Propulsion System Optimization for Advanced Manned Launch System Vehicles

Douglas O. Stanley* and T. A. Talay*
NASA Langley Research Center, Hampton, Virginia 23661

The results of using a computerized preliminary design system to integrate next-generation propulsion system concepts with reference vehicle concepts from the Advanced Manned Launch System (AMLS) study are presented. The major trade study presented is an analysis of the effect of using a single fuel for both stages of two-stage AMLS reference vehicles as opposed to using a separate fuel for the boosters. Other trade studies presented examine the effect of varying relevant engine parameters in an attempt to optimize the reference engines for use with the AMLS launch vehicles. In each propulsion trade discussed, special attention is given to the major vehicle performance and operational issues involved.

Nomenclature

g	= acceleration of gravity (32.2 ft/s^2)
Isp	= specific impulse
LH_2	= liquid hydrogen (at 4.43 lb/ft^3)
LOX	= liquid oxygen (at 71.2 lb/ft^3)
O/F	= oxidizer-to-fuel ratio
T/W	= thrust-to-weight ratio
ϵ	= area ratio

Introduction

OVER the past few years, 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 ongoing Advanced Manned Launch System (AMLS) study (formerly the Shuttle II study).[1,2] The AMLS effort is part of a NASA study to define options for the next manned space transportation system. The goals of this broader effort are to define systems that meet future mission requirements of transporting personnel and payloads requiring a manned presence with an emphasis on improved cost-effectiveness, increased vehicle reliability, and large operational margins.

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 costs relative to current systems. The vehicles 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.

A key technology for any advanced launch system is propulsion. In order to address the propulsion needs of advanced space transportation systems, the space transportation main engine (STME) and space transportation booster engine (STBE) studies were initiated in early 1986, and the phase A studies were recently completed. These studies examined a wide variety of engine designs and liquid propellant combinations to determine the best propulsion systems for use with heavy-lift launchers in the late 1990s. Although the STME/STBE studies are being conducted primarily for application to the Advanced Launch System (ALS) program vehicles, the results of these studies are also useful to the AMLS study. Since the reference engine configurations from the STME/STBE studies are designed to be much more operationally efficient than their predecessors (often at the expense of performance considerations), the results of these studies will be quite useful to the AMLS study by indicating what types of operationally efficient engines will be available to be incorporated into a 1992 vehicle development program.

The purpose of this study is to integrate some of the results of the STME and STBE studies with the AMLS configuration studies in order to identify the most promising vehicle and propulsion concepts for future development. These results are also compared to the use of the current Space Shuttle main engine (SSME) as the primary propulsion system. For a selected propulsion system, further trade studies are conducted for parameter optimization and integration into the fully reusable, two-stage AMLS vehicle concept.

Analysis

The trades presented in this paper require proper consideration of the effects on trajectory, weights/sizing, geometry, and aerodynamics. All of the trajectory analyses for the AMLS vehicle trades presented in this paper were performed using the three-degree-of-freedom Program to Optimize Simulated Trajectories (POST).[3] POST is a three-dimensional generalized point mass, discrete parameter targeting, and optimization program, which allows the user to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate planet. The weights and sizing analysis was performed by using the in-house Aerospace Vehicle Interactive Design (AVID) weights/sizing package containing all of the current AMLS technology assumptions. Some trades also required changes in geometry, packaging, and aerodynamics. These changes were accomplished using the in-house Solid Modeling Aerospace Research Tools (SMART) geometry package[4] and the Aerodynamic Preliminary Analysis System (APAS) aerodynamics program.[5]

Many of the trade studies performed on the reference AMLS configurations require only the use of POST and the

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*Aerospace Technologist. Member AIAA.

AVID weights and sizing program. For example, to determine the effect of lift-off thrust-to-weight ratio (T/W) on the reference fully reusable AMLS vehicle, the necessary modifications must first be made to the propulsion equations of the weights and sizing program to account for the new T/W. Then, an initial guess is made for the mass ratio (i.e., the ratio of gross lift-off weight to burnout or injected weight) of the booster and orbiter. The weights and sizing program 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 weights and 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. Then, a POST 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 method is repeated until enough data points are obtained to demonstrate how the reference vehicle changes with variations in lift-off T/W. Some trade studies, like that of changing booster fuels, require additional iteration with geometry and aerodynamics. It should be noted that each data point represents a converged vehicle design using this method.

Vehicle Concepts

A variety of different vehicle configurations were considered as options for a next-generation manned launch vehicle, including single-stage-to-orbit, expendable, and air-breather/rocket concepts.[1,2] Those chosen for more detailed study are presented in Fig. 1. All three vehicles are designed for the same missions and technology levels. Each vehicle is designed to carry 12,000 lb to a polar servicing orbit (98 deg inclination, 150 n.mi. circular) from the Western test range at Vandenberg Air Force Base. This allows payload capabilities ranging from 20,000 to 40,000 lb to a space station orbit (28.5-deg inclination, 220-n.mi. circular) if launched from the Kennedy Space Center. The cylindrical payload bay is 30 ft long and 15 ft in diameter. Each vehicle also can support a crew of five persons for 5 days. Each orbiter has a 1100-n.mi. cross-range capability to allow once-around abort from polar orbit. Both the ascent and entry trajectories of each 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.

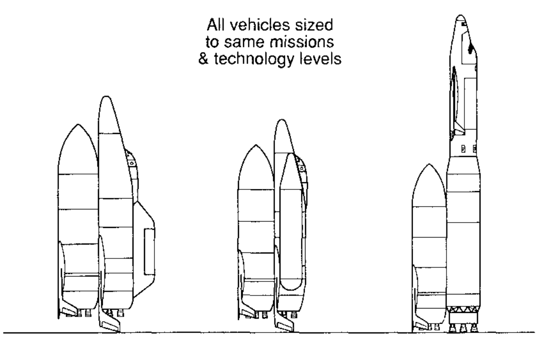

Fig. 1 Reference AMLS vehicle concepts.

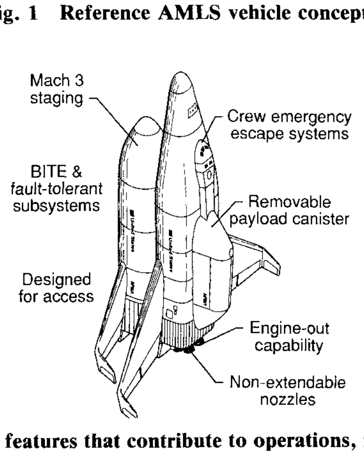

Fig. 2 AMLS features that contribute to operations, reliability, and safety.

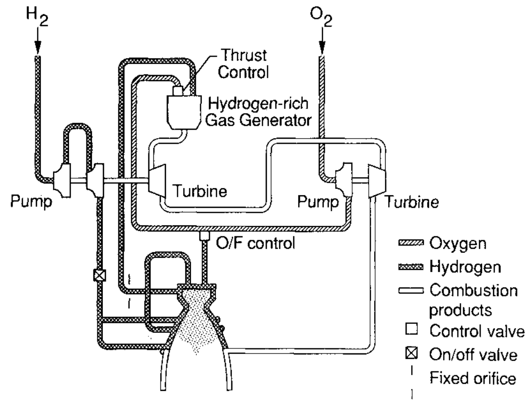

Fig. 3 Simplified flow schematic of reference STME engine.

The first concept shown in Fig. 1 is a parallel-burn, fully reusable, two-stage vehicle with an unmanned winged booster that stages at a Mach number of 3 and glides back to the launch site. Propellant is cross fed from the booster to the orbiter during the boost phase so that the orbiter is full of propellant at staging. 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 wing tip fins for lateral control. Integral, reusable, cryogenic tankage is used on both the booster and orbiter. Figure 2 shows this fully reusable concept and demonstrates the "design-for-operations" approach assumed in the AMLS study, where due consideration is paid to the effects of vehicle design on recurring costs from the outset of the design process.[2]

The second vehicle pictured in Fig. 1 is a partially reusable vehicle with drop tanks attached to the orbiter. This vehicle is similar to the fully reusable vehicle in all respects except that the liquid hydrogen fuel required for the orbiter is carried in expendable drop tanks that are jettisoned after orbital insertion. Since the hydrogen fuel is carried external to the orbiter fuselage, the payload can now be carried internally. The booster is also sized to stage at a Mach number of 3 to avoid an adverse heating environment and glides back to the launch site.

The final option presented is the partially reusable booster-core-glider configuration. In this configuration, the booster also stages at Mach 3 and glides back to the launch site; however, the second stage consists of an expendable core with a glider on top. The glider has no main propulsion and has an internal payload bay. The booster and core stages are sized to be the same diameter to help minimize tank manufacturing costs. A propellant cross-feed system is employed so that the core vehicle is full of propellant at staging and continues to orbit. The entire core stage, including propulsion, is expended after orbital insertion of the glider.

Propulsion Concepts

All three of the STME contractors agreed that the next generation of main engines should use hydrogen fuel and oxygen. There was also general agreement that the significantly higher T/W ratio characteristic of a gas generator cycle engine made it preferable to the higher-performance staged combustion cycle engines. The performance parameters for the phase A en-

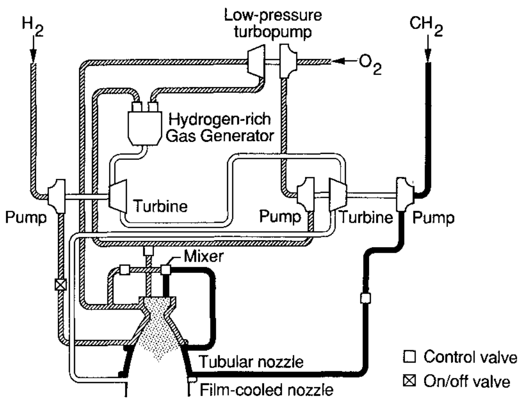

Fig. 4 Simplified flow schematic of reference STBE engine.

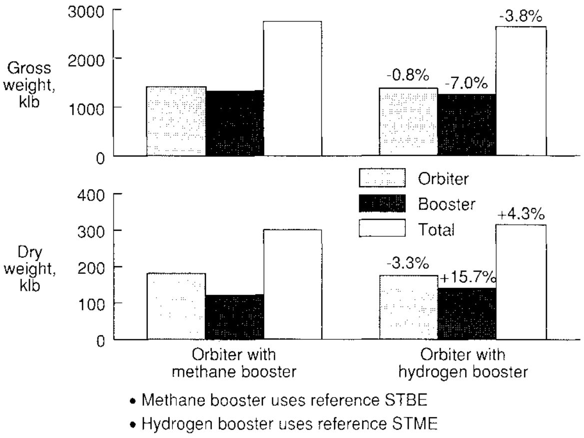

Fig. 5 Single-fuel vs dual-fuel propulsion trade for fully reusable AMLS vehicle.

gines recommended by each of the three contractors were judged to be comparable.[7] For the purposes of the AMLS study, an STME gas generator engine recommended by one of the contractors was chosen as a baseline for the main propulsion system on all of the AMLS vehicle concepts. The nozzle of this engine uses both regenerative and film cooling. A simplified flow schematic is depicted in Fig. 3. For each of the trades presented, this engine has been sized for use with the AMLS vehicles.

As part of the phase A STBE studies, a wide variety of engines were studied using methane, propane, and RP-1 as booster fuels. For the most part, there was general agreement that methane was the best fuel for use in reusable booster engines to be developed for a first flight in the late 1990s. For the purposes of the AMLS study, a baseline STBE engine recommended by the same contractor as the reference STME was chosen as representative of the various engines considered. This engine is a gas generator cycle engine that uses hydrogen fuel in the gas generator to drive the turbopumps and also uses some hydrogen for cooling parts of the nozzle. For each of the trades presented, this engine has also been sized for use with the AMLS vehicles. A simplified flow schematic is shown in Fig. 4.

The STME and STBE engines selected, like the reference AMLS vehicle concepts, have been designed with operational considerations in mind from the outset in an attempt to minimize recurring costs. It is estimated that the number of welds and parts requiring inspection can be dramatically reduced from previous engine designs (notably the SSME). Provisions for easy access to all major components have been a priority from the outset. The STME can throttle from a normal power level of 100–133%, and the STBE can throttle from a normal power level of 100–120%. These throttling capabilities were provided to allow single-engine-out capability from launch to orbit.

Further information concerning the engines chosen for this study can be obtained from Ref. 6. More detailed engine information is available in reports published by the STME/STBE contractors; however, these reports are currently limited to U. S. governmental agencies and their contractors, hence many engine parameters cannot be provided in this paper. It should be noted that each of the STME contractors have extended their phase A studies in an attempt to bring about an order of magnitude reduction in engine production costs over current engine designs. These cost reductions have brought about large decreases in engine performance and reusability and large increases in total engine weight. Although these performance penalties might be acceptable for the unmanned, largely expendable ALS vehicles, they were judged to be undesirable for the more sensitive, manned, reusable AMLS vehicles.

Results

Dual-Fuel vs Single-Fuel Trade Using STME/STBE Reference Engines

The main purpose of this paper is to compare the effects of using a single fuel (hydrogen) for the reference AMLS vehicles as opposed to separate booster and orbiter fuels. Methane and hydrogen fuels have different densities and specific impulses, and their use leads to engines with different T/W values and vehicles with different tank efficiencies. Each of these factors should be properly weighed against the others to get a complete picture of the effect of choosing one fuel over another. The results of changing from a methane-fueled to a hydrogen-fueled booster for the fully reusable AMLS configuration are summarized in Fig. 5. As shown in Fig. 5 the total dry weight penalty for changing to a vehicle with STME engines on the booster from one with STBE engines is only 4.3%, whereas the gross weight of the single-fuel vehicle is actually 3.8% less than its dual-fuel counterpart. Fig. 5 also indicates that the effect of this trade on the booster alone is much more pronounced. The dry weight of the hydrogen booster is 15.7% higher than that of the methane booster, whereas its gross weight is 7% less. (The "dry weight" referred to throughout this paper is the landed weight of the vehicle without fluids, crew, payload, or payload provisions. Because vehicle production costs tend to vary as a direct function of dry weight rather than gross weight, dry weight is an important parameter to examine in future launch system trades.)

It is important to examine the factors that contribute to these percentages. The most obvious reason for the LH_2-fueled booster's higher dry weight is the fact that the propellant bulk density for the STME booster is 31% lower than that of the STBE booster. The reference STME engine also has a lower T/W than that of the STBE. This lower propellant bulk

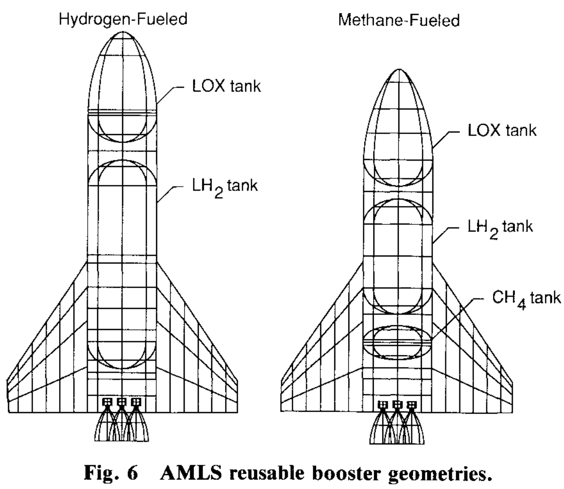

Fig. 6 AMLS reusable booster geometries.

density contributes directly to higher structural dry weights because of increased tank size, and the lower T/W of the STME engine contributes directly to higher propulsion system dry weights. These factors are somewhat offset by the significantly higher specific impulse (Isp) of the STME engine. From the two boosters shown in Fig. 6, one can see that the elimination of the booster methane tank allows an increase in tank efficiency (excluding the engine compartment) for the STME booster of 13%. However, the increases in Isp and tank efficiency cannot completely offset the large decrease in propellant bulk density for the LH_2-fueled system, and a total vehicle dry weight penalty of 4.3% remains (however, the nonpropulsion dry weight penalty is only 2%). The most obvious contributing factor to the lower gross weight of the single-fuel vehicle is the much higher specific impulse of the hydrogen-fueled STME engine. This increase in Isp contributes to a 4.3-% better mass ratio (i.e., ratio of gross weight to orbital insertion weight), which contributes directly to a lower total gross weight. This performance increase tends to outweigh considerations of propellant bulk density, engine T/W, and tank efficiency and leads to a total gross weight decrease of 3.8% for the single-fuel system.

Figure 7 illustrates the results of extending this trade to each of the reference AMLS concepts described earlier. All vehicles are sized for the same missions, and the same levels of technology assumptions are used for each configuration. Although these vehicles have varying degrees of reusability, the basic trends of dry weight and gross weight variation remain. The single-fuel vehicles tend to have slightly higher dry weights and slightly lower gross weights than the dual-fuel vehicles.

Although a 4.3% total dry weight penalty is incurred by the use of STME engines on both the orbiter and booster, there are many advantages that make a single-fuel system desirable. The most significant of these is the deletion of the development program for the methane engine. The estimated development cost of the baseline STBE engine used in this study is \$1.8 billion. This cost savings must be weighed against the increased vehicle production costs caused by the single-fuel vehicle's 2% higher nonpropulsion dry weight. Use of a single fuel is especially attractive for the "designed-for-operations" system approach proposed for AMLS. Operations would be expedited because of the common engine systems on the booster and orbiter. Elimination of the hydrocarbon fuel would also eliminate the associated storage, handling, and management organizational structure. Individual engine production costs would also be reduced because of increased line production of only one type of engine. Cleaner-burning hydrogen fuel also has fewer negative impacts on the engine environment and the environment of the launch area. Burning hydrogen rather than methane would also provide a more benign heating environment for the base heat shield and aft

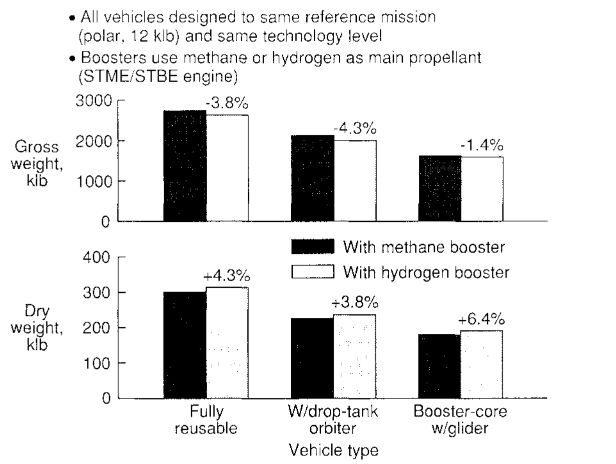

Fig. 7 Single-fuel vs dual-fuel propulsion trade for reference AMLS vehicle concepts.

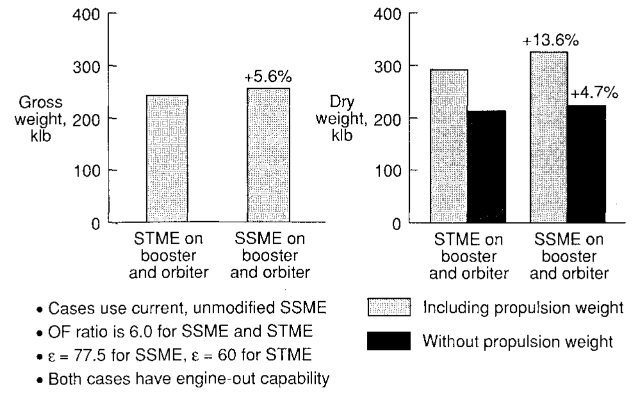

Fig. 8 SSME vs STME trade for fully reusable, all LH_2-fueled AMLS vehicle.

control surfaces of the booster. Because of these many advantages, a LH_2-fueled vehicle was chosen as the baseline for the AMLS study, despite the small dry weight penalty incurred.

The results obtained in the AMLS booster fuel trade compare well with those obtained in Ref. 7 for a generic, two-stage vehicle delivering 30,000 lb to a space station orbit. It should be noted that previous studies of future launch systems have shown much higher dry weight penalties for using LH_2-fueled, two-stage vehicles. The penalty was found to be 10% in the 1984 Orbit-on-Demand (OOD) study[8] and about 8% in the earlier Future Space Transportation Study (FSTS).[9] However, these previous studies have used propane and RP-1 as booster fuels, which are more dense than methane. Perhaps more important, booster engines used in these previous studies had more optimistic T/W values. Hence, if the methane-fueled engines chosen as a reference for the AMLS study are the optimum reusable hydrocarbon engines available for use in the late 1990s, serious consideration of using liquid hydrogen as the primary liquid booster fuel for the next generation of launch vehicles should be made.

Comparison of SSME and Reference STME Engine

Because an all LH_2-fueled vehicle was chosen to be a baseline concept for the AMLS study, the question arises as to whether or not the existing SSME would be an attractive primary propulsion system for a next-generation launch system. The advantages of using the SSME on future launch systems are obvious. The cost of a new engine development program (such as the STME) would be eliminated. There would also be a large experience base to rely on if the SSME were employed For comparison purposes, the fully reusable AMLS vehicle was redesigned using SSME engines on both the booster and orbiter. Figure 8 compares the SSME-powered AMLS fully reusable vehicle to a similar one with STME propulsion. It was found that the vehicle with SSMEs is 13.6% higher in total dry weight and 5.6% higher in gross weight than the comparable STME-powered vehicle; however, it is only 4.7% higher in nonpropulsion dry weight. It is assumed that these relative percentages would not change significantly if nozzles with more optimal area ratios were used on both the STME and SSME during boost phase. From a development viewpoint, this dry weight increase might not be considered large enough to invest in a new engine program. However, the design of the SSME was driven by performance considerations, and its operational characteristics have suffered as a result. Various SSME operational activities are considered to be on the "critical path" of Space Shuttle processing for about 11.5 of the 26 days normally spent in the orbiter processing facility.[10] Use of such an engine in its present form runs counter to the AMLS study goals of significant reductions in recurring costs and vehicle turnaround time. The reference STME chosen for the AMLS study operates at a much lower chamber pressure and, as mentioned previously, employs a variety of features that

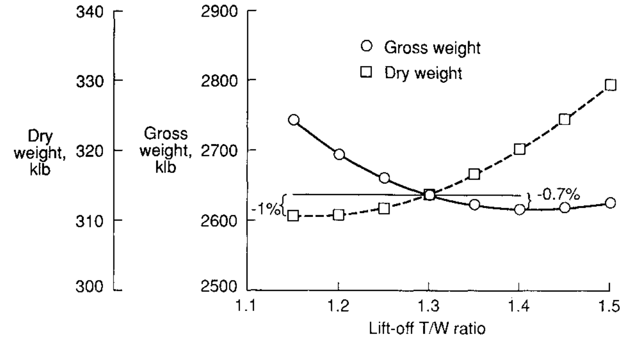

Fig. 9 Lift-off T/W ratio trade for fully reusable, all LH_2-fueled AMLS vehicle.

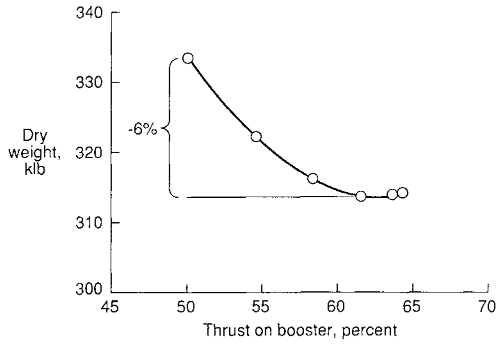

Fig. 10 Lift-off thrust split trade for fully reusable, all LH_2-fueled AMLS vehicle.

should make it more operationally efficient and less expensive per engine. Whether or not these operational advantages offset the cost of developing a new reusable hydrogen engine would depend greatly on AMLS flight rates and fleet size. Further study is required to adequately evaluate the cost effectiveness of employing the SSME or its derivatives on future launch systems.

Fully Reusable Concept Propulsion Trade Studies

The following section contains a series of trade studies conducted to size the reference STME engines for the fully reusable AMLS vehicle and to optimize various propulsion system parameters with respect to overall vehicle dry weight. The parametric relations used to perform these trades were obtained from the designers. Each data point represents a vehicle that is a result of iteration between trajectory, weight/sizing, and (where necessary) geometry and aerodynamics.

Lift-Off Thrust-to-Gross Weight Ratio Trade

Throughout the design of the reference AMLS fully reusable vehicle, a value of 1.3 was assumed for the lift-off T/W. This was judged to be an optimal value based on the results of previous studies[8,9]; however, since such "optimal" parameters tend to be very vehicle-dependent, a trade study was performed using a variety of T/W values. The results of this parametric trade for the single-fuel fully reusable vehicle are presented in Fig. 9. (A similar trade was performed for the dual-fuel vehicle, and the results are almost identical.) This trade was performed for a thrust split of seven STME-type engines on the booster and four identical engines on the orbiter.

The curves presented in Fig. 9 indicate that the minimum total gross weight occurs for a lift-off T/W of 1.4, and the minimum dry weight occurs for a T/W of about 1.15. It should also be noted that the minimum nonpropulsion dry weight occurs for a lift-off 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, as indicated on the graph, the slope of these curves is quite small. Choosing a lift-off T/W of 1.3 allows a healthy thrust margin, minimizes nonpropulsion dry weight, and provides only a 1% penalty in total dry weight.

Thrust Split Trade

In the design of a two-stage, parallel-burn launch system, one must decide what percentage of the total thrust should be attributed to the booster engines and what percentage to the orbiter engines. The variation of total vehicle dry weight with the percentage of total thrust on the booster is presented in Fig. 10 for the single-fuel fully reusable AMLS vehicle. The variation in dry weight for the dual-fuel vehicle is almost identical. These trades were conducted for vehicles with a lift-off T/W of 1.3.

For the LH_2-fueled vehicle, it is desirable to have identical engines (including nozzles) on the booster and orbiter to lower engine production and development costs as well as to simplify engine operations; hence, only those percentages that allow a discrete number of identical engines on the booster and orbiter were considered. Because of the throttling capability of the reference STME engine, at least four engines are required on both the orbiter and booster to insure single-engine-out capability from launch to orbit on each. As indicated on the chart, the vehicle with seven engines on the booster and four engines on the orbiter has the minimum dry weight. This vehicle provides a 6% dry weight reduction over a vehicle with four larger thrust engines on both the booster and orbiter.

Dual-Position Nozzle Trade

One of the engines investigated, as a part of the STME study, employed a two-position nozzle to enhance performance. A primary nozzle with an area ratio of 60 is used during

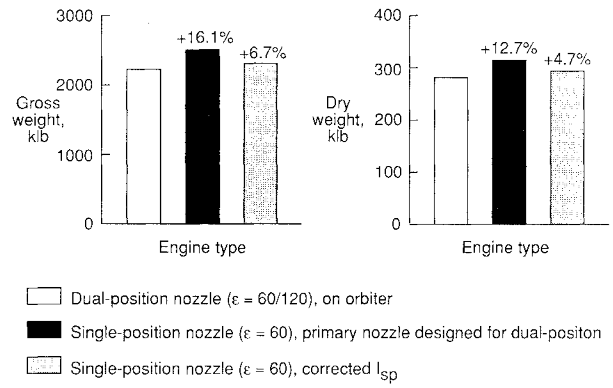

Fig. 11 Dual-position nozzle trade for fully reusable, all LH_2-fueled AMLS vehicle.

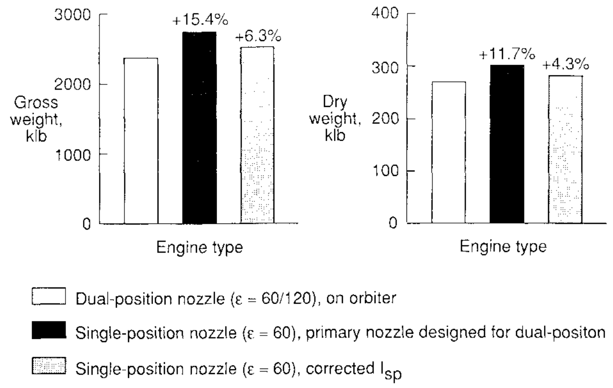

Fig. 12 Dual-position nozzle trade for fully reusable, dual-fuel AMLS vehicle.

the lower part of the trajectory to enhance sea-level thrust. The secondary nozzle is then extended to provide an area ratio of 120 later in the trajectory to enhance vacuum thrust. The single-fuel fully reusable AMLS vehicle was redesigned using this two-position nozzle on the orbiter and just the primary nozzle on the booster. POST was used to choose the optimal time for nozzle extension. This same vehicle was also designed with just the primary nozzle (area ratio of 60) on the booster and orbiter. Finally, the vehicle was redesigned with the same engines on the booster and orbiter; however, the nozzle (still with area ratio of 60) was optimized for use without the secondary nozzle by using a correction factor provided by the designers. Employment of the corrected nozzle gives a higher value of specific impulse than the nozzle that was designed for use with the secondary nozzle extension. The results of this trade for the single-fuel vehicle are presented in Fig. 11, and the results for the dual-fuel vehicle are summarized in Fig. 12. In both cases, there is a penalty of 4–5% in total vehicle dry weight for not using the dual-position nozzle. The added production costs caused by this dry weight increase must be weighed against the added production cost, operational complexity, and developmental risk involved in the use of a two-position nozzle on next-generation AMLS vehicles.

Engine-Out Trade

The reference STME engine used on the AMLS vehicles has the capability to throttle from a normal power level (NPL) of 100–133% in an emergency situation. It was decided from the outset of the AMLS study that the booster and the orbiter should each have the capability of losing an engine anytime during launch and ascent and still completely fulfill the mission requirements. To achieve this engine-out capability the booster and orbiter must have at least four engines apiece. The

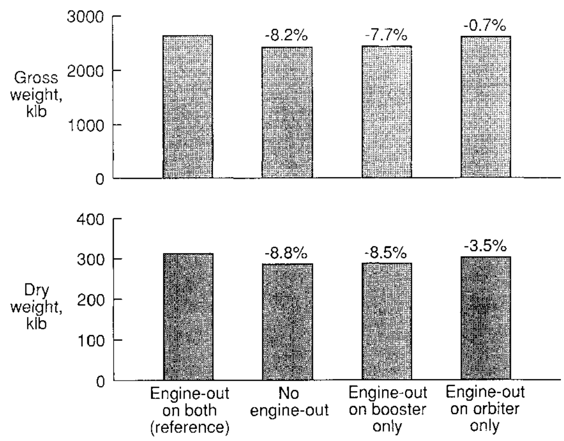

Fig. 13 Engine-out capability trade for fully reusable, all LH_2-fueled AMLS vehicle.

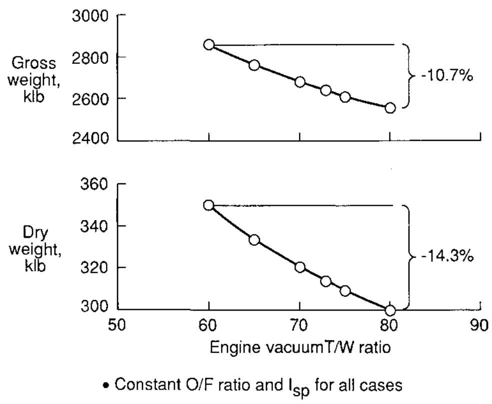

Fig. 14 Reference STME engine T/W ratio trade for fully reusable, all LH_2-fueled AMLS vehicle.

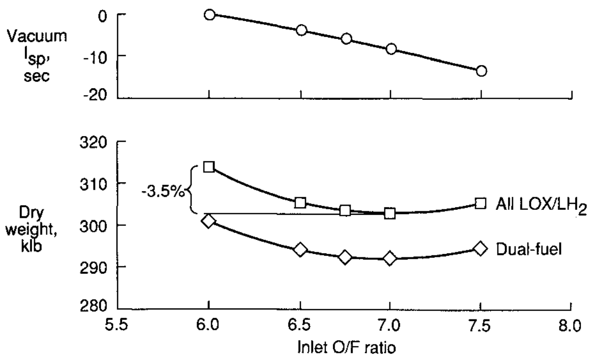

Fig. 15 Mixture ratio trade for reference fully reusable AMLS vehicle.

results of an engine-out capability trade conducted for the single-fuel fully reusable vehicle are presented in Fig. 13. As the chart indicates, a significant dry weight penalty of 8.8% is incurred. However, the increased vehicle reliability should bring about a quantitative reduction in recurring costs and a qualitative increase in crew and mission safety.

Engine T/W Trade

The reference gas generator STME engine has an NPL vacuum T/W in the low 70s. Figure 14 presents the effect on the single-fuel, fully reusable vehicle of using engines with varying T/W values. As indicated in the chart, a 33% improvement in NPL vacuum T/W from 60 to 80 results in a 14.3-% decrease in total vehicle dry weight. The curves presented in Fig. 14 are almost linear; hence, further improvements in engine T/W should provide similar reductions in vehicle weights.

Oxidizer-to-Fuel Ratio Trade

The trade studies presented thus far have used reference STME engines with oxidizer-to-fuel ratios $(O/F) = 6$. Parametric equations were employed, which allow the examination of a variety of O/F values. Figure 15 presents the results of varying the O/F of the reference STME engines for the single-fuel and dual-fuel fully reusable AMLS vehicles. As the O/F is increased from 6 to 7, the vacuum specific impulse decreases by 8 s. However, the increase in propellant bulk density is significant enough to cause a 3.5% overall reduction in total vehicle dry weight despite the penalty in performance. As the inlet O/F is increased past 7, the performance penalty begins to outweigh the higher propellant bulk density, and the total vehicle dry weight begins to increase despite the fact that the total tank volume is still decreasing slightly. Because of the gas generator cycle used on the reference engine, the mixture ratio in the combustion chamber is actually close to 8 when the inlet mixture ratio is 7; hence, because of heat flux problems in the combustion chamber brought about by the high O/F values, the inlet O/F should not be increased past 7 for the given chamber pressure.

A trade study performed using the same reference engines on a partially reusable ALS-type vehicle indicates a minimum vehicle dry weight for an $O/F \approx 6.8$. The fully reusable AMLS vehicle is more sensitive to tank weights and volumes and, hence, has a minimum vehicle dry weight at an $O/F = 7$. The results of these trade studies indicate that an increase in O/F ratio from the current SSME level of 6 should be beneficial in reducing future vehicle system dry weights.

Conclusions

This paper presents the results of the application of STME/STBE engine studies to reference AMLS vehicles. As a result of the many propulsion trade studies that were performed, several conclusions can be drawn.

1) The development of a new hydrocarbon booster engine (such as the STBE) for next-generation, manned launch systems may not be cost-effective for the vehicle types studied. The modest savings in vehicle dry weight provided by the use of a hydrocarbon-fueled booster may be more than offset by engine development program costs and additional operating costs brought about by the use of two different engines and fuels on the vehicle.

2) The development of a new hydrogen engine (such as the STME) for next-generation, manned launch systems probably would prove cost-effective for use as a main (and booster) propulsion system. Although the cost of developing a new reusable hydrogen engine is significant, the reference gas generator STME engine used in this study would lead to a reduction in total vehicle dry weight if used in place of the current SSME. Also, significant reductions in engine production costs, operating costs, and turnaround time could be achieved with the development of such an engine.

3) Use of a dual-position nozzle reduced total system dry weight by $< 5\%$ for the vehicle concepts examined. However, employment of such a nozzle on a next-generation main engine may not prove beneficial for a designed-for-operations system like AMLS because of the increase in development and operation costs and complexity.

4) An increase in oxidizer-to-fuel ratio from the current SSME level of 6 to ~ 7 would be beneficial in reducing future launch system dry weights.

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James A. Martin
Associate Editor