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Design Options for Advanced Manned Launch Systems

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Various concepts for advanced manned launch systems are examined for delivery missions to space station and polar orbit. Included are single- and two-stage winged systems with rocket and/or air-breathing propulsion systems. For near-term technologies, two-stage reusable rocket systems are favored over single-stage rocket or two-stage air-breathing/rocket systems. Advanced technologies enable viable single-stage-to-orbit (SSTO) concepts. Although two-stage rocket systems continue to be lighter in dry weight than SSTO vehicles, advantages in simpler operations may make SSTO vehicles more cost-effective over the life cycle. Generally, rocket systems maintain a dry-weight advantage over air-breathing systems at the advanced technology levels, but to a lesser degree than when near-term technologies are used. More detailed understanding of vehicle systems and associated ground and flight operations requirements and procedures is essential in determining quantitative discrimination between these latter concepts.

Nomenclature

Al-Li	= aluminum-lithium
g	= acceleration due to gravity, 32.2 ft/s^2
GLOW	= gross liftoff weight, lb
H_2	= hydrogen
h	= altitude, ft
LH_2	= liquid hydrogen
LO_2	= liquid oxygen
O_2	= oxygen
Ti-Al	= titanium aluminide
T/W	= thrust-to-weight ratio
t	= time, s
α	= angle of attack, deg
γ_r	= relative flight-path angle, deg
ΔV	= incremental velocity, ft/s
ε	= rocket-engine expansion ratio

Introduction

ON July 20, 1989, President George Bush announced a series of ambitious U.S. space goals, including the establishment of a lunar base and the first manned expeditions to Mars. Because of current high launch costs associated with the Space Shuttle and expendable launch systems such as Titan, Atlas, and Delta, it is unlikely that such space goals can be achieved in an era of restricted budgets. Thus, approaches to lowering launch costs assume ever greater importance in fulfilling future U.S. objectives in space.

Proposed solutions to the problem of providing reliable, low-cost space launches have been numerous over the past several years. Countries, companies, and individuals have brought forth concepts and systems covering nearly every conceivable means of placing people and payloads into low Earth orbit. Varying analysis techniques and mission, technology, and design assumptions make it a formidable, if not impossible, task to compare these various concept solutions on an equal basis. Comparisons become more meaningful if a single analysis group, using the same mission, technology, and design assumptions, analyzes a variety of design concepts.

For a number of years, options for future United States manned space transportation systems have been examined.[1–3] Recent activities have focused on the advanced manned launch system (AMLS),[4] representing a replacement system for the present Space Shuttle. Under consideration are vehicle concepts that embrace the goal of safe, reliable, cost-effective manned access to space beyond the year 2000. Technology level, system complexity and reliability, and modes of ground and flight operations are among the factors recognized as significantly affecting a comparison of the various concepts.

In this paper, single- and two-stage reusable, winged-rocket AMLS concepts are compared with single- and two-stage air-breathing (AB)/rocket systems for delivery missions to space station and polar orbit for two different assumed levels of technology advancement. The purpose is to provide single-source point design information related to the issues of single- vs two-stage and rocket vs AB systems and to draw appropriate conclusions based on these analyses.

Missions

A statement of mission needs is a necessary prerequisite for determining launch system requirements and design. Two sets of AMLS mission specifications have been identified and are therefore considered for the vehicle concept analyses presented. These missions differ significantly in the destination and amount of payload, the number of crew required, and the philosophy of design, especially in the areas of crew safety, mission success, margins, and risk.

Space-Station Mission

This design reference mission for AMLS vehicle concepts calls for the delivery and return of up to 40,000 lb of payload from Kennedy Space Center (KSC) to Space Station Freedom (220 n.mi., 28.5-deg inclination) along with a crew of ten (eight passengers and two-person flight crew). A three-day flight duration with an in-flight margin was budgeted (35 man-days). The payload bay dimensional requirements were a 15-ft diam by 30-ft length. Onboard propellant would provide an incremental velocity ΔV of 1350 ft/s with launch insertion into a 50 × 100-n.mi. orbit. Landing would nominally be at the KSC launch site.

All AMLS vehicles were required to have a crew escape capability characterized by the jettisoning of a crew module using high-impulse solid rocket motors with in-flight stabilization followed by deployment of a parachute system for landing. In addition, all single- and two-stage rocket systems were to have fail-operational single-engine-out capability for each stage from liftoff for added reliability and mission success. A 15% dry-weight growth margin was allocated.

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Table 1 Technologies for AMLS vehicle options

Key technologies	Space Shuttle (reference)	Near-term technology	Advanced technology
Structures	Al structures	Composite structures	Ti-Al composite structures and thermal protection system (TPS)
	Al tanks		
	Limited composites	Reusable Al-Li tanks	Reusable thermoplastic hydrogen tanks
	Ceramic TPS	Durable metallic or ceramic TPS	Reusable Al-Li oxygen tanks
Propulsion	SSME	Lightweight SSME derivative	Extra-lightweight SSME derivative
		Turbojet/ramjet	VMR rocket
			Turborocket, ramjet, scramjet propulsion
Subsystems	Hydraulic power	Electromechanical actuators	Lightweight subsystems using advanced materials
	Monoprop auxiliary power unit (APU)	All-electric	
	Hypergolic orbital maneuvering system (OMS)/reaction control system (RCS)	Lightweight fuel cells, batteries	Activity cooled or carbon-carbon inlets and nozzles
	Fuel cells	Cryogenic/gaseous OMS/RCS	
		Fault-tolerant/ self-check	

Polar Mission

A second AMLS design reference mission considered was a 10,000-lb payload delivery flight from the Vandenberg Western Test Range (WTR) to polar orbit (100 n.mi., 90-deg inclination). For the concepts analyzed, this would also provide an estimated 30,000-lb capability for delivery to and return from the space station. Thus, for these analyses, a secondary requirement imposed was the capability of landing 30,000 lb from orbit. The velocity increment ΔV for on-orbit maneuvering was reduced to 850 ft/s with launch insertion into a 50 × 100-n.mi. orbit, but orbital maneuver propellant tanks were sized to carry an additional ΔV of 350 ft/s. Vehicles were to carry only a crew of three for two days. The payload bay dimensions were set at a 12-ft diam and 20-ft length (3000-ft^3 volume minimum).

In these initial polar-mission studies, geared toward enhancement of vehicle performance, no crew escape or engine-out capabilities were included, and the dry-weight growth margin was reduced to 10%. Further analyses of these concepts will treat the effect of including these requirements.

Technology Levels

Significant advances in many areas of materials, propulsion, and subsystem technologies have occurred since the Space Shuttle was developed. Incorporation of some of these advances into the current Space Shuttle system in a cost-effective manner is a credible option for improving Space Shuttle performance and operations.[5] These and further advances in launch vehicle technologies could have a major influence on future vehicle concepts as well.

For the present study, two technology levels that are advanced beyond those of the present Space Shuttle system were selected to investigate the effects on the various launch vehicle concepts chosen. Each technology level consisted of a set of material, propulsion, and subsystem definitions as listed in Table 1. These two levels are designated "near-term" and "advanced." Near-term technologies are those that either are state-of-the-art or have been demonstrated sufficiently that little additional development is necessary prior to direct application to vehicle development. The advanced level consists of additional technologies that require much more intensive funding and study before they can be applied in wide-scale use. Technologies under study for the National Aerospace Plane (NASP) program today are potentially the primary source of these advancements.

Near-term concepts utilize insulated Al-Li for integral cryogenic propellant tanks and composite structures for intertanks and secondary fairings. Metallic panel or direct-bond ceramics are used for large-area entry-heating thermal protection with titanium or carbon-carbon used for leading-edge and nose-cap areas. All rocket vehicle main propulsion systems are based on a lightweight derivative of the Space Shuttle main engine (SSME) using LH_2 and LO_2 propellants. AB propulsion is represented by a future turbojet/ramjet system utilizing LH_2 fuel. At the subsystem level, significant changes from the Shuttle system are employed. Hydraulics are replaced with all-electric systems employing electromechanical actuators for both engine gimbals and aerosurface controls. Orbital maneuvering, reaction control, and fuel-cell power systems utilize hydrogen and oxygen. Advanced avionics and fault-tolerant, self-check subsystem components are also baselined.

Advanced technology concepts step beyond those proposed for the near term. Ti-Al composite is the main structural material; with an internal insulation layer, it also functions as thermal protection in many areas. Carbon-carbon is used in the highest-heating regions. Slush hydrogen and triple-point oxygen are propellants used in most of the design concepts. Nonintegral hydrogen tanks are constructed from thermoplastics, but oxygen tanks retain the use of Al-Li because of potential oxidation problems associated with the use of thermoplastics. Rocket propulsion systems are based on either an extra-lightweight SSME derivative or a variable mixture ratio (VMR) engine. AB engines are concept-dependent and range from turbojet and turborocket systems to ramjets and scramjets. Subsystems are similar to those for the near-term technology level, but are lighter in weight with more advanced materials utilized.

Analysis Tools

Comparative vehicle designs were obtained from the application of a number of state-of-the-art analysis tools. Basic configuration development utilized the Solid Modeling Aerospace Research Tool (SMART) geometry system, which outputs surface areas, volumes, and internal packaging of systems and resulting efficiencies. The geometry from SMART was used in the Aerodynamic Preliminary Analysis System (APAS) program[6] to obtain the aerodynamics of the configurations from subsonic through hypersonic flight. Program to Optimize Simulated Trajectories (POST)[7] was used to obtain optimum ascent trajectories subject to a variety of user input constraints (e.g., dynamic pressure, normal force, heat rate, and angle of attack). An in-house weights and sizing program, configuration sizing program (CONSIZ), provided a detailed weight and geometry breakdown in conjunction with results obtained from POST. A reference vehicle was obtained for a given mission and constraints only after repeated iterations between these various analysis tools, allowing for trades in fundamental parameters such as thrust-to-weight ratios, thrust splits between booster and main engines, and staging Mach number.

Design Concepts

Figure 1 depicts the range of post-Shuttle-era rocket and AB vehicle options that have been analyzed. All vehicle concepts presented in this paper are fully reusable. AMLS systems with varying degrees of expendable components were explored in Ref. 4. Because of the desire for large crossrange, low entry g-load conditions, horizontal takeoff (for AB systems), and horizontal runway landing, the analyses to date have concentrated on winged configurations for all vehicle elements. This section describes each of the design concepts examined in the course of this study.

AMLS Space-Station Mission

For the AMLS space-station mission, single- and two-stage vertical-takeoff, winged-rocket system designs were considered for the near-term and advanced technology levels. AB design concepts were considered only for the polar-mission studies.

Near-Term Two-Stage Design

Figure 2 depicts the two-stage fully reusable AMLS concept. The main propulsion on the orbiter stage is a lightweight derivative of the current SSME (25% dry-weight reduction with a 15% margin) with a two-position nozzle (sea-level expansion ratio equal to 55 and high-altitude expansion ratio equal to 150). The booster-stage main propulsion is a similar SSME derivative, but with a fixed nozzle expansion ratio of 35. The thrust-to-weight ratio at liftoff was optimized at 1.3 with 60% of thrust on the booster and 40% on the orbiter. Engine thrust levels depend on total thrust levels on each stage and on the numbers of engines assumed per stage. At liftoff, all engines on both stages are running. The unmanned booster stages at Mach 3 and performs an aerodynamic maneuver to set itself on an unpowered glide back to the launch site. These staging and glideback maneuvers are described in detail in Ref. 8. The orbiter uses LO_2-LH_2 propellants crossfed from the booster during the boost phase and LO_2-LH_2 supplied from integral tanks for the rest of the ascent to orbit. The containerized payload (P/L) is carried on the back of the orbiter in an external canister for rapid integration and removal in the operations processing flow. Crew access to the payload canister while in orbit is through a tunnel leading from the forward crew cabin. Aerodynamic fairings cover the tunnel and canister arrangement.

The gross weight at liftoff of this two-stage system (see Table 2) is a little more than half that of the Space Shuttle (2.6 vs 4.5 Mlb). Design issues related to this type of two-stage configuration requiring more in-depth analysis, including the degree of engine gimbal prior to booster staging, the staging sequence and maneuver, and aerodynamic effects of the mated configuration, are presented in Ref. 9.

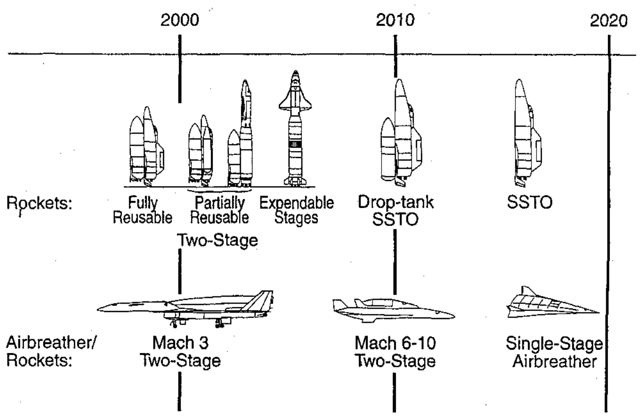


Fig. 1 Post-Shuttle manned-launch-vehicle options.

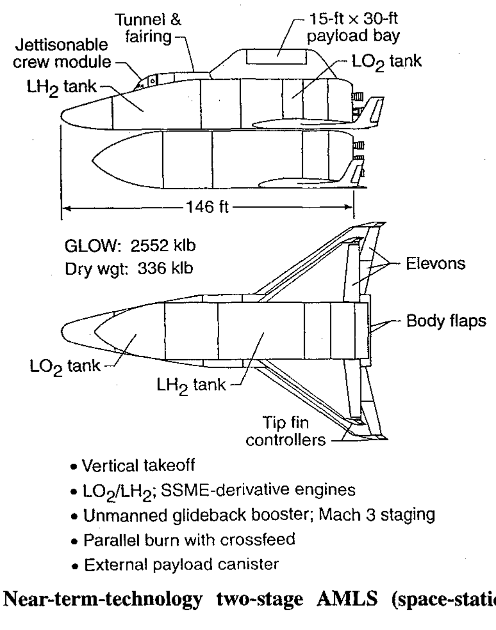


Fig. 2 Near-term-technology two-stage AMLS (space-station mission).

Near-Term SSTO Design

The configuration for the near-term single-stage-to-orbit (SSTO) AMLS vehicle is an adaptation of the orbiter stage of the two-stage system. The same orbiter propulsion characteristics apply. The resulting vehicle, listed in Table 2, graphically demonstrates the infeasibility of this SSTO concept for near-term technologies for a large payload class where safety, reliability, and operability features have been incorporated. With a calculated gross weight of 25.1 Mlb, dry weight of 2.8 Mlb, and length of 391 ft, the SSTO would dwarf the two-stage counterpart. These results must be viewed with caution, as the SSTO sizing for these particular conditions is extremely sensitive to small weight or mass-ratio changes. For example, a 1% decrease in mass ratio was found to be sufficient to halve the weights shown. This large sensitivity to weight growth also entails high risks in development, production, and costs for the near-term SSTO design.

Advanced Two-Stage Design

The advanced technologies listed in Table 1 were applied to the near-term two-stage configuration to yield the advanced two-stage design shown in Fig. 3. The main propulsion was also assumed to be an SSME derivative but with a 50% dry-weight reduction below SSME (a 15% dry-weight margin is included). All other propulsion characteristics were similar to the near-term system. Slush hydrogen and triple-point oxygen were assumed as the propellants. Because of the marked scale reduction of the resulting two-stage system and the outsized appearance of an externally mounted canister, the orbiter was reconfigured to carry the payload canister internally.

As listed in Table 2, with a gross weight of 1.5 Mlb and dry weight of 178 klb, the advanced two-stage system is notably lighter than the near-term two-stage system. The glideback booster is smaller (104 vs 129 ft). But, because the hydrogen and oxygen tanks were rearranged to accommodate an internal payload canister mounting,

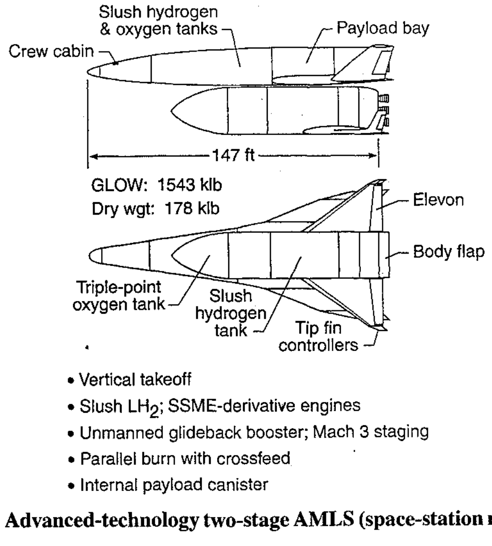
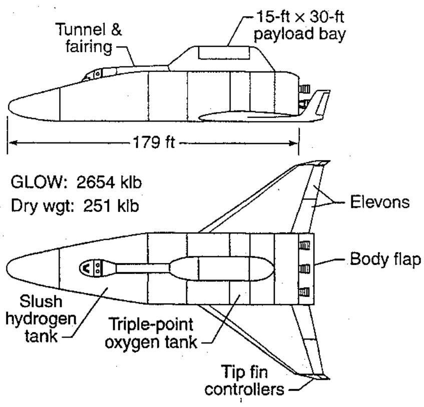


Fig. 3 Advanced-technology two-stage AMLS (space-station mission).

Table 2 AMLS options for space-station mission[a]

	Near-term		Advanced	
Characteristic	Two-stage	Single-stage	Two-stage	Single-stage
		Overall		
Gross weight, klb	2552	25133	1543	2654
Dry weight, klb	336	2755	178	251
Body length, ft	146	391	147	179
		Booster		
Gross weight, klb	1117	—	653	—
Dry weight, klb	131	—	68	—
Body length, ft	129	—	104	—
Propulsion type	$\varepsilon = 35$ SSME derivative[b]	—	$\varepsilon = 35$ SSME derivative[c]	—
		Orbiter		
Gross weight, klb	1436	25133	890	2654
Dry weight, klb	205	2755	110	251
Body length, ft	146	391	147	179
Propulsion type	$\varepsilon = 55/150$ SSME derivative[b]	$\varepsilon = 55/150$ SSME derivative[c]	$\varepsilon = 55/150$ SSME derivative[c]	$\varepsilon = 55/150$ SSME derivative[c]

[a]weight 40 klb; 10 crew to 220 n.mi.; 28.5 deg for 3 days.
[b]SSME weights reduced by 25%; 15% margin added.
[c]SSME weights reduced by 50%; 15% margin added.



- Vertical takeoff
- Slush LH_2; SSME-derivative engines
- External payload canister with aerodynamic shroud

Fig. 4 Advanced-technology single-stage AMLS (space-station mission).

the advanced orbiter is actually slightly longer than its near-term counterpart (147 ft vs 146 ft).

Advanced SSTO Design

Advanced technologies were also applied to the near-term SSTO concept to produce an advanced SSTO design, depicted in Fig. 4. The resulting vehicle size was large enough to allow an external mounting of the payload canister. The main propulsion was also assumed to be an SSME derivative, but with a 50% dry-weight reduction below SSME (15% dry-weight margin). All other propulsion characteristics were similar to the near-term system. Slush hydrogen and triple-point oxygen were assumed as the propellants.

The use of advanced technologies has an enabling effect on a viable SSTO concept as listed in Table 2. Although still larger than the advanced two-stage system (gross weight 2.7 vs 1.5 Mlb, dry weight 251 vs 178 klb), there is a marked size reduction from the near-term SSTO. Indeed, the dry weight of this SSTO system is much less than that of the near-term two-stage system, and the former would likely be competitive provided the technologies are cost-effective to develop.

Polar Mission

The same four single- and two-stage rocket vehicles were resized for the polar mission described earlier. In addition, four AB vehicles were added to the matrix of concepts—a two-stage turbojet/ramjet/rocket-propelled system at near-term and advanced technologies, an air-turborocket/rocket SSTO system using advanced technologies, and a low-speed cycle/ramjet/scramjet/rocket SSTO system using advanced technologies. All AB concepts utilized horizontal takeoff.

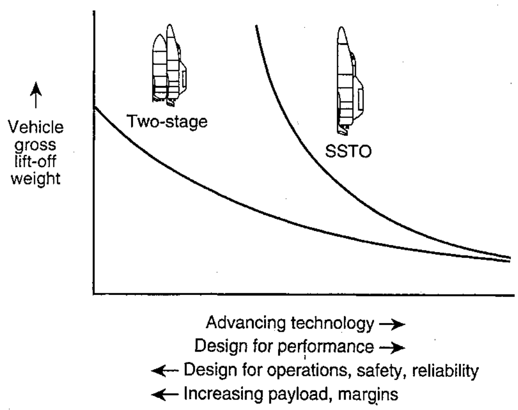


Fig. 5 Factors influencing rocket vehicle sizing.

Rocket Vehicles

The basic characteristics of the rocket vehicles, described individually in the previous section, remained similar except that only a 10% dry-weight margin was applied, launch escape and engine-out capabilities were removed, and the design-for-operations philosophy was not included. Table 3 provides results for these vehicles for the polar mission. Generally, the gross and dry weights have been halved by this change in missions, but for the near-term SSTO system the weight reductions are more dramatic. This enforces the observation that the SSTO design for near-term technology is highly sensitive to factors that drive weight.

Figure 5 depicts the trends in SSTO and two-stage sizing as a function of advancing technology. The SSTO weighs more and is more sensitive to weight growth as the level of technology advancement is reduced. The near-term SSTO described for the space-station mission lies on the high-growth portion of the SSTO curve, whereas the SSTO with the same technology for the polar mission lies much further down this curve. This can be attributed to the lower payload and personnel requirements, lower margins, and removal of crew escape and engine-out capabilities. As indicated in Fig. 5, these

Table 3 AMLS options for polar mission[a]

	Near-term			Advanced					
Characteristic	Two-stage rocket	Two-stage AB	SSTO rocket	Two-stage rocket	Two-stage AB	SSME-SSTO rocket	VMR-SSTO rocket	ATR-SSTO AB	Conical AB
				Overall					
Gross weight, klb	1292	1076	4206	827	644	1359	1334	1087	451
Dry weight, klb	167	440	427	99	221	125	112	214	157
Body length, ft	142	260	220	122	210	144	135	210	220
				Booster					
Gross weight, klb	566	592	—	361	307	—	—	42	—
Dry weight, klb	63	358	—	37	164	—	—	trolley	—
Body length, ft	103	260	—	85	210	—	—	not	—
Propulsion type	$\varepsilon = 35$ SSME derivative[b]	Turbojet/ ramjet		$\varepsilon = 35$ SSME derivative[c]	Turbojet/ ramjet	—	—	Included below	—
				Orbiter					
Gross weight, klb	726	484	4206	465	357	1359	1334	1045	451
Dry weight , klb	103	82	427	62	57	125	112	172	157
Body length, ft	142	126	220	122	116	144	135	210	220
Propulsion type	$\varepsilon = 55/150$ SSME derivative[b]	$\varepsilon = 55/150$ SSME derivative[b]	$\varepsilon = 55/150$ SSME derivative[b]	$\varepsilon = 55/150$ SSME derivative[c]	$\varepsilon = 55/150$ SSME derivative[c]	$\varepsilon = 55/150$ SSME derivative[c]	$\varepsilon = 55/120$ VMR $\varepsilon = 55/150$	Air turborocket scramjet/ SSME derivative[c]	LSS/ ramjet/ rocket

[a]Weight 10 klb; 3 crew to 100 n. mi.; 90 deg for 2 days.
[b]SSME weights reduced by 25%; 10% margin added.
[c]SSME weights reduced by 50%; 10% margin added.

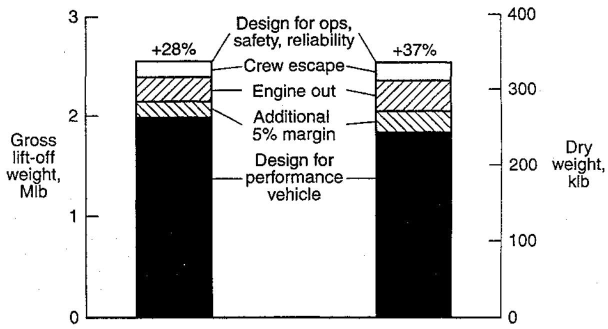


Fig. 6 Designing for operations, reliability, and safety.

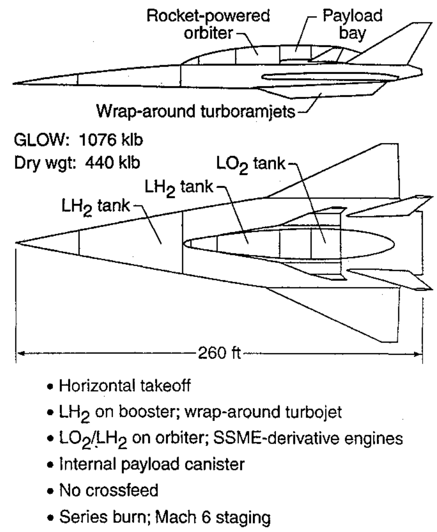


Fig. 7 Near-term-technology two-stage AB-rocket AMLS (space-station mission).

mission and design requirements drive SSTO weights down as one moves to the right on the curve. For example, Fig. 6 shows how the gross and dry weights of a two-stage rocket vehicle, originally designed for performance in fulfilling the space-station mission, grow as additional margin, engine-out, and crew-escape capabilities are added. There are 28% and 37% growths in gross and dry weights, respectively, just for the factors indicated. Other factors that influence operations could further increase these differences. The design-for-performance vehicle weights would be reduced by raising the staging Mach number[10] from 3 to 6, whereas the design-for-operations vehicle's weight would rise if the optimum booster and dual-position orbiter SSME-derivative engines nozzles were replaced by common, fixed nozzles. Thus, technology is but one factor that controls SSTO feasibility and the sizing of two-stage systems. The near-term SSTO for the polar mission, while still large, is more readily achievable. The basic observations of the previous section apply to the other vehicles.

An advanced SSTO was also designed for the polar mission using VMR rocket engines in place of the SSME derivatives on the advanced rocket SSTO. This vehicle, similar in appearance to the SSTO shown in Fig. 4, is described in Ref. 11. Up to Mach 2.4, the VMR engine burns oxygen and hydrogen in a ratio of 14:1 by weight with a nozzle expansion ratio of 60. At that point, the engine transitions to a 7:1 mixture ratio, and the nozzle is extended to provide an expansion ratio of 120 for the remainder of the acceleration to orbit. Slush propellants are used. The results are shown in Table 3. The reduction of hydrogen requirements using the VMR engine translates into a smaller hydrogen tank and overall higher propellant bulk density for the SSTO design.

Near-Term Two-Stage Airbreather

Figure 7 details the general configuration of the near-term, two-stage airbreather. This is a horizontal takeoff system utilizing a runway and its own takeoff-landing gear. Fueled by LH_2, the unmanned first stage is powered initially by turbojets. At Mach 3 the turbojets are shut down and ramjet operation begins. Figure 8 shows the propulsion package to be of a "wraparound" design, that is, the ramjet wraps around the turbojet machinery in an annular manner. Ramjet operation continues to the staging point at Mach 6. The flight trajectory follows a 1000-psf dynamic-pressure limit. The same basic technologies are used as for the near-term rocket system. (See Table 1.) In designing the vehicle for an effective aerodynamic shape, the LH_2 tank has taken on a multilobed conformal design to permit efficient use of the vehicle volume. The first-stage airbreather requires carbon-carbon material for the inlet

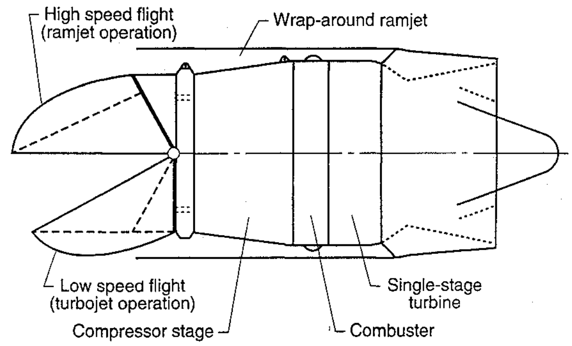


Fig. 8 Wraparound turbojet design.

of the propulsion package as well as on other leading edges and the nosecap region. Nozzle structural regions are actively cooled.

The manned orbiter stage of the AB system is powered to orbit from the staging point (Mach 6, 100 kft, 8-deg climb) exclusively by SSME derivative rockets (same characteristics as those used on the near-term vertical-takeoff rocket systems). There is no crossfeed of propellants from the first stage, as for the rocket systems. The crew cabin is located near the payload bay, and the crew uses a television system for forward vision at landing. For aerodynamic efficiency of the mated system, the orbiter cross section is flattened and has a multi-lobed tank system for both the LH_2 and LO_2 tanks. In other regards, the technologies are the same as for the rocket system orbiter stage.

The gross weight of the two-stage AB vehicle is less than that of either the single- or the two-stage rocket system (see Table 3), because the airbreather stage does not carry any LO_2, which is required by the rocket systems. On the other hand, the dry weight is much higher than for the rocket two-stage system, and even exceeds that of the near-term rocket SSTO. Primary reasons for this are the additional weight imposed by the AB engines and the very high drag losses (and resulting increased hydrogen use) during the acceleration to the staging point.

Advanced Two-Stage Airbreather

The advanced two-stage AB vehicle has a configuration similar to that of the near-term system, but uses the advanced technologies noted in Table 1. The propulsion systems are lighter-weight versions of those used for the near-term system. Slush hydrogen is used by the AB-stage propulsion, but the orbiter stage retains the use of LH_2 and LO_2. The reason for this is the significant aerodynamic heat load seen by the vehicle during the 38-min acceleration to the staging point. Slush or triple-point propellants would be difficult to maintain in the orbiter stage without excessive insulation requirements.

Advanced technologies permit large gross- and dry-weight reductions from the near-term two-stage airbreather as shown in Table 3. Compared with the advanced single- and two-stage rocket systems, the gross weight of the airbreather is less than that of either, but the dry weight, more important in determining development and production costs, is higher than that of either. Thus, at neither technology level do the two-stage AB systems show a dry-weight advantage over equivalent-technology rocket systems.

Advanced Single-Stage Airbreather

Rocket and air-turborocket (ATR) propulsion units were used as the basis of an advanced-technology AB SSTO. This design concept, detailed in Ref. 12, was resized for the present polar mission and is shown in Fig. 9. Similar in concept to the British Aerospace horizontal takeoff and landing horizontal takeoff and landing (HOTOL) vehicle, this SSTO utilizes an unpowered trolley during the takeoff roll. Using ATR propulsion for the horizontal takeoff acceleration, the vehicle rotates to a 20-deg angle of attack at Mach 0.4 and separates from the trolley. The vehicle accelerates to and holds a 1000-psf dynamic pressure limit until the ATR shuts down at Mach 6. Rocket engines then power the vehicle to orbit. Slush hydrogen and triple-point oxygen are used as main propellants.

As shown in Table 3, the gross weight of this ATR/rocket-propelled SSTO is less than for either rocket SSTO, again because

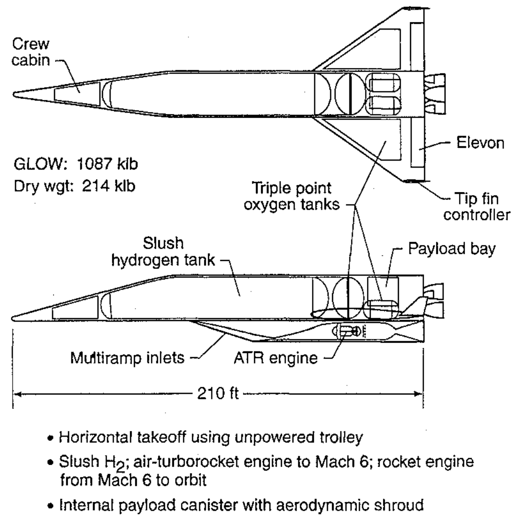


Fig. 9 Advanced-technology ATR-rocket SSTO design (polar mission).

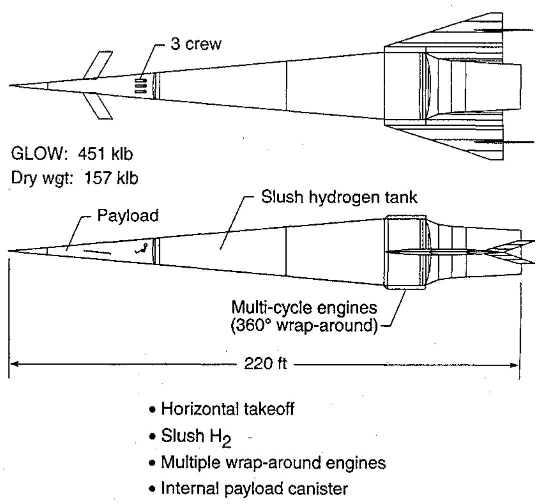


Fig. 10 Advanced-technology AB conical-accelerator SSTO design (polar mission).

of offloading of a substantial amount of oxygen, which the ATR utilizes directly from the atmosphere. But the dry weight of this vehicle is higher than that of the rocket SSTO vehicles. In addition, the weight of the trolley must be accounted for in a total system itemization.

Advanced Conical-Accelerator SSTO Vehicle

The conical-accelerator vehicle (Fig. 10) was based on government baseline analysis experience and original aerospace plane concepts.[13] The main propulsion system uses a multimode slush-hydrogen-fueled propulsion system with low-speed, ramjet, scramjet, and rocket cycles. The propulsion package wraps completely around the conical vehicle. The vehicle has a 5-deg-half-angle forebody over which the flow is compressed on the entire forebody. The engine cowl depth was designed so the bow shock would intersect the cowl lip at Mach 25. A 2000-psf dynamic pressure limit was established for flight.

Results obtained for this advanced-technology vehicle show it to have the lowest gross weight of all the SSTO vehicles considered. (See Table 3.) This is an expected result, given the large range of Mach numbers over which the various AB engine cycles work, which greatly reduces the oxygen carried onboard. It is also slightly smaller in dry weight than the ATR/rocket SSTO described in the previous section and does not use a trolley for takeoff, but the dry weight remains larger than for the advanced-technology rocket SSTO vehicles already presented.

Discussion

Certain observations can be made based on the design concept analyses presented above. Figures 11 and 12 present scale figures of the near-term and advanced-technology AMLS vehicle options, respectively, for the polar mission.

Single- vs Two-Stage Concepts

Much speculation exists as to whether a future manned launch system should have multiple stages or a single stage. Results presented in this paper provide some answers to this question for fully reusable, winged concepts. Technology levels and mission, design, and operational requirements are major influential factors. SSTO sensitivity to weight growth constitutes high risk in development costs. The size and weight disparity between single- and two-stage concepts is significantly worsened when requirements call for large-payload and large-crew missions with design-for-operations features (as for the space-station mission—see also Fig. 5). Should development of a rocket replacement for the Space Shuttle using near-term technologies be desired, the configurations examined above indicate that a two-stage system should be preferred.

With the evolution of advanced technologies, the decision is less clear-cut. While a two-stage rocket system continues to exhibit dry-weight advantages over all-rocket or AB SSTO vehicles, the benefits of staging are less than when near-term technologies are employed. The lower dry weight of the two-stage system suggests lower design, development, test, and evaluation (DDT&E) costs, but vehicle integration factors and operations costs must be also be included in the cost of ownership. Operations costs of similar-scale SSTO systems are less than those of two-stage systems, since the SSTO concept does not require booster processing, orbiter integration with a booster, or checkout of duplicated systems. For high flight rates, operations cost reductions make the SSTO the likely choice. For low flight rates, the decision is less certain. Detailed cost analysis, which takes into account all factors of DDT&E, operations, facilities, and vehicle attrition, must be conducted.

Unlike the rocket systems, an advanced-technology two-stage AB-rocket system weighs more than either of the two SSTO airbreathers examined. This can be attributed to a number of factors. Foremost are the drag losses of the two-stage system vs the SSTO. The two-stage system has a complicated aerodynamic design. Flying a high-dynamic-pressure trajectory increases the total integrated vehicle drag. There are structural penalties associated with orbiter-booster integration and separation mechanisms as well as subsystem duplication on the two stages. High heating precludes the use of slush propellants on the orbiter. (They were present in the SSTO designs.) Also, the booster must include fuel to allow it to either return to the launch site or reach a favorable downrange landing site. Allowing for a return-to-launch-site abort for the two-stage AB system with the attached orbiter drives wing design loads (and weights) and creates a penalty in return cruise performance. All these factors in the AB systems combine to cancel out the advantages of staging seen in the rocket systems.

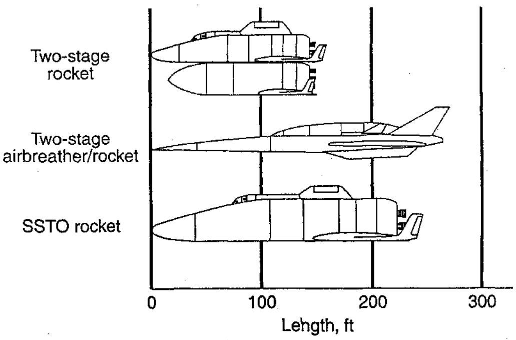


Fig. 11 Near-term-technology AMLS concepts (polar mission).

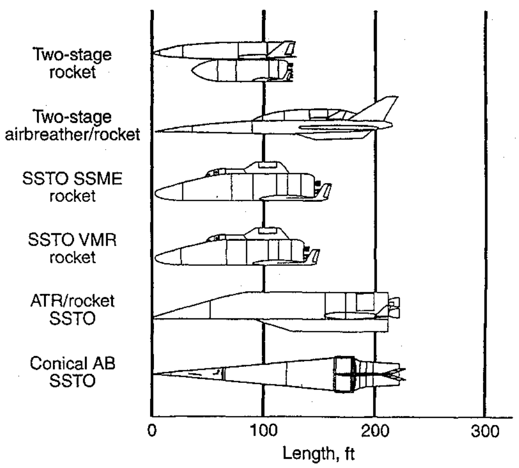


Fig. 12 Advanced-technology AMLS concepts (polar mission).

Rocket vs AB Vehicles

An equally intense issue is whether future space transportation systems benefit from the use of AB propulsion. Several factors related to performance, design, missions, operations, and programmatics must be included in a complete evaluation.

AB propulsion reduces onboard oxidizer requirements, resulting in lower gross liftoff weight. Figure 13 summarizes the GLOW of the various near-term and advanced concepts fulfilling the polar-mission requirements. The two-stage AB system has the lowest GLOW of the near-term systems, and advanced single- and two-stage airbreathers weigh less than their all-rocket counterparts. This does not, however, translate into propellant cost savings, because of increased use of hydrogen by the airbreathers to overcome higher drag losses during ascent. Figure 14 shows the total ideal ΔV needed by the various advanced systems to reach polar orbit. Clearly, all of the AB systems have larger losses than their rocket-powered counterparts. Much of these loss differences are due to the higher drag associated with the AB vehicles during the ascent. Table 4 lists the total hydrogen and oxygen (liquid or slush) requirements for each of the polar-mission design concepts. Based on a ratio of costs of LH_2 to LO_2 of roughly 20:1 and assuming slush hydrogen and oxygen have this same ratio, propellant cost ratios of airbreathing concepts relative to their rocket-powered counterparts were obtained and are listed in Table 4. For the near-term systems, the AB-concept propellant cost is 273% of the rocket-vehicle propellant cost. For advanced

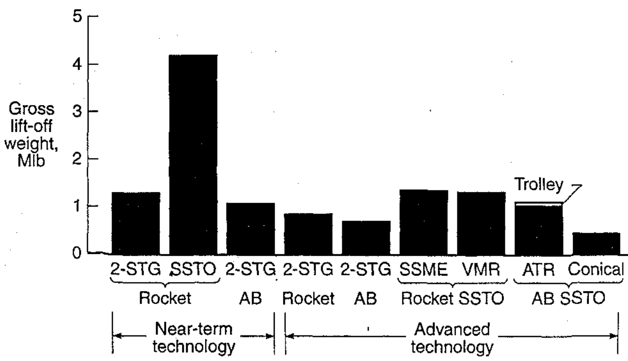


Fig. 13 GLOWs of AMLS concepts (polar mission).

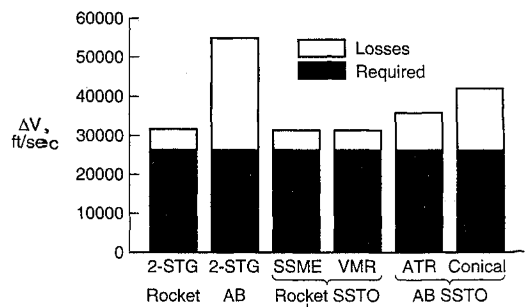


Fig. 14 Total ideal ΔV required to reach orbit for AMLS concepts (polar mission).

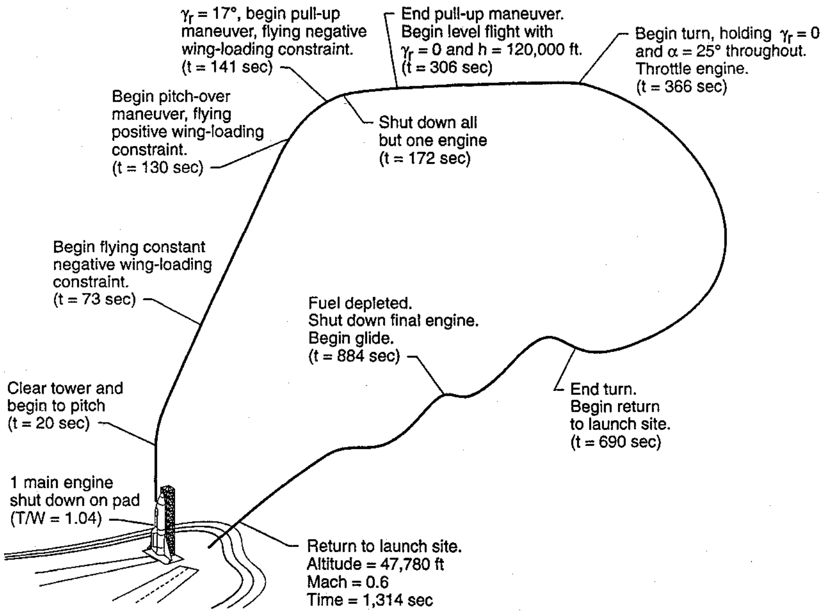


Fig. 15 Return-to-launch-site abort from launch pad for rocket SSTO design (from Ref. 11).

Table 4 Propellant usage for AMLS options (polar mission)

Vehicle	Oxygen (liquid or triple point), klb	Hydrogen (liquid or slush), klb	Ratio of propellant costs to baseline rockets
	Near-term technology		
Two-stage rocket	932	155	1.00
Two-stage AB	53	548	2.73
	Advanced technology		
Two-stage rocket	598	100	1.00
Two-stage AB	237	179	1.47
SSME-SSTO	1024	171	1.00
VMR-SSTO	1059	126	0.81
ATR-SSTO	638	192	1.01
Conical AB SSTO	0	452	2.03

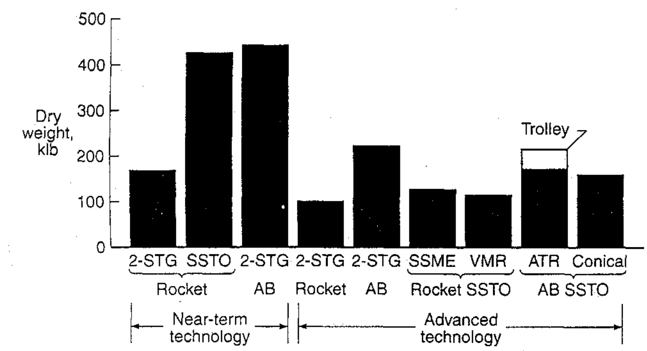


Fig. 16 Dry weights of polar-mission AMLS concepts.

two-stage systems, the airbreather propellant cost is 147% of the two-stage rocket propellant cost. For advanced SSTO systems, the propellants for the ATR-powered SSTO cost only 1% more than those for the SSME-propelled rocket, but 25% more than those for the VMR-propelled rocket. The conical-accelerator propellant cost is 203% of the SSME-propelled rocket propellant cost and 251% of the VMR-propelled rocket propellant cost. Thus, in no case does any AB concept show smaller propellant costs than its rocket-propelled counterpart.

There are, however, safety and abort advantages to the reduced GLOW and minimization of oxidizer carried on the airbreathing systems. The rocket vehicles have a higher explosive potential in case of a catastrophe because of the close proximity and amount of oxidizer and fuel carried. In case of abort from a vertical takeoff, the rocket vehicle must jettison or burn off its fuel load before landing on its main gear, which is normally designed for empty landed weight, unlike horizontal-takeoff AB vehicles with landing gears that are designed for GLOW. (The ATR-powered SSTO, which uses a trolley, is an exception.) Reference 11 demonstrates that rocket-powered SSTO vehicles can have a full range of single-engine-out abort opportunities without violating vehicle loading constraints of the nominal ascent and entry trajectories. Figure 15, from Ref. 11, summarizes the major events of an abort trajectory that allows the rocket-powered SSTO vehicle to burn off all of its propellants and safely return to the launch site following shutdown of one main engine.

Figure 16 summarizes the dry weights of the polar-mission vehicles. Without exception, the all-rocket vehicles weigh less than their AB counterparts. Several factors account for this. The thrust-to-weight ratio of the airbreathing propulsion systems is significantly less than for the SSME-derivative or VMR rockets. There are substantial structural penalties in obtaining optimized aerodynamic and propulsion integration for both the single- and two-stage airbreathers. Aerodynamic design for the two-stage airbreathers is especially complicated and is reflected in high drag losses during the ascent. The high drag losses, as noted earlier, result in higher hydrogen fuel and tank volume requirements. High heating and dynamic-pressure loads generated by the trajectories typically flown for AB systems add to thermal protection and structural weights.

DDT&E and production costs are proportional to the dry weight and complexity of vehicle system design. With their lower dry weights and simpler propulsion systems, the rocket vehicles thus can reasonably be expected to cost less.

Vehicle operations is another area where definitive analysis is necessary to draw the proper comparisons. Just as it is erroneous to assign the complexity of present-day Space Shuttle operations to any future vertical-takeoff rocket system, neither does horizontal takeoff automatically confer airplanelike operation upon AB systems for these space transportation systems. The measure of complexity in either system is in the manpower, task times, and facilities required to process and launch the vehicle. Table 5, from Ref. 4, for example, demonstrates that through careful design and requirements analysis of the near-term two-stage rocket system shown in Fig. 1, the number of technician man-hours required for ground processing of the two-stage AMLS can be reduced to less than 25% of that required for the Space Shuttle. Without a glideback booster, the manpower requirements for the SSTO vehicles depicted in this paper could be even lower.

Table 5 Comparison of technician man-hours for ground operations (pre-51-L)[a]

Task	Shuttle (historical data), technician man-hours	AMLS (estimates), technician man-hours
Quality engineering	1,071	480
Launch accessories	425	72
Integration	9,813	4,114
Purge, vent, and drain	669	1,445
Mechanisms	1,611	333
Structure/handling	3,487	360
TPS	10,712	48
Propulsion	8,404	3,904
Propellants	4,080	118
Environmental control and life support system (ECLSS)	1,730	640
Prime power	1,332	1,200
Avionics	1,604	1,133
Pyrotechnics	2,664	2,664
Flight-crew systems	185	10[b]
Contingency	4,896	3,371
P/L install/remove	3,876	0[c]
P/L bay (configure/reconfigure)	3,336	0
APU	416	0
Hydraulics	1,245	0
External tank (ET)	10,100	0
Solid rocket booster (SRB)	23,000	0
Total	94,925	20,406

[a]Taken from Ref. 4.
[b]Assumed 20% for AMLS.
[c]372 man-hours included in integration.

Whether a rocket or an AB system is preferred from an operations point of view is not obvious. Both vehicle systems require runways—the airbreathers for takeoff and landing, the rocket systems for landing only. Processing and checkout of both systems can be conducted horizontally. All two-stage systems require vehicle integration—rocket systems, which crossfeed propellants, more so than two-stage airbreathers, which do not. Both utilize hydrogen and oxygen (except for the conical accelerator), in either liquid or slush form. This requires hydrogen and oxygen storage (and preferably on-site manufacturing) facilities. When comparing operations scenarios, the significant system that is peculiar to rockets is in ground support equipment, namely, the launch pad complex and erector required to support a vertical launch. Operationally efficient launch sites are possible that restrict themselves solely to supporting launch operations. While the AB concepts do not require a launch pad, they possess several unique vehicle systems not found on the rockets, including integrated low-speed cycle, turborocket, ramjet, and/or scramjet engines and actively cooled panels for engine inlets and nozzles. How do the additional operations costs of maintenance and checkout of the more highly integrated advanced AB systems compare with charges associated with maintaining and operating a simplified launch pad? Only through detailed quantitative operations analysis can such comparisons and costs be determined.

Evaluation of system designs must also take into account operational capabilities related to missions. What are the missions to be flown, and who are the users? Civilian space missions involving payload delivery to orbit are best handled by high-performance rocket systems. Military requirements that stress rapid rendezvous and orbital intercept, loiter, recall, or self-ferry capabilities favor AB systems. AB vehicles are characterized by the ability to fly cruise legs and set up offset launches. Such factors greatly penalize rocket systems. For the two-stage AB system, the first stage could also serve as a basis, either directly or in terms of demonstrated technologies, for a civilian or military hypersonic transport.

Capabilities and costs will ultimately decide which, if any, of the systems considered fulfill the intended objectives.

Conclusion

Based on an analysis of fully reusable winged rocket and AB systems for payload delivery missions to space-station and polar orbits, the following observations can be made:

1) Two-stage rocket systems appear preferable to single-stage ones when using near-term technologies, coupled with given mission and operational requirements. Two-stage rocket systems have markedly lower dry weights and propellant costs than equivalent two-stage AB systems.

2) The use of advanced technology enables viable SSTO designs. Two-stage rocket systems retain a dry-weight advantage over single-stage systems at an advanced technology level, but the benefits of staging are clearly reduced. Unlike the rocket systems, the dry weight of the two-stage advanced AB system studied is more than that of equivalent-mission single-stage AB designs. When operations are factored in, an SSTO design is the likely choice for an advanced manned space transportation system.

3) For advanced technology levels, both single- and two-stage rocket systems have lower dry weights and propellant costs than their AB counterparts.

4) DDT&E and production costs, based on dry weight and vehicle complexity, are likely to be less for the rocket vehicle concepts. Operations cost assessments must await detailed analysis of various systems unique to both rocket and AB concepts.

5) Rocket vehicles, as accelerators, hold a performance advantage in direct orbit delivery missions. AB systems hold operational advantages where offset launch, recall, loiter, and self-ferry capabilities are important.

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