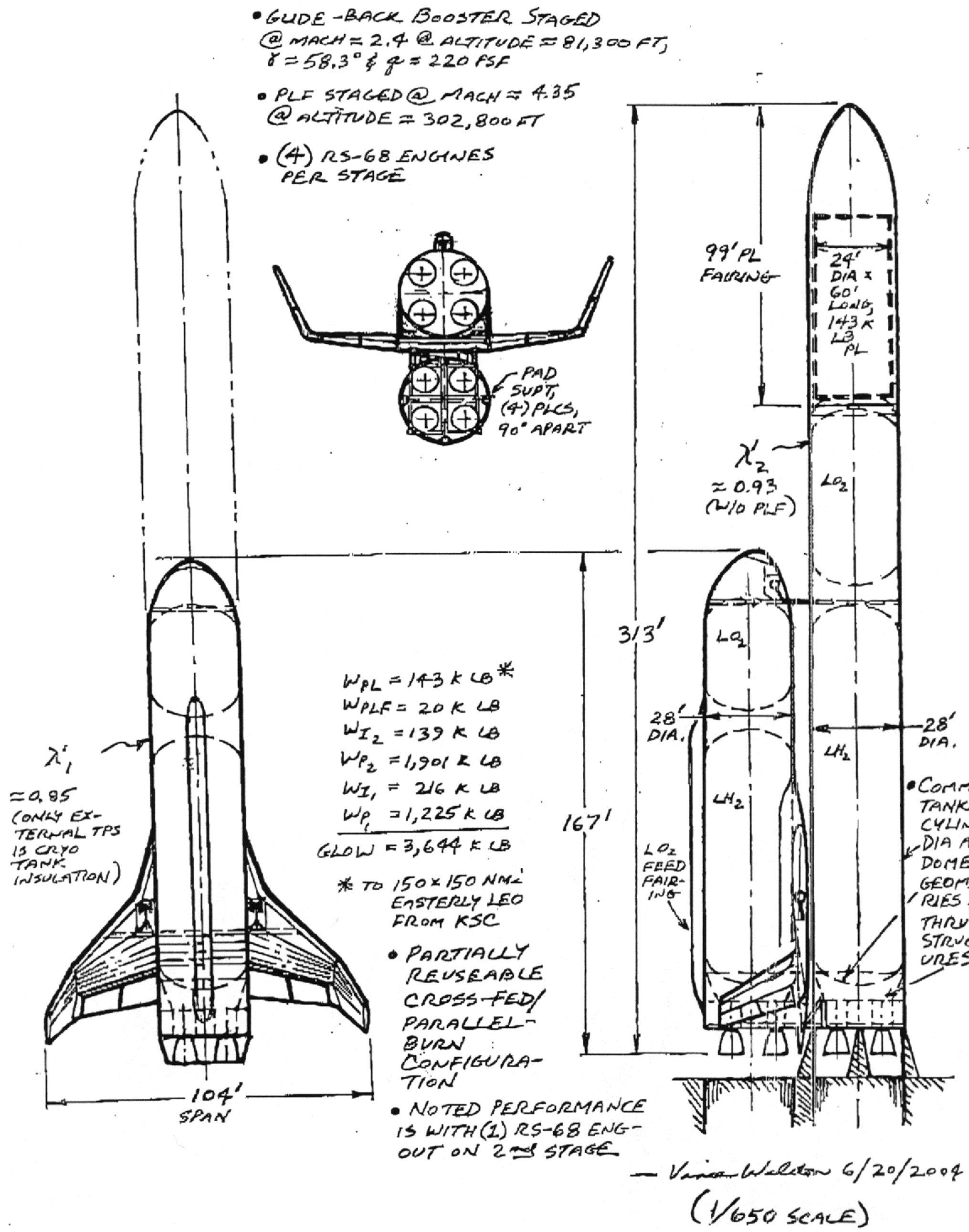

Fig. 2 Launcher views and vehicle data.

stretched and there is sufficient space for the added engine and its feed subsystem. This upgrade would also be compatible with RS-68 gimbal capability for overall c.g. tracking during the parallel-burn portion of the launch trajectory. It was found that this upgrade would allow a payload to LEO increase to 74 t (163,000 lb), a 9.1 t (20,000 lb) increase, which would be potentially very useful. The staging Mach number would be reduced to about 1.8, allowing an even more benign return for the reusable booster.

VII. Comparisons to the Design Complexity of the Shuttle

Reduction in recurring cost is an important consideration in launch vehicle design. The shuttle system, and example of a reusable system, did not achieve low recurring costs as originally envisioned in the early 1970s, in part because of excessive complexity. Four examples will be given.

First, the shuttle's main propulsion system (SSME), though high in performance, is complicated and operates very near the edge of its performance envelope; the SSME requires 28 unique subsystems for support from the vehicle or ground. Second, the shuttle requires a great variety of fluids for operation (it flies with 28 different fluid commodities) and several of these are toxic; each fluid has to be procured and controlled according to specifications. There are 102 total unique subsystems that require fluid servicing for each launch and several using the same commodity (17 separate helium servicing locations). Third, 24 mechanical component mating operations are required between one SSME and the orbiter (a total of 72 for all three SSMEs) and 12 electrical component matings are needed for each SSME (a total of 36). Fourth, there are 13 constricted/closed compartments on the shuttle. Closed compartments that provide possible entrapment of combustible gases/fluids require the addition of purge systems, hazardous gas detection systems, and corrective actions, when required, to provide safe control of the system [3], all of which drive the need for added ground infrastructure, resulting in increased cost and turnaround time. Confined spaces limit access for planned operations and unplanned maintenance, adding to turnaround time, and decrease the safety of the operations.

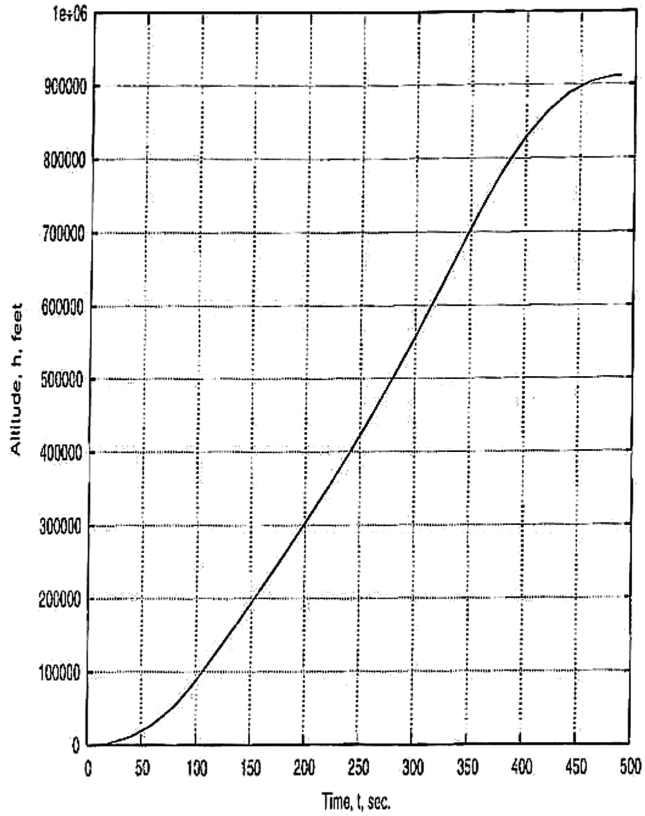

Fig. 3 Altitude vs time.

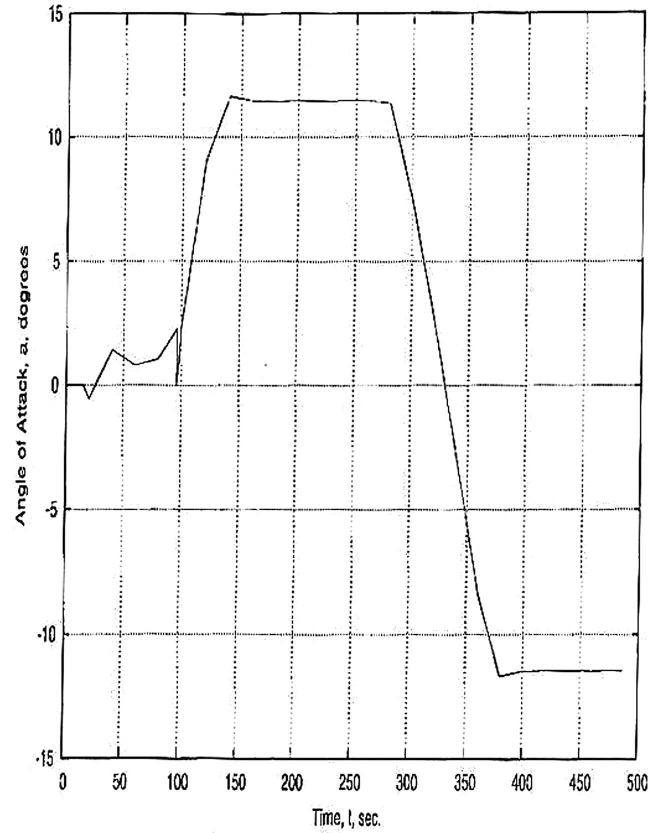

Fig. 4 Angle of attack vs time.

These four examples are representative of many that could be chosen; these indicate a lack of integration of flight functions to require the minimum ground infrastructure, flight hardware logistics support, and minimum sustaining engineering [4]. In all, the number of *planned* shuttle maintenance actions between missions is about 2200; the number of *unplanned* maintenance actions between missions averages about 800 [4].

Conversely, the reusable booster of the TSTO system described here avoids these major impediments to low recurring costs. The reusable portion, the booster, returns from a very benign staging condition (Mach 2.4) rather than LEO. It requires no RCS or orbital maneuvering system. The main propulsion system of both the booster and core is much simplified compared with the shuttle's SSMEs. (Solid motors, which cannot be shut down once started, are not used.) The number of fluids on board both stages is kept to an absolute minimum; none of them are toxic, and the total unique subsystems that require fluid servicing for each launch are reduced significantly vs the shuttle system. The number of closed/constricted compartments requiring purge and hazardous gas detection systems has been reduced significantly.

Furthermore, this TSTO, a design that is keyed to ease of maintenance and sustainability, capitalizes on several simple but effective methodologies that have been shown in a variety of studies [3–6] to aid in minimizing costs. First, there are no centralized hydraulic systems on either stage. Second, both stages use identical main propulsion systems, and no engine development is required (though slight modifications to the RS-68s are necessary). Third, no new technology development is required for either stage, and fourth, this design facilitates use of existing infrastructure (present engine, tankage, interstage production locations). Flight turnaround time is reduced through operational simplicity in the architectural design, reduced dependency on specialized equipment, improved diagnostics tools like system health management, and increased margins. The objective is heavy lift capability at lower costs than fully expendable heavy lift systems currently under study, which can be built without the need for new facilities, with tankage and interstage fabrication machinery that is presently in use, with engines that are presently in production, and a significant net reduction in personnel requirements.

VIII. Reduction in Recurring and Life Cycle Costs

Each space shuttle orbiter was intended to fly 10 flights per year each without extensive maintenance and recertification between flights (expected 160 h turnaround). However, design complexity and hardware dependability only permits less than four flights per year per orbiter. The shuttle has averaged about 100 component replacements per flight with about 400 expendable or limited life parts [4]. The SSME initial design life projection was 55 flights before entering depot cycle, but limited life hardware has required extensive labor, time, and engine depot support, resulting in high costs per flight. At the time of its inception, the reliability requirements flow-down necessary to support the design life estimate were not well understood. The crucial and essential tasks of balancing the design life requirements with safety and maintainability objectives were less than effective.

A very large shortfall exists in the shuttle's life cycle cost projections because they were based on allocations that never came into fruition, e.g., 29.5 t (65,000 lb) to orbit each flight and 40 launches per year using four orbiters. Also the design, development, test, and evaluation cost projection had a large shortfall because of immature technologies, causing an extended schedule for this development activity. Allocations of the operational functions could not be met because there was insufficient engineering management processes in place to provide the necessary control required. Consequently, the shuttle is a high recurring cost system.

The conceptual work leading to this partially reusable TSTO design originated in the desire to move away from high recurring cost and high life cycle cost (whether reusable or fully expendable) by balancing design requirements with maintainability, sustainability, and affordability objectives. The result of this approach has led to the present reusable/expendable configuration for heavy lift applications.

IX. Summary

This report has presented a partially reusable, TSTO concept for heavy payload delivery. The choice of booster staging condition, the use of identical propulsion, thrust structure and propellant feed systems among the two stages, the choice of relatively low-cost, high-thrust RS-68 engines, the elimination of maintenance intensive, centralized hydraulic systems, and the reduction in fluid types and unique servicing operations, among other selections, led to a significantly lower recurring cost, reduced life cycle cost flight system. Reductions in recurring costs can be achieved if the functional requirements and design/flight methodology for the reusable element (in this case, the booster) are focused on maintainability, sustainability, and affordability, as well as on commonality with the expendable element (in this case, the core stage). Minimization of development costs can be achieved if present construction facilities and production lines are used.

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