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Conceptual Design of a Fully Reusable Manned Launch System

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The conceptual design of a rocket-powered, two-stage fully reusable launch vehicle has been performed as a part of the advanced manned launch system (AMLS) study by NASA. The main goals of the AMLS study are to provide routine, low-cost manned access to space. Technologies and system approaches have been studied that would contribute to significant reductions in operating time and manpower relative to current systems. System and operational characteristics of the two-stage fully reusable vehicle are presented, and the various tools and methods used in the design process are summarized. The results of a series of trade studies performed to examine the effect of varying major vehicle parameters on the reference two-stage fully reusable vehicle are also summarized.

Nomenclature

g	= acceleration of gravity, 32.2 ft/s^2
h	= altitude, ft
I_{sp}	= specific impulse, s
L	= length of vehicle, ft
M_e	= Mach number at boundary-layer edge
q_{max}	= maximum dynamic pressure, psf
$Re\theta$	= momentum-thickness Reynolds number
Rn	= nose radius, ft
T/W	= thrust-to-weight ratio
x	= distance from nose along vehicle centerline, ft
ΔV	= incremental velocity, ft/s
ϵ	= nozzle area ratio

Introduction

IN recent years, NASA has begun studies to define options for the next manned space transportation system. The goals of this broad NASA effort are to define systems that meet future mission requirements of transporting personnel and payloads requiring a manned presence, while emphasizing improved cost-effectiveness, increased vehicle reliability and personnel safety, and large operational margins. Three approaches are being examined for satisfying future manned launch needs. One approach is the evolution of the current Space Shuttle via subsystem and block changes. Another is the definition of a small personnel launch system (PLS) for carrying people and small amounts of cargo to and from space. The third approach is that of a new, more operationally efficient, advanced manned launch system (AMLS) to replace the present Space Shuttle.[1]

The goals of the AMLS study are to examine systems that provide routine, low-cost manned access to space. Technologies and system approaches are being studied that will contribute to significant reductions in operating time and manpower relative to current systems. A rocket-powered, two-stage vehicle would be expected to have a 2005 initial operating capability in order to gradually replace an aging Shuttle fleet. Hence, a 1992 technology readiness date has been assumed to represent normal growth (evolutionary) technology advancements in vehicle structure, propulsion, and subsystems. Although many of these assumed technological advancements contribute to significant weight savings in the vehicle, a portion of this weight savings has been applied to aspects of vehicle design that enhance the operations, reliability, and safety factors of the system.

A wide variety of vehicle types and propulsion systems have been examined in the conceptual and preliminary design of next-generation manned launch systems as a part of the AMLS study. These include single-stage systems, systems utilizing airbreathing propulsion, and systems with varying degrees of reusability.[2] For the assumed flight rate, payload class, and technology readiness, a rocket-powered, two-stage fully reusable system was selected for detailed study. This paper summarizes the conceptual design of this two-stage fully reusable launch vehicle. A variety of parametric trade studies to better optimize this two-stage AMLS vehicle were also performed. The results of many of these trades are presented here.

Analysis Methods

The conceptual design of next-generation launch systems requires proper consideration of the effects of trajectory, weights/sizing, geometry, aerodynamics, and aeroheating. All of the trajectory analysis for the two-stage fully reusable vehicle was performed using the three-degree-of-freedom Program to Optimize Simulated Trajectories (POST). POST is a generalized point mass, discrete parameter targeting and optimization program that allows the user to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate plant.[3] The weights and sizing analysis was performed using the NASA-developed Configuration Sizing (CONSIZ) weights/sizing package. CONSIZ provides the capability of sizing and estimating weights for a variety of aerospace vehicles using mass-estimating relations based on historical regression, finite element analysis, and technology level. All of the geometry and subsystem packaging of the AMLS vehicle was performed using the NASA-developed Solid Modeling Aerospace Research Tool (SMART) geometry package. SMART is a menu-driven interactive computer program for generating three-dimensional Bezier surface representations of aerospace vehicles for use in aerodynamic and structural analysis.[4] The Aerodynamic Preliminary Analysis System (APAS) was used to determine vehicle aerodynamics. In the subsonic and low supersonic speed regimes, APAS utilizes slender body theory, viscous and wave drag empirical

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techniques, and source and vortex panel distributions to estimate the vehicle aerodynamics. At high supersonic and hypersonic speeds, a noninterference finite element model of the vehicle is analyzed using empirical impact pressure methods and approximate boundary-layer methods.[5] An aeroheating analysis of the AMLS vehicle was also performed using the empirical, Space-Shuttle-correlated Miniver aeroheating package. Miniver uses a Blasius solution with Eckert reference enthalpy for laminar analysis, a Schultz-Grunow skin friction method for turbulent flow, and a Fay-Riddell method for stagnation point analysis.[6] Figure 1 demonstrates the iterative process required between these various disciplines to obtain a vehicle point design.

Many of the trade studies performed on the two-stage fully reusable vehicle require only the use of POST and the CONSIZ weights/sizing program. For example, to determine the effect of liftoff thrust-to-weight ratio T/W on the AMLS vehicle, the necessary modifications must first be made to the propulsion equations in CONSIZ to account for the new T/W. Then, an initial guess is made for the mass ratio (i.e., the ratio of gross liftoff weight to burnout or injected weight) of the booster and orbiter. CONSIZ then provides the user with a detailed weight and geometry statement for the sized vehicle configuration. The engines, represented as parametric equations, are also sized for the vehicle in this process. Because the sizing process geometrically scales the vehicle up and down, the vehicle aerodynamics do not change significantly (as long as the center of gravity remains relatively constant); only the reference areas change. Next, a POST ascent trajectory is run with appropriate vehicle weights, reference areas, and engine constants to obtain new mass ratios. These revised mass ratios are inserted into the weights program, and the same process is repeated until convergence. This entire method is repeated until enough data points are obtained to demonstrate how the reference vehicle changes with variations in liftoff T/W. Using this method, each data point represents a converged vehicle design.

Vehicle Concept

Mission and Guidelines

The design reference mission for the two-stage fully reusable AMLS vehicle calls for the delivery and return of up to 40,000 lb of payload from Kennedy Space Center (KSC) to Space Station Freedom (220 nmi, 28.5-deg inclination) along with a crew of 10 (eight passengers and a two-person flight crew). A three-day flight duration with an inflight 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 following launch insertion into a 50×100 nmi orbit. Landing would nominally be at the KSC launch site.

The AMLS vehicle was required to have a crew escape capability characterized by the jettisoning of the crew module using high-impulse solid rocket motors with inflight stabilization followed by the deployment of a parachute system for landing. In addition, both the booster and orbiter have single-engine-out capability from liftoff for added reliability and mission success. A 15% dry weight growth margin was also allocated. The orbiter was required to have a 1100-nmi crossrange capability to allow once-around abort for launch to a polar orbit and to increase daily landing opportunities to selected landing sites. All trajectories for this vehicle have maximum acceleration limits of 3 g and normal load constraints on the wings equivalent to a 2.5-g subsonic pull-up maneuver.

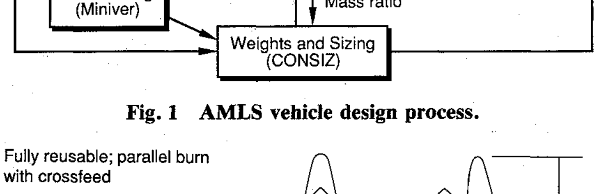


Fig. 1 AMLS vehicle design process.

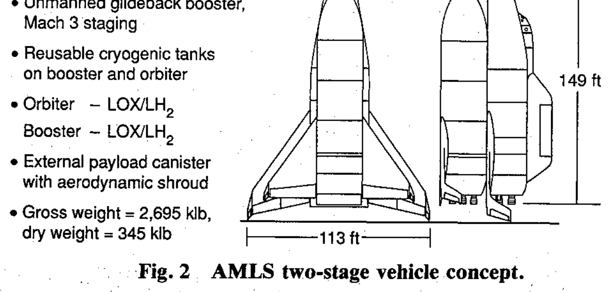


Fig. 2 AMLS two-stage vehicle concept.

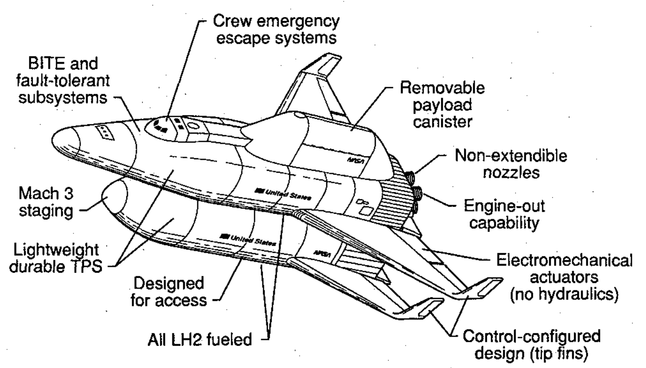


Fig. 3 AMLS vehicle designed for operations, reliability, and safety.

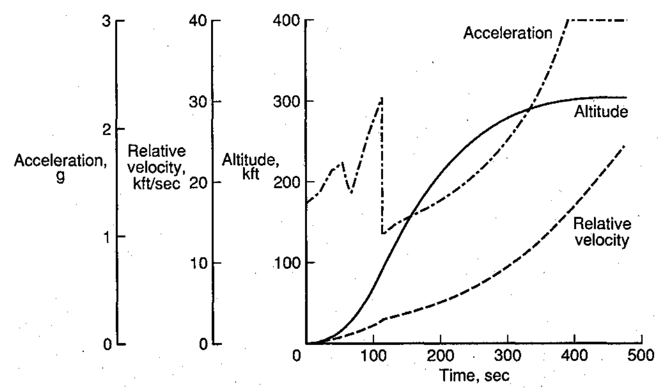


Fig. 4 AMLS ascent trajectory plots.

Vehicle Configuration

The two-stage fully reusable vehicle is depicted in Fig. 2. The vehicle is envisioned to be operational by the year 2005; hence, a technology readiness date of 1992 was selected for all vehicle systems. Utilizing this near-term technology level, Ref. 1 demonstrates that a two-stage vehicle would be preferable to a single-stage-to-orbit (SSTO) design for the AMLS mission and design philosophy.

The AMLS vehicle is a two-stage, parallel-burn design that consists of a manned orbiter and an unmanned winged booster that stages at a Mach number of 3 and glides back to the launch site. Propellants are cross fed from the booster to the orbiter during the boost phase so that the orbiter's propellant tanks are full at staging. Both the booster and orbiter use

Table 1 Characteristics of Space Shuttle main engine derivative engine

Parameter	Orbiter	Booster
Area ratio	77.5:1	35:1
Sea-level thrust, lb	418,500	454,000
Vacuum thrust, lb	513,500	497,000
Sea-level I_{sp}, s	369.6	400
Vacuum I_{sp}, s	453.5	440
Mixture ratio	6:1	6:1
Length, in.	167	146
Weight, lb	6,885	6,340

liquid hydrogen (LH_2) and liquid oxygen (LO_2) as propellants. Other choices of propellants were considered in Ref. 7. This single-fuel approach greatly streamlines operations and eliminates the need for the development and maintenance of separate hydrocarbon engines for only a small weight penalty.[7] The orbiter also employs a detachable payload canister concept to allow off-line processing of payloads and rapid payload integration. Both the booster and orbiter are control configured and employ wingtip fins for lateral control. Integral, reusable cryogenic tankage is used on both the booster and orbiter. As shown in the figure, the total vehicle dry weight is 345,000 lb, and the gross weight is 2,695,000 lb. The total liftoff T/W of the vehicle is about 1.3. Figure 3 presents another view of the AMLS vehicle and summarizes details that contribute to a design-for-operations approach, where due consideration is paid to the effects of vehicle design on recurring costs from the outset of the design process.[8]

The reference AMLS orbiter utilizes four Space Shuttle main engine (SSME) derivative engines for main propulsion, whereas the reference booster uses six of the same engines with a lower area ratio ϵ. The reason for choosing this particular thrust split is presented in a later section. The performance characteristics of each of these engines is summarized in Table 1. The performance of the SSME derivative is only slightly enhanced; however, a 25% weight reduction (with a 15% growth margin) over the original engine is assumed based on the use of reinforced plastic composites and other near-term structures. To make the engine more operationally efficient, the SSME derivative would utilize integrated health monitoring and controller advancements, built-in test equipment (BITE), and single-cast construction to reduce welds wherever possible.[9] These engines are throttled back for normal operation to 75% on the orbiter and 83% on the booster to provide single-engine-out capability on each and to increase individual engine life.

Flight Performance

The nominal POST ascent trajectory for the two-stage fully reusable vehicle is presented in Fig. 4. As shown in the figure, the initial T/W is 1.3. As propellant is burned, the vehicle accelerates until it enters the transonic flight regime at high dynamic pressure ($q_{max} = 700$ psf) at about 50 s. The large increase in drag causes the rate of acceleration to decrease for a short period of time. The vehicle then accelerates until staging occurs at Mach 3 at an altitude h of 91,000 ft. The unmanned booster then separates from the orbiter 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 more detail in Ref. 10. The orbiter continues to accelerate until the longitudinal acceleration limit of 3 g is encountered at 390 s. The engines are throttled to maintain this limit until orbital insertion occurs at 480 s into a transfer orbit with a 50-nmi perigee and 100-nmi apogee. Further details on ascent trajectories for the AMLS vehicle are contained in Ref. 11.

The nominal POST entry trajectory for the fully reusable orbiter is presented in Fig. 5. After performing a deorbit burn, the vehicle reaches nominal atmospheric interface (h = 3,000,000 ft) at a relative flight-path angle of -1 deg and an angle of attack of 30 deg. Throughout the majority of the entry profile, the angle of attack of the orbiter remains between 25 and 30 deg to allow hypersonic trim, maximize lift-to-drag ratio, and minimize leeside heating. POST was employed to minimize the maximum stagnation point heat rate during entry while still achieving sufficient cross range (a minimum of 1100 nmi) to allow once-around abort from a polar orbit. At an altitude of 260,000 ft, the stagnation point heat rate reaches 65 Btu/ft$^2\cdot$s. The bank angle of the vehicle is then modulated between 0 and 90 deg for about 1700 s to hold the heat rate below 69 Btu/ft$^2\cdot$s. This was found to be the minimum value that the maximum stagnation point heat could be held within and still achieve the desired cross range. When an altitude of 200,000 ft is reached, the bank angle gradually decreases, and the vehicle prepares for terminal energy management maneuvers. Using this approach, the orbiter is able to achieve about 1300 nmi of cross range.

Materials and Structures

The major material and structural technologies assumed for the AMLS booster and orbiter are summarized in Figs. 6 and 7. Both the booster and orbiter utilize a stiffened ring-frame

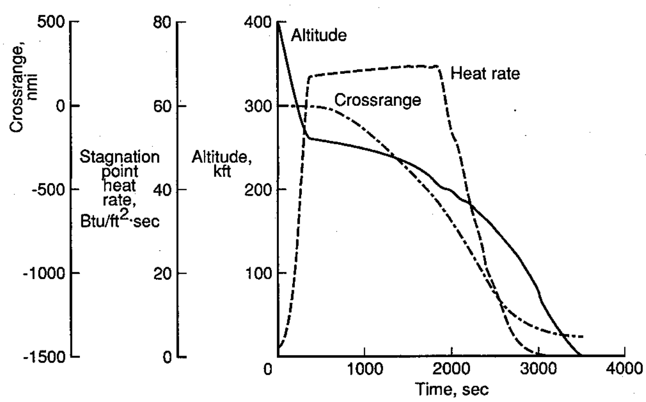


Fig. 5 AMLS entry trajectory plots.

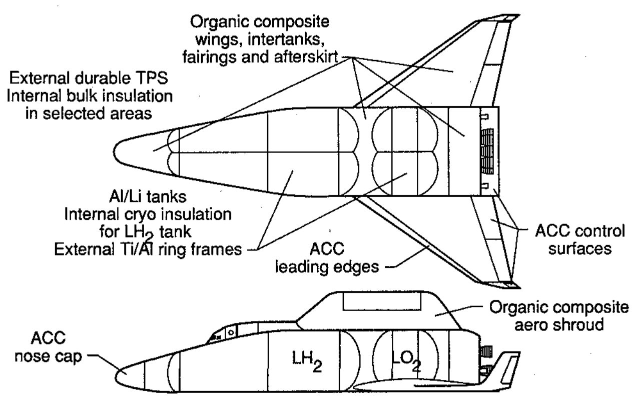


Fig. 6 AMLS orbiter materials.

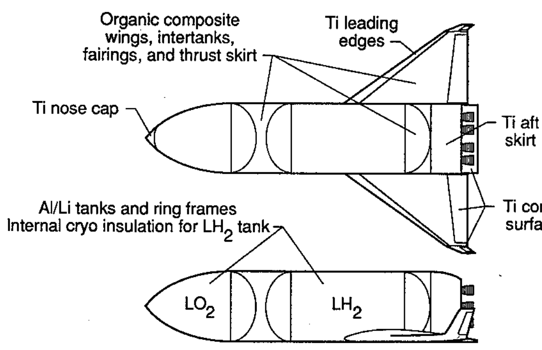


Fig. 7 AMLS booster materials.

construction with carrier panels and bonded durable metallic thermal protection system (TPS) tile sections where appropriate. The orbiter employs composite (graphite polyimide) wings, intertanks, fairings, and skirts that act as carrier panels for a durable metallic TPS on all windward and some leeward surfaces and for an advanced carbon-carbon (ACC) TPS on the vehicle nose, leading edges, and control surfaces. The booster, which experiences a much more benign heating environment, also employs composite wings, intertanks, and skirts, but utilizes a titanium structure for nose cap, leading edge, and surface control regions. Reusable cryogenic tankage is a crucial technology for the development of the two-stage fully reusable vehicle. Both the booster and the orbiter use a weldable aluminum-lithium alloy for integral hydrogen and oxygen tanks. The hydrogen tanks employ internal cryogenic insulation and external titanium-aluminide ring frames, whereas the oxygen tanks use external insulation with similar ring frames. As shown in Fig. 6, the orbiter propellant tanks are of a dual-lobe construction to allow a wide, flat orbiter planform. This greatly reduces planform loading during entry, thereby allowing the maximum heat rate to be two-thirds that of the Space Shuttle Orbiter.

Using the entry profile described earlier, the Miniver program was used to perform a windward centerline heating analysis of the orbiter vehicle. Some of the results of this analysis are presented in Fig. 8. For each x value along the windward centerline, the maximum value of the radiation equilibrium temperature that each point encounters throughout entry is plotted. For an emissivity of 0.8, the resulting temperatures require the use of an ACC material from the nose tip to 15 ft back along the centerline. From that point to the rear of the vehicle, Inconel superalloy (S/A) TPS panels with fibrous insulation are assumed. For windward and some leeward regions with temperature less than 1000°F, titanium (Ti) multiwall TPS panels would be employed. Figure 9 (from Ref. 12) shows the three durable TPS concepts used on the AMLS vehicle. As shown in the figure, all concepts are similar in weight to the current Shuttle Reusable Surface Insulation (RSI), which is far less durable. Further details on the construction and testing of each of these TPS concepts are contained in Ref. 12.

Operations

As mentioned previously, an attempt was made to give due consideration to ground and flight operations from the outset of the design of the two-stage fully reusable vehicle. Many of the advanced technologies and structures discussed earlier contribute to significant weight reductions and performance benefits over the current Space Shuttle; however, a large portion of this weight savings has been applied to aspects of vehicle design that enhance the operability, reliability, and safety of the system. Figure 3 summarizes many of these design-for-operations features. At the subsystem level, hydraulics are replaced with all-electric systems employing electromechanical actuators for engine gimbals and aerodynamic surface controls. Toxic hypergolic propellants in orbital maneuvering and reaction control systems are replaced by cryogenic hydrogen and oxygen utilizing common tankage with the main engine propellants. The advanced avionics employed are lighter, more powerful, and can help decouple the vehicle from a majority of ground-based mission control functions, thus introducing a significantly higher level of autonomy. Subsystems that are fault tolerant and possess built-in test equipment to monitor system conditions are essential for streamlined operations, especially in the propulsion system. Subsystem units, where feasible, are of a modular design for easy removal and replacement. Staging at a Mach number of 3 to allow for booster glideback and using a common booster and orbiter fuel (LH_2) for the AMLS vehicle both lead to small increases in vehicle dry weight yet contribute to significantly more streamlined operations. Allowing for single-engine fail-operational capability on both the booster and orbiter and incorporating a crew emergency escape module on the orbiter both lead to significant dry weight penalities but were judged to be important to enhance mission reliability and safety.

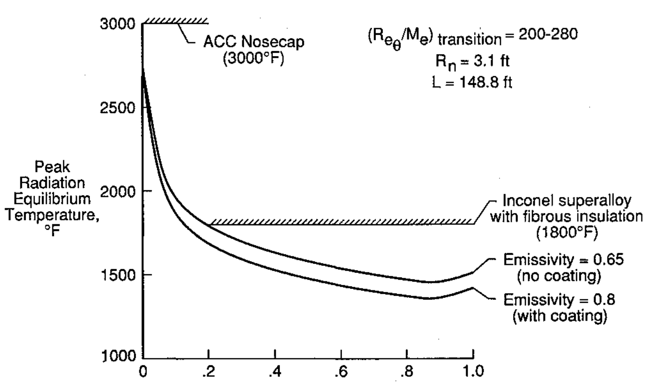


Fig. 8 AMLS orbiter entry windward centerline peak heating distribution.

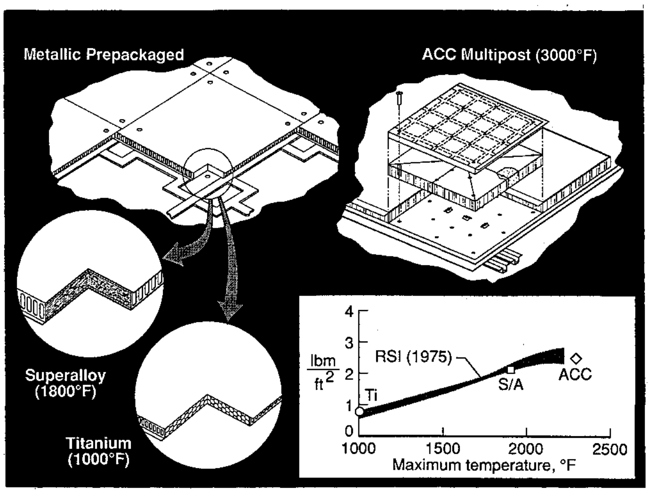


Fig. 9 Durable TPS concepts (from Ref. 12).

Analyses of AMLS ground operations have concentrated on estimating man-hours and timelines for the two-stage fully reusable vehicle based on historical data for the processing of a typical Space Shuttle flight (before the Challenger accident in 1986). Over 250 Shuttle processing actions were accounted for, and Shuttle task times were retained in the AMLS estimate unless new technologies, subsystems, or procedures were used. Elimination of systems eliminated manpower and task times. Introduction of new or unique technologies on the AMLS vehicle required estimates based on engineering judgment or comparable non-Shuttle system requirements. A rationale was developed for each of the processing actions to explain task time and manpower changes for the AMLS vehicle. Table 2 (from Ref. 2) gives an overview of the results of these analyses. As indicated in the figure, the processing manpower required for the AMLS vehicle, expressed in technician man-hours, is reduced to less than one-fourth that of the Space Shuttle. Ground and launch processing concepts for the two-stage fully reusable vehicle are pictured in Figs. 10 and 11 (from Ref. 13). The vehicles are processed horizontally after landing. The orbiter, booster, and payload are processed separately and then mated horizontally. The vehicle is then towed to the pad and erected for rapid launch. Further details on this ground operations analysis are contained in Ref. 8.

Parametric Trades

Liftoff Thrust-to-Weight Ratio Trade

Throughout the initial design of the two-stage AMLS fully reusable vehicle, a value of 1.3 was assumed for the liftoff

Table 2 Comparison of advanced manned launch system (AMLS) and Space Shuttle operational requirements for technician man-hours (from Ref. 2)

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
Thermal protection system	10,712	48
Propulsion	8,404	3,904
Propellants	4,080	118
Environmental control and life support system	1,730	640
Prime power	1,332	1,200
Avionics	1,604	1,133
Pyrotechnics	2,664	2,664
Flight crew systems	185	10
Contingency	4,896	3,371[a]
Payload install/remove	3,876	0[b]
Payload bay (configure/reconfigure)	3,336	0
Auxiliary power unit	416	0
Hydraulics	1,245	0
External tank	10,100	0
Solid rocket bosster	23,000	0
Total	94,925	20,406

[a]Assumed 20% for AMLS. [b]372 man-hours included in integration.

T/W. This was judged to be an optimal value based on the results of previous studies[14,15]; however, since such optimal parameters tend to be vehicle dependent, a trade study was performed using a variety of T/W values. The results of this parametric trade are presented in Fig. 12. This trade was performed for a thrust split of 60% of the liftoff thrust of the SSME-derivative engines on the booster and 40% on the orbiter.

The curves presented in Fig. 12 indicate that the minimum total gross weight occurs for a liftoff T/W of 1.5, and the minimum total dry weight occurs for a T/W of about 1.15. However, the minimum nonpropulsion dry weight occurs for a liftoff T/W of 1.3. The dry weight increases for higher T/W values because of the additional propulsion weight needed to achieve the required high thrust values. The gross weight increases for lower T/W values because of the additional time and propellant required to accelerate to orbital velocities. However, the slope of these curves is quite small. Choosing a liftoff T/W of 1.3 allows a healthy thrust margin, minimizes nonpropulsion dry weight, and causes less than a 1% increase in total dry weight over the minimum value.

Staging Mach Number Trade

Staging Mach number is another important design parameter for a two-stage fully reusable launch system. Reusable boosters considered in previous studies have staged at a variety of Mach numbers.[15,16] The design-for-operations approach used in the AMLS study led to the selection of 3 as the staging Mach number. Using the POST trajectory program, previous studies have demonstrated that the AMLS booster can glide back, unpowered, from a Mach 3 staging to both the Eastern Test Range (ETR) at Kennedy Space Center and the Western Test Range (WTR) at Vandenberg Air Force Base.[10] If a reusable booster stages at Mach numbers significantly greater than 3, it will require an additional propulsion capability, such as airbreathing engines, to enable a return to the launch site, and it will also require some additional TPS or heat sink material because of the increased aerodynamic heating encountered during a return from higher staging Mach numbers.

Figures 13 and 14 show how the total system dry weight and gross weight vary with staging Mach number, taking into account the additional weight of the airbreathing engines, fuel, and TPS required for the booster in each case. These results assumed a liftoff T/W of 1.3 and a thrust split of 60% on the booster and 40% on the orbiter. These graphs indicate that, even when the extra engines and TPS are accounted for, both the dry weight and gross weight of the vehicle configuration are minimized at a staging Mach number of about 5.5 or 6.0. A study was also performed to see how the total gross and dry weights vary with staging Mach number when no extra TPS or airbreathing engines are added. These results are also presented in Figs. 13 and 14. These graphs show that if the AMLS two-stage configuration were to stage at Mach 6 with the necessary TPS and airbreathing propulsion on the booster, instead of staging at Mach 3 where no additional systems are required, a 4% savings in dry weight and a 14% savings in gross weight could be accomplished.

On the basis of these results, the desirability of a staging Mach number of 6 may appear obvious. However, there are

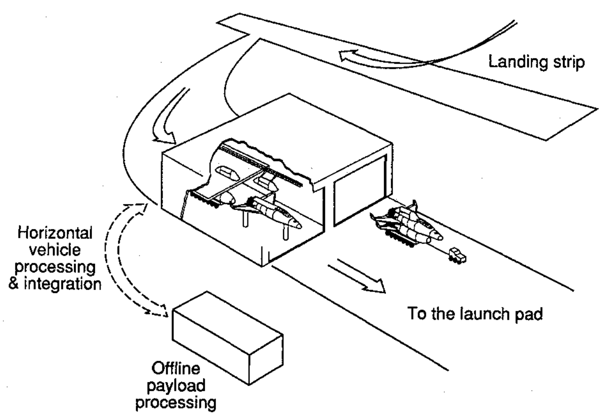


Fig. 10 AMLS ground processing concept.

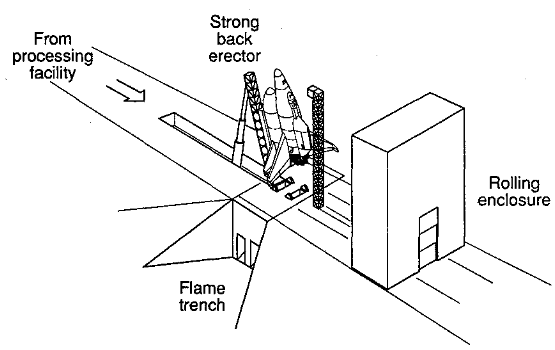


Fig. 11 AMLS launch processing concept.

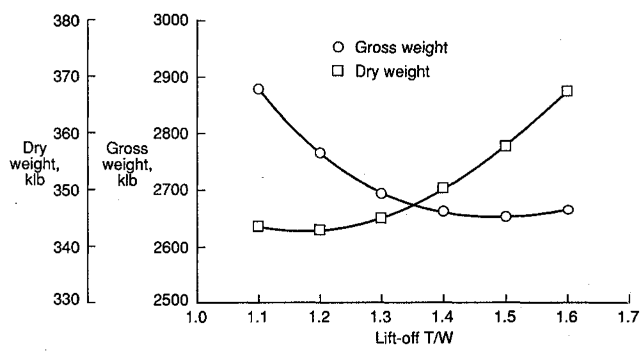
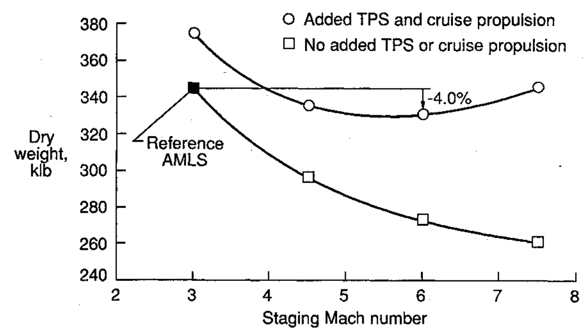


Fig. 12 Liftoff T/W trade for AMLS vehicle.

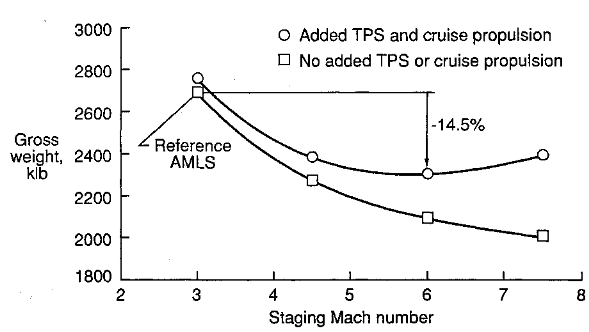
many other issues to be considered. The main arguments for a Mach 6 staging system are the fairly significant weight savings mentioned earlier that lead to reduced production costs and the ability of the booster to have go-around capability upon return to the launch site for landing using airbreathing engines. However, the decrease in operations costs and complexity caused by the elimination of the entire airbreathing system, coupled with the decrease in development and testing costs and time, could more than offset these advantages if a Mach 3 staging booster is employed. The elimination of the airbreathing return engines, which could malfunction, should also lead to an increase in vehicle reliability. A Mach 3 staging system should also be more reliable because of the benign heating environment, line-of-sight communication with the booster from the launch site, and shorter booster return time (7 min).

A final issue to be considered is the size match between the orbiter and the external payload canister. As the staging Mach number increases, the orbiter continues to decrease in size significantly. The reference Mach 3 staging orbiter pictured in Fig. 2 has a length of 149 ft, whereas the corresponding Mach 6 staging orbiter has a length of only 119 ft. Hence, additional dry weight would likely have to be added to configure the Mach 6 staging orbiter to properly accommodate the required payload volume and to assure that the aerodynamic performance is not compromised substantially. After consideration of all of the issues involved, a Mach 3 staging system was adopted for the two-stage fully reusable configuration; however, a more detailed quantitative study of the operational complexity of a Mach 6 staging system would be required to properly evaluate these results.



• Lift-off T/W held to 1.3
• Thrust split held to 60% on booster, 40% on orbiter

Fig. 13 Dry weight variation with staging Mach number for AMLS vehicle.



• Lift-off T/W held to 1.3
• Thrust split held to 60% on booster, 40% on orbiter

Fig. 14 Gross weight variation with staging Mach number for AMLS vehicle.

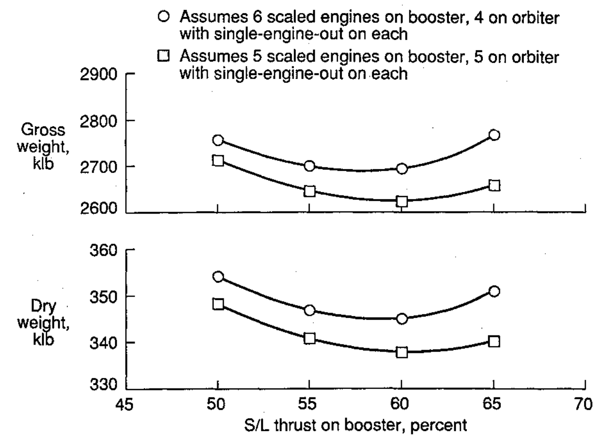


Fig. 15 Thrust split trade for AMLS vehicle (with liftoff $T/W = 1.3$).

Thrust Split Trade

In the design of a two-stage, parallel-burn launch system, the percentages of the total thrust attributed to the booster and orbiter engines significantly influences vehicle sizing. The variation of total vehicle dry weight and gross weight with the percentage of sea-level thrust on the booster is presented in Fig. 15 for the two-stage fully reusable vehicle. For the purpose of this trade, the SSME-derivative engines are scaled up or down as appropriate to satisfy the thrust percentages. These trades were conducted for vehicles with a liftoff T/W of 1.3. Both the booster and orbiter can each lose the thrust of a single SSME-derivative engine and still fully complete the design mission by throttling up the remaining engines. For the case of six engines on the booster and four on the orbiter, the booster engines operate at a normal power level of 83% and the orbiter engines at 75%. For the case of five engines on each, all engines operate at a normal power level of 80%. For emergency operation, the engine power levels increase to their maximum rated level of 100%.

As indicated in the figure, the vehicle with about 60% of the liftoff thrust on the booster has the minimum dry and gross weights. The configuration that assumes five engines on both the booster and orbiter has a lower dry weight over the entire range of thrust splits than the case with six engines on the booster and four on the orbiter. This is because the orbiter engines are only throttled back to 80% rather than 75%. Hence, the orbiter, which must travel the entire trajectory and is the heaviest and most sensitive stage, pays less of a penalty to have single-engine-out capability. By further scaling down the size of the orbiter engines, the number of engines on the orbiter could perhaps be increased to more than five to generate a vehicle with an even lower dry weight; however, additional engines would increase the risk of multiple engine shutdowns on the manned orbiter, thereby decreasing overall reliability and safety.

The two particular engine distributions between the booster and orbiter shown in Fig. 15 were chosen because six unscaled SSME derivatives ($\epsilon = 77.5$) could be used in the booster and four of the same unscaled SSME derivatives ($\epsilon = 35$) could be used on the orbiter with almost no penalty when compared with the ideal case of using scaled SSME derivatives. A vehicle was also designed using five unscaled SSME derivatives on both the booster and orbiter. This vehicle had almost the exact same total dry weight as the vehicle with six unscaled SSME derivatives on the booster and four on the orbiter; however, the dry weight of the more costly and sensitive orbiter vehicle was significantly higher than the orbiter with only four engines. Hence, the configuration with six unscaled SSME derivatives on the booster and four on the orbiter was chosen as a reference. All other combinations of numbers of unscaled SSME derivatives on the booster and orbiter would require a large weight penalty to incorporate because of the poor thrust match.

Single-Engine-Out Trade

A ground rule of the AMLS study was that the booster and orbiter should each have the capability of losing the thrust of an engine anytime during launch and ascent and still completely fulfill the mission requirements. As mentioned earlier, to achieve this engine-out capability, the engines on both the orbiter and booster are throttled back for normal usage. Then, in the event of losing a single engine, the remaining engines are throttled to 100% to compensate for the loss of thrust. As indicated in Fig. 16, the penalty for this additional capability using unscaled SSMEs on the reference two-stage vehicle is a significant 9% in dry weight. However, the increased vehicle reliability and mission success should bring about a quantitative reduction in recurring costs and a qualitative increase in crew and mission safety. Throttling the main engines in this manner should also contribute to longer engine life and increased engine reliability to help offset the large dry weight penalty.

Dual-Position Nozzle Trade

One of the enhancements to the SSME currently under investigation is the employment of a dual-position nozzle to

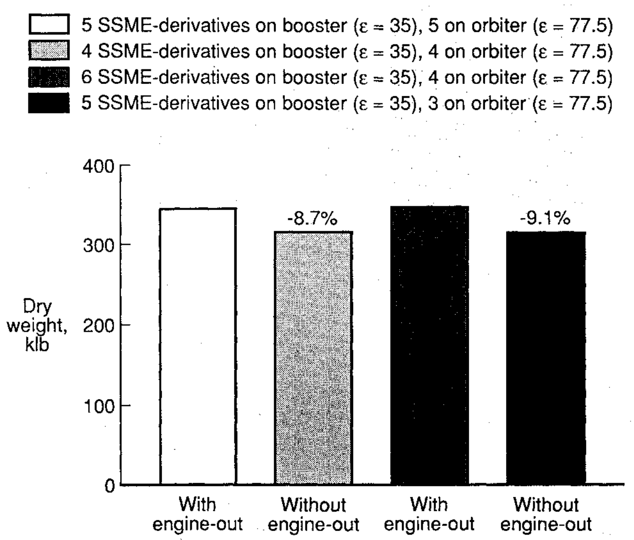


Fig. 16 Single-engine-out trade using unscaled SSME-derivative engines for AMLS vehicle.

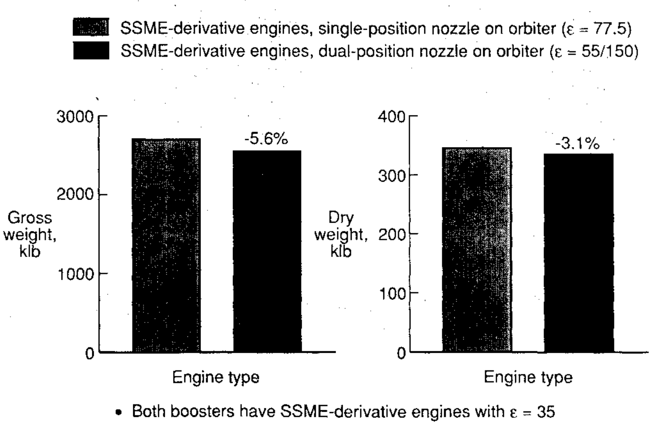


Fig. 17 Dual-position nozzle trade for AMLS vehicle.

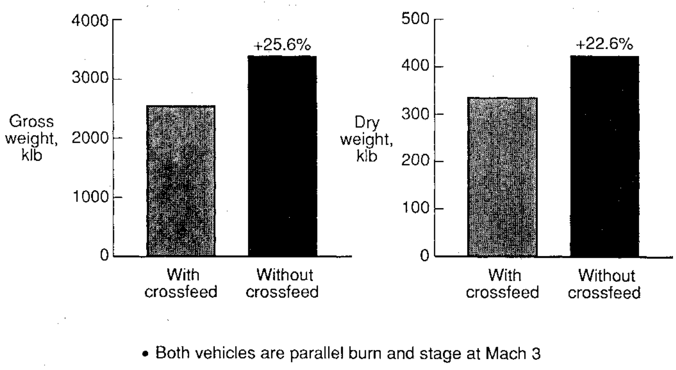


Fig. 18 Cross-feed trade for AMLS vehicle.

enhance performance. The primary nozzle, which is regeneratively cooled, with an area ratio of 55 would be used during the lower part of the trajectory to enhance sea-level thrust. The secondary nozzle, which is film cooled, is then extended to provide an area ratio of 150 later in the trajectory to enhance vacuum thrust. The two-stage fully reusable vehicle was redesigned using SSMEs with this dual-position nozzle on the orbiter and a single-position nozzle with an area ratio of 35 on the booster. POST was used to determine the optimal time for nozzle extension. The results of this trade using scaled SSMEs on the booster and orbiter are summarized in Fig. 17. A 3% penalty would be incurred by not using the dual-position nozzle. The added production costs caused by this vehicle dry weight increase must be weighed against the developmental risks, added production costs, and the operational complexity involved in the use of a dual-position nozzle.

Cross-Feed Trade

The ascent configuration employs a cross-feed system whereby propellants are drawn from the booster propellant tanks and fed directly to the orbiter main engines allowing the orbiter tanks to be full of propellants at staging. Figure 18 illustrates the weight savings afforded by the utilization of such a system on the Mach 3 staging fully reusable vehicle. A parallel-burn vehicle without cross-feed capability would have a 26% higher gross weight and a 23% higher dry weight. Using this cross-feed system, the booster and orbiter are sized so that the booster propellants are depleted when the vehicle reaches Mach 3. At this point, the booster glides back to the launch site, and the orbiter continues to orbit with the payload. The added cost and complexity of such a system were judged to be minimal when compared with the large dry and gross weight savings on the vehicles, especially since there is an experience base with the cross-feeding of cyrogenic propellants from the Space Shuttle external tank to the orbiter.

Payload Inclination Trade

Although the AMLS fully reusable vehicle is designed to carry 40,000 lb of payload to the Space Station (28.5-deg inclination, 220 nmi), the amount of payload that can be transported to orbits with other inclinations using this same vehicle is also of interest. Depending on the mission, the two-stage fully reusable vehicle would utilize two different launch sites because of launch azimuth constraints. For missions to low-inclination orbits, the vehicle would be launched from ETR at Kennedy Space Center. For missions to high-inclination orbits, the vehicle would be launched from WTR at Vandenberg Air Force Base. The WTR facility would be needed because polar launches from ETR would have to occur over land or require expensive orbital plane changes, neither of which is desirable. The results of this payload inclination trade are summarized in Fig. 19. All launches from ETR that were examined include sufficient orbital maneuvering system (OMS) and propellant weight to get to and from a 220-nmi circular orbit ($\Delta V = 1350$ ft/s), are configured for a 35-man-

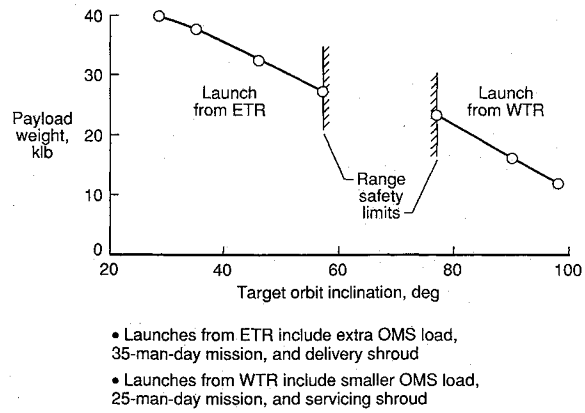


Fig. 19 Payload inclination trade for AMLS vehicle.

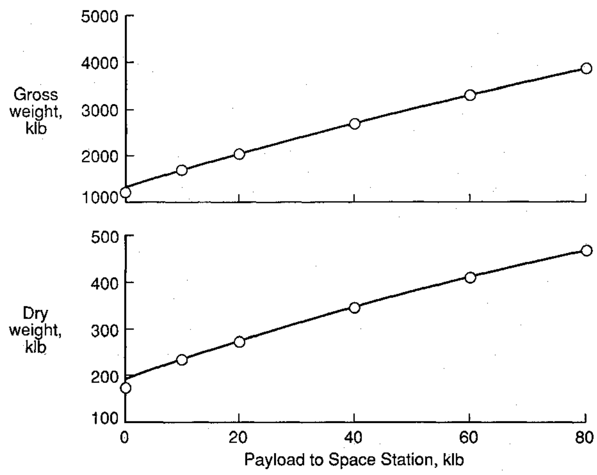


Fig. 20 Payload sizing trade for AMLS vehicle.

day mission, and employ a payload shroud configured for delivery missions. All launches from WTR that were examined include sufficient OMS propellant to get to and from a 150-nmi circular orbit ($\Delta V = 850$ ft/s), are configured for a 25-man-day mission, and employ a payload shroud configured for servicing missions. The figure indicates that, as the inclination angle of the target orbit decreases, the payload capability of the vehicle increases. This is because lower inclination angles allow the vehicle to utilize a larger component of the Earth's rotational velocity to give it a sizable initial inertial velocity. Since the same vehicle is used for each mission, the vehicle has the capability of returning 40,000 lb of payload from any target orbit.

Payload Sizing Trade

The reference mission for the two-stage AMLS vehicle was chosen to be the delivery and return of 40,000 lb from the Space Station. Should future mission needs change, the two-stage fully reusable vehicle may be designed to other reference mission payload weights. Figure 20 presents the results of a trade study in which the two-stage fully reusable vehicle was resized for a range of Space Station design mission payloads. For each payload, the delivery shroud was reconfigured to allow sufficient volume and support equipment for a reasonable payload density and shape. The vehicle weight variation is essentially linear with the exception of the 0-lb-payload vehicle, which has no shroud. The slope of these linear variations indicates that, if 1 lb of payload were added to the vehicle, its total dry weight would increase by about 3.6 lb. Of this total, 2.1 lb of the increase is in the orbiter total and 1.5 lb of the increase is attributed to the booster.

Summary

A rocket-powered, two-stage fully reusable launch vehicle has been designed as a part of the advanced manned launch system study to examine options for a next-generation manned space transportation system. A reference geometry was chosen, the vehicle aerodynamics were evaluated, a propulsion system was selected, ascent and entry trajectories were analyzed, a centerline heating analysis was performed, baseline structural concepts and thermal protection system materials were selected, and a weights and sizing analysis was performed. Analyses of operational characteristics and manpower requirements for the AMLS vehicle were performed to determine what new technologies and methods could be employed to reduce vehicle turnaround time and recurring costs. Exploitation of a number of new technologies results in significant weight savings that can be returned to the vehicle in the form of robust subsystems, increased reliability, and assured mission success. Technology developments in the areas of reusable cryogenic tankage, low-cost main propulsion with integrated health monitoring, low-maintenance thermal protection systems, electromechanical actuators, and self-monitoring fault-tolerant systems will be instrumental in assuring the readiness of low-cost, next-generation space transportation systems.

A series of parametric trade studies were also performed on the reference AMLS vehicle to determine the effect of varying major vehicle parameters. A number of these were summarized in this paper. A liftoff thrust-to-weight ratio of 1.3, a staging Mach number of 3, and a thrust split of four Space Shuttle main engine derivative engines on the orbiter and six of the same engines with a smaller area ratio on the booster were selected as a result of these trades. The effect of having single-engine-out capability on both the booster and orbiter was found to be a significant 9% penalty in total dry weight. Use of a dual position nozzle was found to provide only a 3% benefit in total vehicle dry weight. The study also showed that the cross feeding of propellants from the booster to the orbiter main engines allowed a significant 23% dry weight reduction. The variation of payload capability was examined for a variety of target orbit inclinations for launch from both the Kennedy Space Center and Vandenberg Air Force Base. The vehicle was also resized for a number of different payload delivery and return missions to the Space Station Freedom, and total vehicle sensitivity to payload and dry weight increases was determined.

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