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Two-Stage Launch Vehicles for Heavy Payloads

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Four approaches are presented to configuring large, all-rocket, two-stage-to-orbit launch vehicles for delivering heavy payloads to low Earth orbit. The payload capability for each configuration is 176,000 lb launched due east into a 220-n mile circular orbit. This capability was chosen so as to be comparable to the payload capability of the shuttle-derived Magnum expendable heavy lift launch vehicle concept characterized by NASA. In the first option presented, a reusable, winged stage is used to boost a parallel burn, expendable core stage to low Earth orbit. For the second option, both the booster and orbiter are winged, fully reusable stages. The third option differs from the second only in the fuel type used by the booster stage. The fourth configuration differs in that the winged, reusable orbiter utilizes an expendable payload shroud, rather than an internal payload bay. Its forward shroud is mounted to the orbiter's nose structure via a special structural attachment. Results indicate that a heavy-lift Earth-to-orbit strategy should consider using a shared reusable booster. The booster should be a common component of another two-stage-to-orbit launch system, to boost smaller core stages. This would allow recouping the boosters' initial nonrecurring costs across a larger number of missions and programs.

Introduction

THE goal of this study was to design a flexible, cost-effective, two-stage-to-orbit (TSTO) launch system capable of placing into low Earth orbit (LEO) the heavy components required for beyond geosynchronous Earth orbit (GEO) human exploration missions, such as human Mars and lunar missions; lunar surface telescopes; for emplacement of space solar power satellites; large, next-generation space telescopes; or commercial platforms, space station upgrades, or any other mission requiring large payload masses or volumes. The starting point for the study was to take the current NASA shuttle-derived Magnum heavy-lift launch vehicle concept as a point of comparison. The TSTO concepts presented herein were configured to lift the same payload mass (and payload volume) to the same final orbit as the Magnum,[1] which was conceived to deliver a 176-klb (80-metric-ton) payload launched due east into a 220-n mile, 28.5-deg circular LEO. The 176-klb payload represents a sizeable capability that would make possible a great variety of programs that might otherwise be impractical due to the mass and volumetric constraints of smaller launch systems. The TSTO designs would be comparable in terms of the payload mass (and payload bay size) delivered to orbit, but in other respects would not necessarily be similar to the Magnum vehicle.

Four approaches to configuring large, all-rocket-propulsion TSTO launch vehicles are presented in this study. For all options, the two stages, booster and core stage, operate in a parallel burn mode, with all engines of both stages thrusting at liftoff. For each configuration, the core (or orbiter stage) utilizes cryogenic H_2/O_2 propellant. In the first option, a reusable, winged rocket stage is used to boost an expendable rocket core stage to LEO, with the booster staging at an appropriate altitude and flying back to a runway landing. The booster utilizes rocket propellant fuel one/ (RP-1/) O_2 propellant. In the latter three options, both the boost and core stages are winged, reusable vehicles. Options 2 and 3 are differentiated by booster propellant choice; for option 2, the booster utilizes RP-1/O_2 and for option 3, H_2/O_2. For the fourth option, both boost and orbiter stages are winged and reusable, though in this case the orbiter carries an expendable payload shroud that is not returned from LEO. Here the orbiter has no internal payload bay structure as do options 2 and 3; the payload shroud is held over the orbiter nose cone by a special transition structure that is jettisoned before reentry. For options 2 and 3, the payload bay is positioned between the oxidizer and fuel tanks. Each of the four configurations can accommodate a payload 92 ft in length. Table 1 lists these four all-rocket TSTO options.

Design Options and Assumptions

Like the Magnum vehicle, each of these TSTO vehicles is configured to deliver 176 klb to 220-n mile circular LEO at 28.5 deg. Initially, the main propulsion system (MPS) boosts the vehicle to a 100×220 n mile phasing orbit; the vehicle's orbital maneuvering system (OMS) provides boost to the final 220-n mile circular orbit. The OMS is utilized again for deboost from orbit for reentry. MPS engines for the booster are either the O_2/RP-1 Rocketdyne RS-76 or the O_2/H_2 Rocketdyne RS-68. Main engines for the core stage are O_2/H_2 Russian RD-0120 engines only. A single booster engine out capability is carried for each TSTO option. The engines have single position nozzles. The OMS system for the core vehicle utilizes O_2/H_2 propellant. Reaction control system (RCS) propellant is O_2/ethanol. Vehicle diameters of 27, 30, and 33 ft were evaluated, and for each case, the payload bay or shroud diameter varied with the vehicle body diameter.

During the boost phase of the ascent, each TSTO option utilizes MPS propellant crossfed from its booster to its core stage, so that the core stage tanks are full at separation. The RP-1 fueled boosters (options 1, 2, and 4) carry a separate H_2 tank for crossfeed to the core vehicle. Aerosurfaces include wings sized for a landing wing loading of 70 lb/ft^2, dual vertical wing tip fins, forward deployable horizontal canards, and an aft body flap. Maximum g loads allowed during ascent simulation were 4.5. Core stage thrust to weight T/W at separation was typically 1.2. Integral load bearing tankage and interstage structures are all cylinders, with the H_2 tanks made of composite material and the RP-1 and O_2 tanks made of aluminum lithium. Interstages were also of composite material. The weight per area values used for the vehicles thermal protection system (TPS) material, distributed over the vehicles external surface area, is 1.0 lb/ft^2 for the reusable orbiter stages and 0.25 lb/ft^2 for each booster. Each of the boosters considered utilizes identical postboost flyback system elements, which allow it to return to a runway landing near the launch area. The boosters utilize turbojet engines of sufficient thrust to provide low-speed flyback for return. The JP-8 jet propellant, tankage, installation, and turbojet elements collectively weigh 65,000 lb. This number was taken directly from NASA-sponsored analysis on booster flyback.

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Analysis Tool Used in Evaluations

The conceptual design of Earth-to-orbit (ETO) vehicles is a complex, iterative process requiring the synthesis of a variety of engineering disciplines. The launch vehicle design code[2] (LVDC) was used to generate data for this analysis. LVDC is a multidisciplinary, modularly structured software tool for conceptual design, analysis, and evaluation of a broad range of future launch systems. LVDC uses specialized conceptual design programs; these engineering software tools are linked in a modular fashion to form an iterative computational chain for designing and optimizing a variety of vehicle types. At present, the main applications of LVDC include generating and evaluating fully reusable single-stage-to-orbit vehicles, fully and partially reusable TSTO, multistage expendable launch vehicles, air-launched vehicles, and combined rocket/airbreather (ramjet, scramjet) concepts. The vehicles may be winged or ballistic and launched vertically or horizontally. Tandem staging and parallel staging is selectable; with the parallel staged vehicle, propellant transfer can also be modeled. Booster flyback capability can also be modeled. System interrelationships and functional dependencies too extensive for hand calculation are mathematically modeled and integrated to provide a detailed parametric study tool. The program's capability for reiteration facilitates rapid evaluations and trade studies.

The programs sizing and configuration algorithms are coupled with flight routines to simulate propulsive and aerodynamic flight to orbit. Code outputs include linear dimensions, masses, volumes, areas, forces, pressures, flight times, altitudes, velocities, staging events, lift and drag coefficients, wing loadings, and others. Subsequent design iterations are run to tailor the design to specific criteria of interest, such as minimum dry mass, gross takeoff mass, or some other figure of merit. The combination of the vehicles thrust profile, aerodynamic behavior, structural content, and configuration elements forms an internally consistent blueprint for a launch vehicle concept.

The aerodynamics module relies on a blend of simplified aerodynamic theory and empirical relationships, which result in acceptable agreement with wind-tunnel test data. The subprogram generates a table of axial and normal aerodynamic force coefficients as a function of Mach number and angle of attack based on airframe geometry determined in the airframe/subcomponents system weights module. The propulsion module computes composite vehicle I_{sp} as a function of throttle, altitude, mixture ratio, nozzle exit area, and others. The ascent trajectory is integrated, using the actual I_{sp}, thrust, and mass at every altitude increment to get the correct velocity gained. Lift, drag, dynamic pressure, thrust forces, and other axial and normal forces are determined. Maximum flight loads are fed into the structural sizing module to determine the required interstage and tank wall thickness requirements. The simulation throttles and/or shuts down engines in flight to keep the vehicle within predetermined limits.

Though the simulated trajectory profiles generated for the four TSTO options are each slightly different, a typical MPS delta-velocity ΔV budget for the group is listed in Table 2. This total ΔV gets the orbiter or core stage up to a 100×220 n mile phasing orbit. The OMS provides the additional ΔV for circularization into 220 n mile as well as providing ΔV for deboost into a reentry path.

Magnum Vehicle Configuration

Three Magnum vehicle configurations are shown in Fig. 1. The Magnum's 5.7×10^6 lb gross liftoff weight (GLOW) falls midway between those of the shuttle (4.5×10^6 lb) and the Saturn V

Table 1 TSTO configuration options

Option	Booster type	Booster propellant	Core stage type	Core propellant	Payload (P/L) location
1	Reusable	O_2/RP-1	Expendable	O_2/H_2	Top shroud
2	Reusable	O_2/RP-1	Reusable	O_2/H_2	Internal P/L bay
3	Reusable	O_2/H_2	Reusable	O_2/H_2	Internal P/L bay
4a	Reusable	O_2/RP-1	Reusable	O_2/H_2	Top shroud
4b	Reusable	O_2/RP-1	Reusable	O_2/H_2	Piggyback

Table 2 Typical TSTO ascent-to-orbit ΔV budget

Velocity, ft/s	Description
25,787	Final periapsis velocity of 100×220 n mile phasing orbit
−1,340	Initial surface velocity at 28.5° latitude
24,447	ΔV increase required of MPS, no losses
3,027	Turning, pitch, and backpressure losses
+710	Atmospheric drag losses
+2,171	Gravity losses
5,908	Total losses
30,355	Total MPS ΔV to reach phasing orbit, with losses

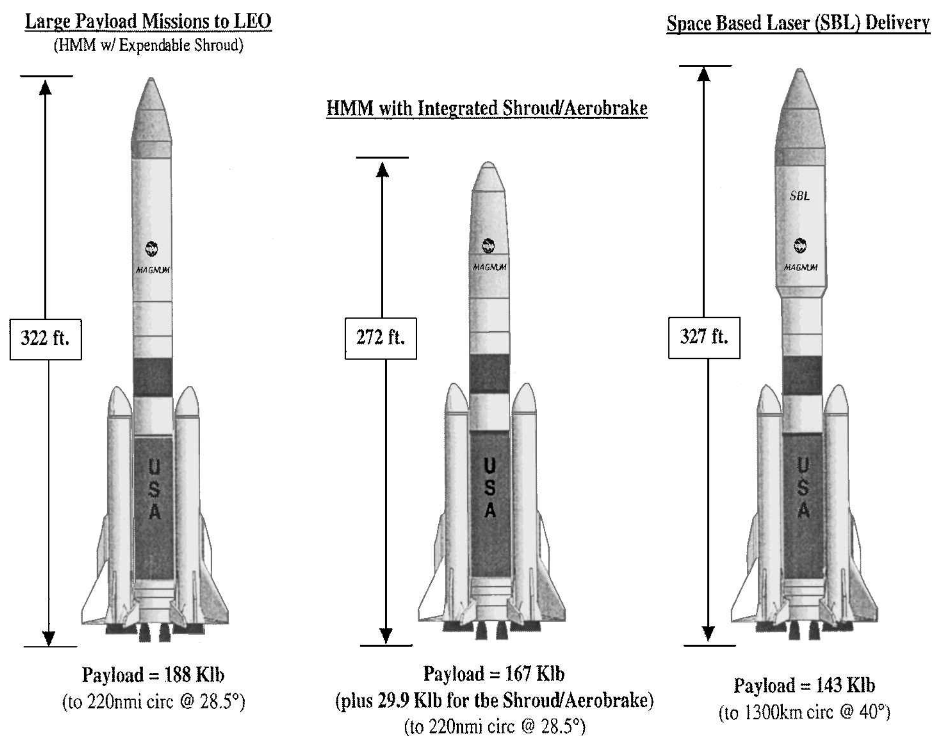

Fig. 1 Magnum launch vehicle configurations.

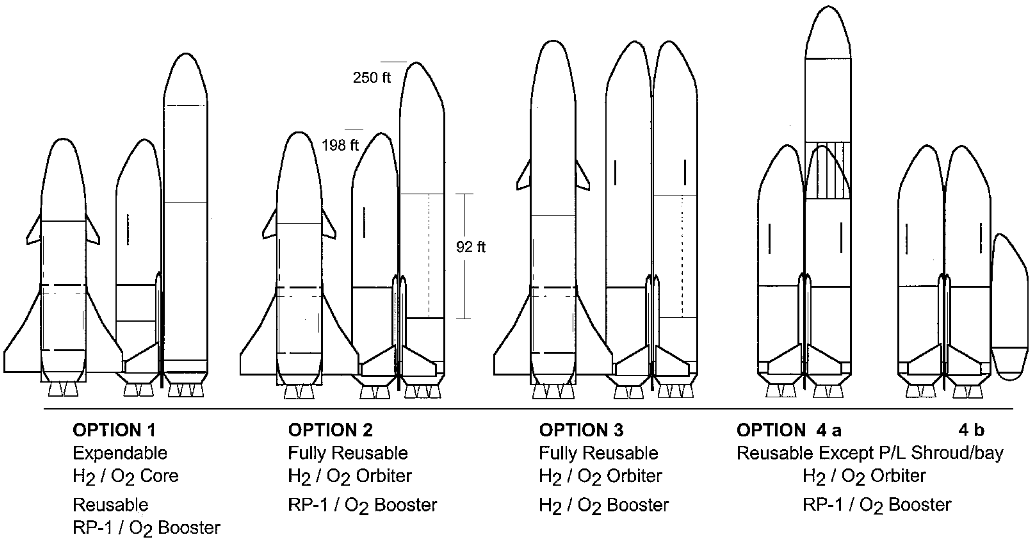

Fig. 2 Four options for all-rocket, heavy-lift TSTO.

Table 3 TSTO configuration advantages and disadvantages

Option 1[a]	Option 2[b]	Option 3[c]	Option 4[d]
		Advantages	
Lower initial costs	Fully reusable	Fully reusable	Fully reusable except shroud
Lighter weight	Smaller booster than option 3	Common engines possible	Potential common external dimensions booster and core
Less complex	Common wings possible	Nontoxic exhaust	Smaller orbiter than options 2 or 3
No core wing/landing gear	Larger choice of RP-1 engines	Same external dimensions for booster and core possible	
Minimal TPS	Fewer engines required than option 3		
		Disadvantages	
Recurring cost of core	Two fuels/engine types	Physically large	Recurring cost of shroud
Two fuels/engine types	Third (H_2) tank on booster	Few large H_2 fuel engines available	No P/L return
Third (H_2) tank on booster		Large number of booster engines required	Abort results in loss of P/L
No abort, no P/L return			Two fuels/engine types
			Third (H_2) tank on booster

[a]Expendable H_2 core, reusable RP-1 booster. [b]Reusable H_2 orbiter, reusable RP-1 booster. [c]Reusable H_2 orbiter, reusable H_2 booster. [d]Expendable shroud H_2 orbiter, reusable RP-1 booster.

(6.4×10^6 lb) GLOWs. The Magnum is a shuttle-derivative configuration.

TSTO Options

The four all-rocket TSTO options considered are shown in Fig. 2. Each uses crossfeed H_2/O_2 propellant from the booster to the orbiter stage so that its tanks are full at separation. The expendable core vehicle, option 1 (Fig. 2, far left), has the advantages of lower initial costs, lighter GLOW and dry weight, and, because the core stage has no return requirement, less complexity (no wings, landing gear, or payload bay). This configuration may accommodate upper stages more easily. Its disadvantages relate to the cores inability to abort and the recurring costs for core production. Option 2 (Fig. 2, second from left), illustrates the all-reusable RP-1/O_2 booster TSTO system. Though the H_2 fuel orbiter and RP-1 fuel booster vehicles are typically of different sizes, it may be possible for their wings to be identical because their landing weights can be made very similar. Identical wing structure would provide some commonality benefit and reduce design and development costs. Having two different fuels on the same vehicle, and including a third tank on the booster to supply crossfed H_2 to the orbiter, are disadvantages.

Option 3 (Fig. 2, third from left) is the all-reusable H_2/O_2 TSTO. Because of the low density of hydrogen, this design is physically larger than other options. An advantage is the potential for the booster and orbiter to have identical external dimensions, providing full aerodynamic commonality and partial structural commonality. Because physical size is largely a function of propellant loading, the designer can vary the separation condition to set the propellant split so that the lengths are equivalent. Also, common engines would be possible, though not necessarily optimal. Another advantage of H_2/O_2 is nontoxic exhaust (H_2O).

Advantages of the fourth option (the reusable vehicle with expendable shroud, Fig. 2, far right) would be its shorter orbiter size, allowing the external dimension to be matched with that of the booster. Also, wings and landing gear mass would be less, as would the TPS weight because there is less exposed surface area to protect on reentry. One viable configuration variation for this vehicle is to utilize an aft-mounted, external payload module instead of a top-mounted shroud, option 4b of Fig. 2. The external module would be placed in a piggyback position with its forward attach point at the structural interstage between the orbiter fuel and oxidizer tanks. Its aft attach point would be at the aft thrust structure. Various size external payload modules could be used, including those housing passenger modules and upper stages. Unenclosed payloads could be mounted as well, such as winged vehicles. Such a configuration change would reduce the weight load to be supported by the top of the orbiter (the forward interstage) but would increase the cross-sectional area and, thus, increase the in-flight aerodynamic drag loads. A complete list of advantages and disadvantages for each of the four is given in Table 3.

Engine Candidates

Three engine candidates were considered for the vehicles in this analysis; performance data for each are given in Table 4. These include the 1000-klb vacuum thrust O_2/RP-1 Rocketdyne RS-76, the 440-klb O_2/H_2 Russian RD-0120, and the 745-klb O_2/H_2 Rocketdyne RS-68 engines.

Option 1 TSTO: Expendable Core, Reusable Booster, RP-1 Fueled

Key weight and performance characteristics of the option 1 expendable core TSTO are given in the first column of Tables 5–7.

Table 4 Main propulsion engines used in analysis

Engine	Thrust, vacuum, klbf	I_{sp}, vacuum, s	Chamber pressure, psia	Nozzle expansion	Throttling capability, %	Engine weight, lb
RS-76	1,000	340.5	2,645	34.0:1	50	8,720
RS-68	745	410.0	1,410	21.5:1	60	13,500
RD-0120	441	455.0	3,234	87.5:1	45	7,603

Table 5 Propulsion and performance parameters (masses in kilopounds)

Parameter	Option 1		Option 2		Option 3		Option 4a		Option 5	
Stage	Core	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster
Propellant	H_2/O_2	RP/O_2	H_2/O_2	RP/O_2	H_2/O_2	H_2/O_2	H_2/O_2	RP/O_2	H_2/O_2	RP/O_2
Engine	Rd0120	RS-76	Rd0120	RS-76	Rd0120	RS-68	Rd0120	RS-76	Rd0120	RS-76
Vacuum I_{sp}, s	455.0	340.5	455.0	340.5	455.0	410.0	455.0	340.5	455.0	340.5
Thrust vacuum, klb	440.8	1000	440.8	1000	440.8	745	440.8	1000	440.8	1000
Throttle limit, %	45	50	45	50	45	60	45	50	45	50
Total engines	5	6	5	8	8	10	5	8	4	6
Engine out	1	1	None	1	None	1	None	1	1	2
Diameter, ft	27	27	33	33	33	33	33	33	27	27
Height, ft	259	182	250	198	276	276	280	179	182	182
Wing span, ft	n/a	76	88	88	122	109	77	85	76	76
GLOW, klb	3,984		5,832		6,657		5,128		3,407	
Total stage weight	1,418	2,556	1,925	3,907	2,467	4,196	1,752	3,377	904	2,503
P/L weight	176	n/a	176	n/a	176	n/a	176	n/a	60	n/a
Total dry weight	154	289	282	354	414	509	241	347	183	289
Propellant mass fraction	0.860	0.902	0.823	0.916	0.802	0.885	0.831	0.906	0.766	0.902
Vehicle T/W liftoff	1.49		1.39		1.29		1.56		1.43	
MPS ΔV, ft/s	29,708		30,389		30,238		29,831		29,802	
ΔV split, ft/s	22,393	7,315	22,105	8,284	23,147	7,093	21,964	7,867	20,770	9,032
Separation altitude, n mile	27.5/Mach 5.6		32.3/Mach 6.2		29.6/Mach 5.6		27.8/Mach 6.0		31.7/Mach 7.4	

Table 6 Propellant weights for each configuration (masses in kilopounds)

Parameter	Option 1		Option 2		Option 3		Option 4a		Option 5	
Stage	Core	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster
Propellant	H_2/O_2	RP/O_2	H_2/O_2	RP/O_2	H_2/O_2	H_2/O_2	H_2/O_2	RP/O_2	H_2/O_2	RP/O_2
GLOW, klb	3984		5832		6657		5128		3407	
Total stage weight	1418	2556	1925	3907	2467	4196	1752	3377	904	2503
Payload	176	n/a	176	n/a	176	n/a	176	n/a	60	n/a
Propellant burned	1515	1732	2078	3451	2948	2444	1854	2358	1038	1732
Crossfeed propellant	−474	+474	−676	+676	−1157	+1157	−574	+574	−411	+411
Propellant onboard	1041	2206	1403	4127	1791	3601	1280	2932	628	2143
Reserve propellant	12	16	16	25	21	26	11	22	7	16
Residual propellant	3	9	3	13	6	9	3	13	2	9
Startup propellant	16	44	19	62	31	49	19	62	12	44
OMS propellant	11	n/a	17	n/a	17	n/a	14	n/a	7	n/a
RCS, APU propellant	6	2	9	2	12	2	8	2	5	2
Total dry weight	154	289	282	354	414	509	241	347	183	289

Table 7 Vehicle dry weight data for each configuration (masses in kilopounds)

Parameter	Option 1		Option 2		Option 3		Option 4a		Option 5	
Stage	Core	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster
Propellant	H_2/O_2	RP/O_2	H_2/O_2	RP/O_2	H_2/O_2	H_2/O_2	H_2/O_2	RP/O_2	H_2/O_2	RP/O_2
Total dry weight, klb	153.5	289.3	281.8	353.9	414.3	509.1	241.0	346.7	182.6	289.3
Shroud plus support	24.5	n/a	n/a	n/a	n/a	n/a	36.5	n/a	n/a	n/a
Nose structure	n/a	9.1	11.2	10.9	10.6	10.1	19.7	13.7	8.8	9.1
H_2 tank plus valves	30.0	18.2	17.9	13.3	48.4	89.8	21.0	12.3	9.9	18.2
RP tank plus valves	n/a	16.2	n/a	24.5	n/a	n/a	n/a	21.8	n/a	16.2
Interstages struct.	12.5	13.5	15.5	21.1	18.3	18.0	16.0	20.9	8.4	13.5
Structure-P/L bay	n/a	n/a	66.8	n/a	70.0	n/a	n/a	n/a	39.6	n/a
O_2 tank plus valves	12.1	20.8	15.2	30.2	18.8	32.1	14.0	27.2	7.2	20.8
Crossfeed system	2.4	1.5	2.4	1.5	3.1	2.4	2.4	1.5	2.1	1.5
Orbiter-to-booster truss	n/a	3.3	n/a	4.1	n/a	4.2	n/a	3.9	n/a	3.3
Thrust structure	5.8	14.2	6.6	21.7	10.8	21.6	6.6	21.7	4.6	14.2
Propulsion										
Main	38.6	52.6	38.6	70.1	61.6	136.0	38.6	69.8	30.9	52.6
OMS	1.3	n/a	1.5	n/a	1.6	n/a	1.4	n/a	1.1	n/a
RCS	2.6	n/a	3.4	n/a	4.1	n/a	3.1	n/a	2.2	n/a
Aerosurfaces	n/a	25.8	29.2	32.2	62.3	48.5	23.5	31.3	19.8	25.8
Landing gear	n/a	8.1	10.0	10.5	20.9	16.0	7.7	10.3	6.5	8.1
TPS	1.1	4.3	24.0	5.6	29.0	8.2	16.1	5.3	15.2	4.3
Power/avionics	7.6	6.1	7.7	6.5	8.7	8.4	7.9	6.2	6.5	6.1
Flyback elements	n/a	65.0	n/a	65.0	n/a	65.0	n/a	65.0	n/a	65.0
Weight growth	15.0	30.6	31.8	36.7	46.1	48.8	26.5	35.8	19.8	30.6

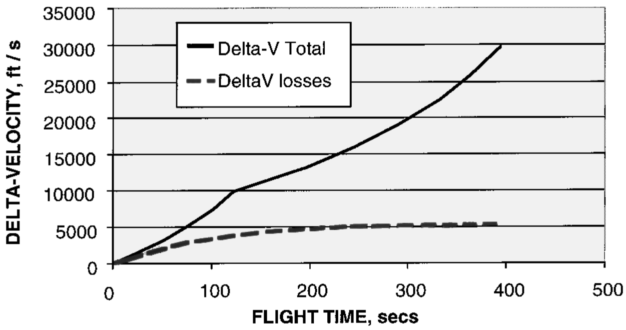

Fig. 3 Option 1 TSTO ΔV vs flight time.

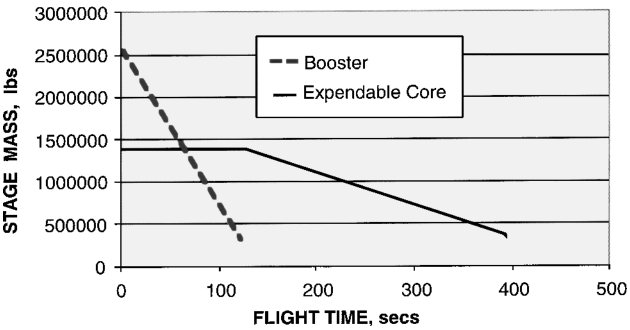

Fig. 4 Option 1 TSTO weight vs flight time.

Vehicle *T/W* is 1.49 at liftoff with single engine out capability on both core and booster stages. The GLOW of the combined stages is 3.98×10^6 lb. The core utilizes five RD-0120 engines, receives 474 klb of crossfeed O_2 and H_2 from the booster during the boost flight phase, and holds 1.04×10^6 lb of propellant for postboost flight. The dry weight for the core is 154 klb, and its total mass is 1.42×10^6 lb.

The booster utilizes six RS-76 engines and separates from the core stage at an altitude of 28 n mile (Mach 5.6). Vehicle total mass is 2.56×10^6 lb, which includes 1.73×10^6 lb of usable and 474 klb of crossfeed propellant. Dry mass is 289 klb. Both the booster and core are 27 ft in diameter. The core is 259 ft in height, the booster is 182 ft, and the boosters wingspan is 76 ft. Delta-velocity and weight are plotted vs flight time in Figs. 3 and 4. The booster provides 7315 of the 29,708-ft/s total ΔV required to the 100×220 n mile phasing orbit. Drag, gravity, and steering losses account for 5206 ft/s of the total. Propellant mass fraction (PMF; equal to propellant/total nonpayload weight) is 0.86 and 0.90 for the orbiter and booster, respectively.

Option 2: Reusable Orbiter, Reusable Booster, RP-1 Fuel

The second column of Tables 5–7 lists characteristics of the option 2, fully reusable, RP-1 fueled booster, H_2-fueled orbiter TSTO. *T/W* at liftoff is 1.39 with single engine out capability on the booster only. With a GLOW of 5.83×10^6 lb, this vehicle is almost 2×10^6 lb heavier than the option 1 TSTO. The orbiter uses five RD-0120 engines, receives 676 klb of crossfed O_2 and H_2 during the boost phase, and holds 1.40×10^6 lb of postboost propellant. Its dry mass is 282 klb; its total mass is 1.93×10^6 lb. The booster utilizes eight RS-76 engines and separates at 32 n mile (Mach 6.2). Its 3.91×10^6 lb total mass includes 3.45×10^6 lb of usable and 676 klb of crossfeed propellant. Dry mass is 354 klb. Both orbiter and booster are 33 ft in diameter. PMF is 0.82 and 0.92 for the orbiter and booster, respectively. Isometric views are shown in Fig. 5. The two vehicles attach wing to wing, near the landing gear structural hard points. Wingspan for both the booster and orbiter is 88 ft. MPS ΔV to phasing orbit is 30,389 ft/s; losses are 5908 ft/s.

Option 3 TSTO: Reusable Orbiter, Reusable Booster, H_2 Fuel

The third column of Tables 5–7 lists characteristics of the option 3 fully reusable, all-H_2 fuel TSTO. Vehicle *T/W* at liftoff is 1.29 with single engine out capability on the booster only. With a GLOW of 6.66×10^6, this vehicle is almost 3×10^6 heavier than the option 1

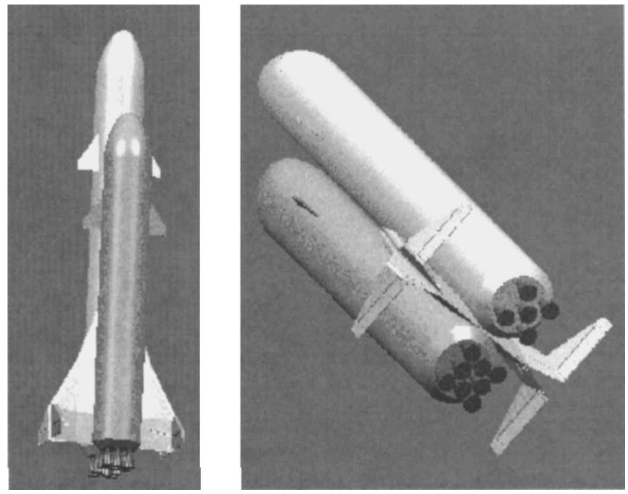

Fig. 5 Option 2 TSTO views.

expendable core TSTO and almost 1×10^6 lb heavier than the option 2 fully reusable, RP-1 booster TSTO. The orbiter has eight RD-0120 engines, receives 1.16×10^6 of crossfeed O_2 and H_2, and holds 1.79×10^6 lb of postboost propellant. This stages total mass is 2.47×10^6 lb, and its dry mass, 414 klb, is nearly 50% heavier than that of option 2 (282 klb). The booster utilizes 10 RS-68 engines, separates at 29 n mile (Mach 5.6), and its total mass, 4.20×10^6 lb, includes 2.44×10^6 of usable and 1.16×10^6 lb of crossfeed propellant. The H_2-fueled booster dry mass is 509 klb. Both option 3 orbiter and booster are 33 ft in diameter and 276 ft in length. (The separation condition was chosen to give equivalent length.) PMF is 0.80 (orbiter) and 0.88 (booster). MPS ΔV splits for the orbiter and booster are 23,147 and 7093 ft/s.

Option 4 TSTO: Reusable Orbiter with Expendable Shroud

Characteristics of option 4a are listed in the fourth column of Tables 5–7. With a GLOW of 5.1×10^6 lb, this configuration is 704 klb lighter than its option 2 counterpart that utilizes an internal payload bay. Vehicle *T/W* at liftoff is 1.56 with single engine out capability on the booster. The orbiter uses five RD-0120 engines, receives 574 klb of crossfeed, and holds 1.28×10^6 lb of postboost propellant. The orbiters total mass is 1.75×10^6 lb, and its dry mass, at 241 klb, is 40 klb lighter than that of the option 2 orbiter. The booster utilizes eight RS-76 engines, separates at 28 n mile (Mach 7.4), and its 3.38×10^6 lb total mass includes 2.36×10^6 lb of usable and 574 klb of crossfeed propellant. Both orbiter and booster are 33 ft in diameter and 179 ft in length (not including the length of the payload shroud). (Again, the separation point was chosen to give equivalent length.) PMF is 0.83 and 0.91. The MPS ΔV splits for the orbiter and booster are 21,962 and 7867 ft/s.

Liftoff Weight Comparisons

Figure 6 lists GLOW values for each concept. The all-H_2-fueled, fully reusable option is the heaviest of the concepts and requires the most engines. As mentioned earlier, the H_2/O_2 RS68 engine was used for this option 3 booster; a higher I_{sp}, staged combustion engine would have improved its performance but would require development. Option 3 GLOW (6.7×10^6 lb) is roughly equivalent to that of the Saturn V (6.4×10^6 lb); option 2 GLOW (5.8×10^6 lb) is roughly equivalent to the Magnum (5.7×10^6 lb). Vehicle procurement cost is strongly related to vehicle dry weight. Detailed dry weights for all configurations are given in Table 7.

Shared Booster TSTO Concept

Obviously, a heavy-lift Earth to orbit (ETO) strategy should consider using a shared reusable booster. The question then centers around what role the heavy-lift program should have in defining such a booster. As an example from this analysis, given the availability of the 2.56×10^6 lb RP-1 fueled booster of option 1 (first column of Table 5), what smaller capacity orbiter could be coupled with it to address other ETO missions? Could a smaller orbiter share major

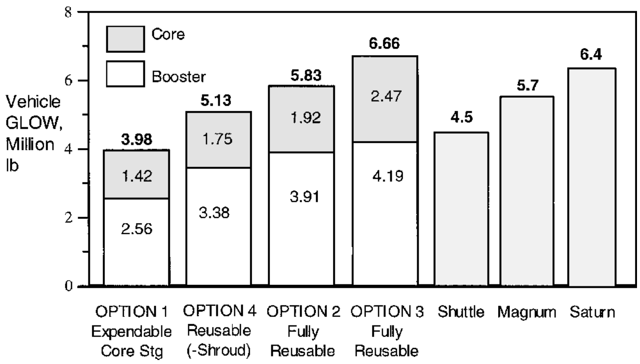

Fig. 6 GLOW comparisons for each option.

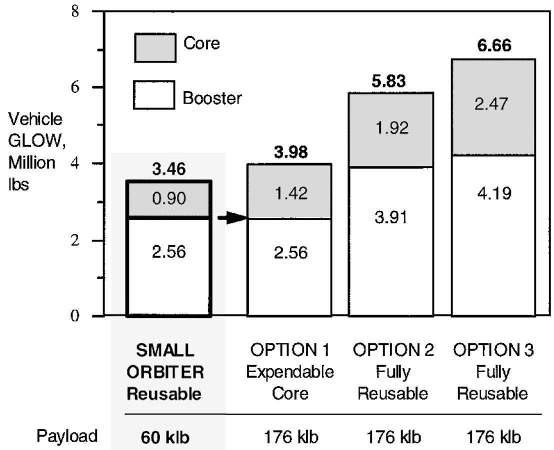

Fig. 7 Common booster with smaller orbiter added to comparison.

subsystems for commonality with the booster? With these questions in mind, a smaller H_2/O_2 reusable orbiter was paired to the option 1 booster (Figs. 7 and 8). This smaller TSTO configuration is capable of inserting a 60-klb payload into a 220×220 n mile, 28.5 deg LEO. The potential exits for this orbiter to have the same outer dimensions as the booster and the same size wing. Weight and performance data is given in the fifth column of Tables 5–7, where it is labeled as option 5. When matched with the option 1 booster, the combined GLOW of this configuration is 3.41×10^6 lb, 2.4×10^6 lb less than the similarly configured but larger option 2 vehicle. Vehicle *T/W* is 1.43 with three engine out capability; two engines on the booster and one on the orbiter can fail at liftoff and the vehicle can achieve its prescribed orbit. Staging Mach number (7.4 at 32 n mile) is slightly faster than the heavy lift concepts. This smaller orbiter has four RD-0120 engines, requires 411 klb of crossfeed propellant, and holds 627 klb of usable postboost propellant. The orbiters dry mass is 183 klb, its total mass is 904 klb, and its PMF is 0.766. Total ΔV is 29,802 ft/s. The booster could be a common component of both

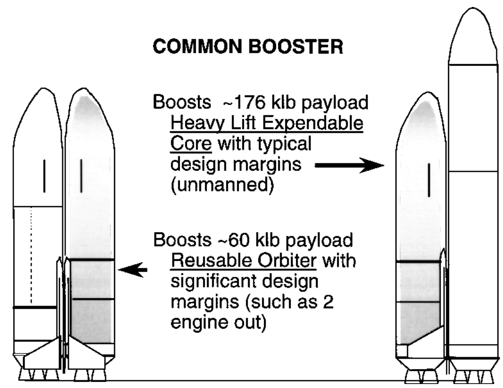

Fig. 8 Common booster strategy.

the larger and smaller launch systems, which would allow recouping the booster's initial nonrecurring costs across a larger number of missions. In Fig. 8, a reusable booster is shown alongside both a large expendable core stage and the smaller orbiter stage.

Conclusions

Four heavy-lift TSTO configurations were evaluated. The entire expendable core/reusable booster option 1 combination is lighter, or about the same weight as, just the booster alone for either of the two fully reusable options (2 and 3). The option 3 all-H_2 vehicle is the heaviest, is physically the largest, and requires the most engines of all of the options considered. The option 4 vehicle is the lightest of the reusable configurations, and would be a good choice if payload recovery is not a driving requirement. Because the number of heavy-lift missions expected per year would be much less than missions flying smaller payloads, making dual use of a booster common to several classes of missions might prove to be economically beneficial. One advantage of pairing the heavy-lift booster with a smaller orbiter would be the robustness gained by the boosters excess thrust capability for this class of orbiter. The pair could be operated with significant design margins (such as multiple engine out) and might achieve human-rating status via the demonstration a sufficient number of successful cargo-only flights.

Acknowledgment

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