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Comparison of Single-Stage and Two-Stage Airbreathing Launch Vehicles

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In this paper a predominantly airbreathing SSTO vehicle is compared with three different TSTO configurations that stage at Mach numbers of 10, 12, and 14. The first stage of the TSTO vehicle uses the same propulsion system type and airframe shape as the SSTO vehicle except for modifications required to integrate the orbiter on top of the first stage. The TSTO configuration incorporates the same technologies, mission, and design methodology as the SSTO vehicle to allow a consistent comparison. The technologies employed on each of the vehicles are consistent with a successful NASP technology development program in the areas of structures, subsystems, and propulsion systems. In an attempt to examine whether or not a more ideally integrated TSTO configuration could be competitive with an SSTO vehicle, the TSTO configurations were each redesigned with several hypothetical assumptions and compared to the reference SSTO vehicle. To determine the effect of structural and subsystem technologies on the relative weights of the SSTO and TSTO configurations, weight sensitivity trades are also presented. A comparison of the results to SSTO and TSTO rocket-powered configurations using the same technologies, mission, and design methodology is also presented.

Nomenclature

g	= acceleration of gravity (32.2 ft/s^2)
S_{ref}	= aerodynamic surface reference area, ft^2
T_{sl}	= sea level thrust, lb
W_0	= initial gross weight, lb
ΔV	= incremental velocity, ft/s

Introduction

OVER the past several years, the United States has been engaged in an aggressive technology development program to enable the design of an operational airbreathing single-stage-to-orbit (SSTO) vehicle early in the next century as a part of the National Aero-Space Plane (NASP) Program. If an SSTO vehicle could be built that is similar in size and weight to a comparable two-stage-to-orbit (TSTO) vehicle, it would enjoy many advantages because only one vehicle would have to be developed, manufactured, and operated. Historically, all U.S. and foreign launch systems have consisted of multiple stages to reduce the amount of weight that must be carried to orbit, thus producing a smaller and less costly vehicle. This paper will examine whether similar benefits can be achieved by designing a fully reusable TSTO launch system that consists of a rocket-powered second stage and an airbreathing first stage which is similar in configuration to a NASP-derived SSTO vehicle.

In this paper, a predominantly airbreathing SSTO vehicle is compared with three different TSTO configurations which stage at Mach numbers of 10, 12, and 14. The first stage of the TSTO vehicle uses the same propulsion system type and airframe shape as the SSTO vehicle except for modifications required to integrate the orbiter on top of the first stage. The TSTO configuration incorporates the same technologies, mission, and design methodology as the SSTO vehicle to allow a consistent comparison. The technologies employed on each of the vehicles are consistent with a successful NASP technology development program in the areas of structures, subsystems, and propulsion systems.

In an attempt to examine whether or not a more ideally integrated TSTO configuration could be competitive with an SSTO vehicle, a number of trade studies are also presented. The TSTO configurations were each redesigned assuming an ideally integrated orbiter stage that contributed no additional aerodynamic drag. They were also redesigned assuming the maximum achievable tank efficiency for the booster stage. An additional trade examined the effect of inflight refueling or downrange landing of the booster after staging to eliminate the need for cruise-back propellant. To determine the effect of structural and subsystem technologies on the relative weights of the SSTO and TSTO configurations, weight sensitivity trades are also presented. A comparison of the results to SSTO and TSTO rocket-powered configurations using the same technologies, mission, and design methodology is also presented.

Analysis Methods

The conceptual design of next-generation launch systems requires proper consideration of the effects of trajectory, weights/sizing, geometry, and aerodynamics. Both the SSTO and TSTO vehicles were designed using a common methodology in each of these disciplines. All of the trajectory analyses for the SSTO and TSTO vehicles were performed using the three-degree-of-freedom Program to Optimize Simulated Trajectories (POST). The POST is a generalized point mass, discrete parameter targeting and optimization program that

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allows the user to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate planet.[1] The weights and sizing analysis were performed using the Configuration Sizing (CONSIZ) weights/sizing code. The CONSIZ code provides the capability of sizing and weight estimation for a variety of aerospace vehicles using weight-estimating relations based on finite element analysis or historical regression with appropriate reductions for application of advanced technologies. All of the geometry and subsystem packaging of the vehicles was performed using the Solid Modeling Aerospace Research Tool (SMART).[2] The 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. The Aerodynamic Preliminary Analysis System (APAS) was used to determine vehicle aerodynamics.[3] In the subsonic and low-supersonic speed regimes, the APAS utilizes slender-body theory, viscous and wave drag empirical 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. Figure 1 demonstrates the iterative process required between these various disciplines to obtain a vehicle point design.

Vehicle Concepts

Mission and Guidelines

The design reference mission for the SSTO and TSTO vehicles examined in this study is derived from detailed studies examining payload capture requirements for future NASP-derived vehicles.[4] Each vehicle is designed to deliver a 10,000-lb payload and a crew of three to a 100-n.mi. circular orbit inclined at 90 deg when launched from Edwards Air Force Base. Each vehicle has a payload-return capability of 30,000 lb. A nominal 24-h mission duration with a 24-h reserve is provided; however, an additional 72-h reserve is possible if the required systems and supplies are considered as payload. A 3000-ft^3 payload bay with a minimum diameter of 12 ft and a minimum length of 20 ft is integrated with each vehicle. Orbital maneuvering system (OMS) propellant provides an incremental velocity (Δ) capability of 500 ft/s in addition to the OMS propellant required for nominal orbit insertion and deorbit.

Both the SSTO and TSTO vehicles were designed assuming a number of other common ground rules. The technologies employed on all vehicles are consistent with a successful NASP technology development program in structures, propulsion, thermal protection systems (TPS), and subsystems. Crew escape is provided for each vehicle by ejection seats in the appropriate portions of the flight regime. In addition, each vehicle is designed to be fail-safe in the event of a single engine failure. A 10% dry weight growth margin is also allocated. The orbiter stages are required to have 1100-n.mi. 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 have maximum axial acceleration limits of 3 g. In addition, normal load constraints equivalent to a 2.5-g subsonic pull-up maneuver on entry for the orbiter stages and a 1.5-g subsonic pull-up maneuver at takeoff for the booster stages are provided on all nominal trajectories.

Reference Configurations

Single-Stage-to-Orbit

The SSTO vehicle utilized in this study is similar in configuration to the NASP-derived vehicle shown in Fig. 2 (from Ref. 5). It is a predominantly airbreathing vehicle that is augmented by rocket engines during takeoff, the transonic flight regime, and the final boost into orbit. The vehicle utilizes a low-speed cycle airbreathing propulsion system during subsonic, transonic, and low-supersonic flight. It then transitions to a ramjet propulsion system for supersonic and low-hypersonic flight. Supersonic-combustion ramjet, or scramjet, engines are used during the atmospheric portion of the hypersonic flight regime. Rockets are then used to accelerate the vehicle to orbital insertion. The airbreathing propulsion system is located on the bottom of the vehicle, and the rocket engines are located on the aft end. The forebody of the vehicle is used to compress air for the propulsion system prior to entry into the large inlets, and the aft body is used as an expansion nozzle for the main engines. To provide high propellant bulk density, the main propellant tanks initially contain triple-boiling point oxygen (81.5 lb/ft^3) and slush hydrogen (5.12 lb/ft^3). These propellants also serve as a heat sink for the thermal management system during ascent. As shown in Fig. 2, the vehicle employs low-profile twin vertical tails to provide lateral control and lateral directional stability. The leading edges are swept back significantly and are located far aft on the fuselage to avoid shock impingement.

A number of advanced technologies are employed on the SSTO vehicle design that are currently under development as a part of the NASP program. Titanium-aluminide monolithic and composite materials are used for the main structural components and also function as a thermal protection system on acreage areas of the body and wing with the addition of internal insulation. Hydrogen-cooled panels are utilized for the inlets and nozzles, and the stagnation regions (e.g., the aerosurface leading edges and fuselage nose cap) are actively cooled using heat pipe technology. Advanced carbon-carbon (ACC) is utilized near the stagnation regions. The hydrogen and oxygen main propellant tanks are semi-integral with the vehicle fuselage. The hydrogen tanks are constructed with reinforced polyetheretherketone (PEEK) thermoplastics, whereas the oxygen tanks are constructed of aluminum-lithium. Subsystem weights are consistent with those assumed for future operational NASP-derived vehicles.

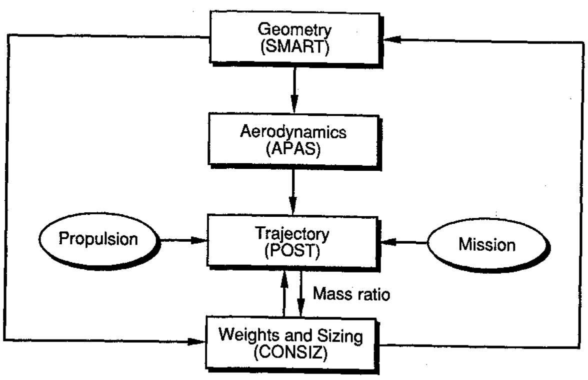

Fig. 1 Launch vehicle design process.

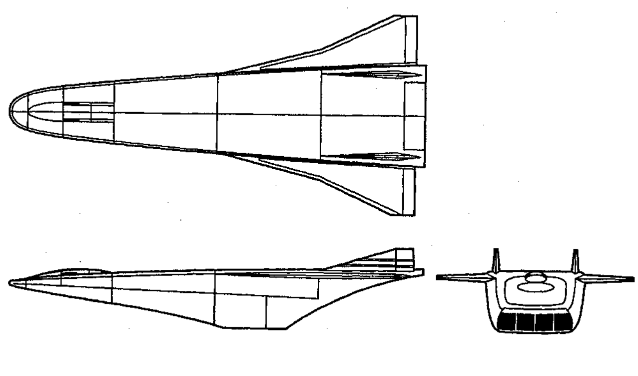

Fig. 2 NASP-derived SSTO vehicle.

Two-Stage-to-Orbit

The first stage of the TSTO vehicle is similar in configuration to the SSTO vehicle just discussed. The technologies utilized in structures, tankage, propulsion, and subsystems are all identical to the SSTO vehicle and are summarized in the preceding. The reference booster stages at Mach 10 and utilizes onboard propellant to cruise back to the launch site. The orbiter continues on to orbital insertion using only rocket propulsion. As with the SSTO vehicle, rocket engines are still required on the booster stage for thrust augmentation during takeoff and during the transonic flight regime. It uses the same propulsion system type and airframe shape as the SSTO vehicle except for modifications required to integrate the orbiter on top of the booster; however, the internal packaging of propellant tanks and subsystems is different because of the different propellant requirements. The booster body must be deep enough to bury the orbiter into the top sufficiently to eliminate shock impingement, minimize aerodynamic drag, and still allow volume for the wing carry-through structure. It must be wide enough to accommodate the maximum orbiter span between the twin vertical tails shown in Fig. 2. It also must be long enough to provide a minimum aerodynamic drag profile and to provide sufficient air capture for the main propulsion system. Because of these design considerations, the tank efficiency (propellant volume/body volume) of the Mach 10 booster is only 36% as compared to 57% for the SSTO vehicle.

The orbiter for the reference Mach 10 TSTO vehicle is shown in Fig. 3 relative to the Mach 12 and 14 TSTO vehicles. This orbiter is a scaled and repackaged version of that described in Ref. 6. A single vertical tail is used rather than movable wing-tip fins to prevent shock impingement from the twin vertical tails of the booster.[6] The payload bay is located just aft of the forward crew compartment to ease crew access. This placement, however, results in a rather large shift in the vehicle center of gravity between payload-in and payload-out conditions. Because of this center-of-gravity shift, a relatively large body flap and elevons are required to allow the hypersonic-trim angle of attack to remain between 25 and 40 deg on entry. A double-delta, low-aspect ratio wing design was selected because of this trim requirement and to achieve a minimum orbiter span in order to decrease the booster width.

The technologies employed on the orbiter are consistent with those utilized on the booster stage and the SSTO vehicle. Titanium-aluminide materials are used for the main structural components and also function as a TPS on acreage areas of the wing and fuselage with the addition of internal insulation. ACC is utilized for the nose cap and wing leading edges. The main propellant tanks are semi-integral with the vehicle fuselage. The liquid hydrogen tank is constructed with reinforced PEEK thermoplastics, while the liquid oxygen tank is constructed of an aluminum-lithium alloy. The main propulsion system is assumed to be two advanced staged-combustion cycle rocket engines, each with a vacuum thrust-to-weight ratio of 143, a nozzle area ratio of 150, and a vacuum specific impulse of 462.5 s. Normal boiling point propellants are utilized on the orbiter rather than slush propellants because of the relatively long time between takeoff and staging with no propellant reconditioning. Subsystem weights are consistent with those assumed for future operational NASP-derived vehicles.

Parametric Trades

Staging Mach Number Trade

A parametric trade study was performed to examine the effect of staging Mach number on the TSTO configuration. Staging Mach numbers of 10, 12, and 14 were examined. For each staging Mach number, iterations were performed on the vehicles between the disciplines of weights/sizing, trajectory, geometry/packaging, and aerodynamics using the tools described earlier until a converged TSTO configuration point design was obtained. The total system gross and dry weights are presented in Figs. 4a and 4b relative to the reference SSTO configuration, which transitions to rocket propulsion at Mach 14. The dry weight of a vehicle is defined as the weight of the vehicle without propellants, fluids, payload, and crew. It is an important figure of merit for launch vehicles because development and production costs tend to vary as a function of total

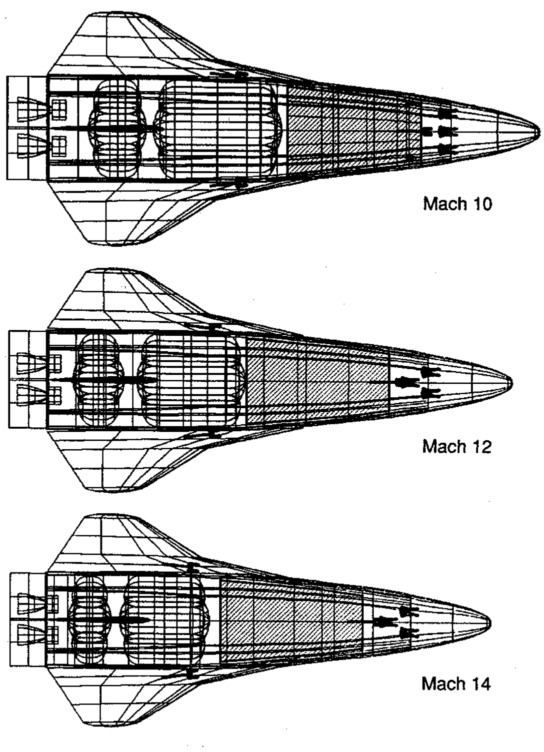

Fig. 3 Orbiters from NASP-derived TSTO configuration.

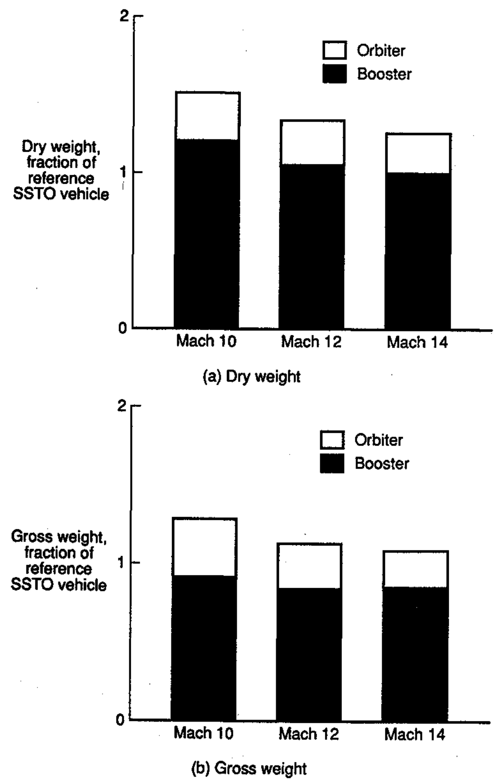

Fig. 4 Relative weights of TSTO configuration as a function of staging Mach number.

vehicle dry weight. Both the dry and gross weights of the TSTO configurations appear to approach a minimum at a staging Mach number of 14. Staging Mach numbers of greater than 14 were not considered because the scramjet propulsion system is approaching its maximum performance capability.

A number of factors contribute to the relative weights of the TSTO configurations with different staging Mach numbers. Figure 5 shows the variation in tank efficiency (propellant volume/body volume) for both the booster and orbiter vehicles with staging Mach number. As already noted, the tank efficiency of the Mach 10 booster is only 36% because it must be wide enough and deep enough to integrate the relatively large orbiter on top. This size mismatch between the booster and orbiter thus leads to higher system weights than would be necessary for an ideally integrated configuration. As the staging Mach number increases to 14, the orbiter becomes smaller, and the booster is required to carry more fuel to cruise back to the launch site. Hence, the relative size of the booster and orbiter is such that the orbiter can be more easily integrated, thereby decreasing the aerodynamic drag profile and allowing the maximum tank efficiency of the booster (55%) to be utilized. Figure 5 also indicates that the orbiter tank efficiency decreases for higher staging Mach numbers. The orbiters for each staging Mach number are shown relative to each other in Fig. 3. As the orbiter is scaled down in size for higher staging Mach numbers, the payload volume remains fixed to satisfy the reference mission. Hence, the vehicle must be repackaged, resulting in a lower tank efficiency. The packaging of the Mach 14 orbiter in Fig. 3 indicates the difficulty of decreasing the size of the orbiter any further for the given payload bay size. This is one reason that the TSTO configuration weights tend to level off for staging Mach numbers of about Mach 14. Another factor that tends to increase the configuration weights for higher staging Mach numbers is the increased fuel required for booster cruise back to the launch site.

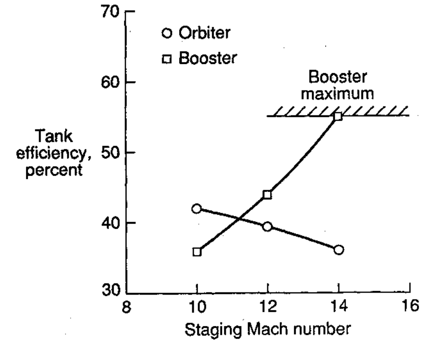

Fig. 5 Tank efficiency of booster and orbiter as a function of staging Mach number.

Configuration Sensitivity Trades

Several characteristics of the two-stage system were investigated to determine the theoretical minimum dry weight achievable with an ideal TSTO configuration. Figures 6a, 6b, and 6c summarize the results of these trades for the Mach 10, 12, and 14 TSTO configurations, respectively. These figures give the dry weights of each ideal configuration relative to the reference SSTO configuration, which transitions to rocket propulsion at a staging Mach number of 14. The weights presented in each column of Figs. 6a–6c represent vehicle point designs that have been converged on between the disciplines of weights/sizing, trajectory, geometry/packaging, and aerodynamics using the tools described previously. The columns labeled "Baseline" refer to the TSTO configurations for each staging Mach number presented in Fig. 4a.

The weights in the columns labeled "SSTO aerodynamics" in Figs. 6a–6c were obtained by substituting the aerodynamic coefficients and reference area from the reference SSTO configuration for those from each TSTO configuration in the reference ascent trajectories. The vehicles were then resized and repackaged appropriately. The resulting configuration represents the theoretical optimum case of integrating the orbiter completely within the booster vehicle, thereby eliminating additional aerodynamic drag. Without considering additional integration complexity, the reduction in drag results in a total dry weight reduction of 3–6%, depending on the staging Mach number. In reality, this integration would require additional structural weight penalties and would degrade the propellant packaging efficiency of the booster.

The weights in the columns labeled "No cruiseback fuel" in Figs. 6a–6c were obtained by eliminating the fuel required for each booster to return to the launch site after staging. The booster from each resulting configuration would have to land at a downrange site or be refueled during flight. Either of these options would significantly increase the operational complexity of each system. Elimination of the cruise-back fuel

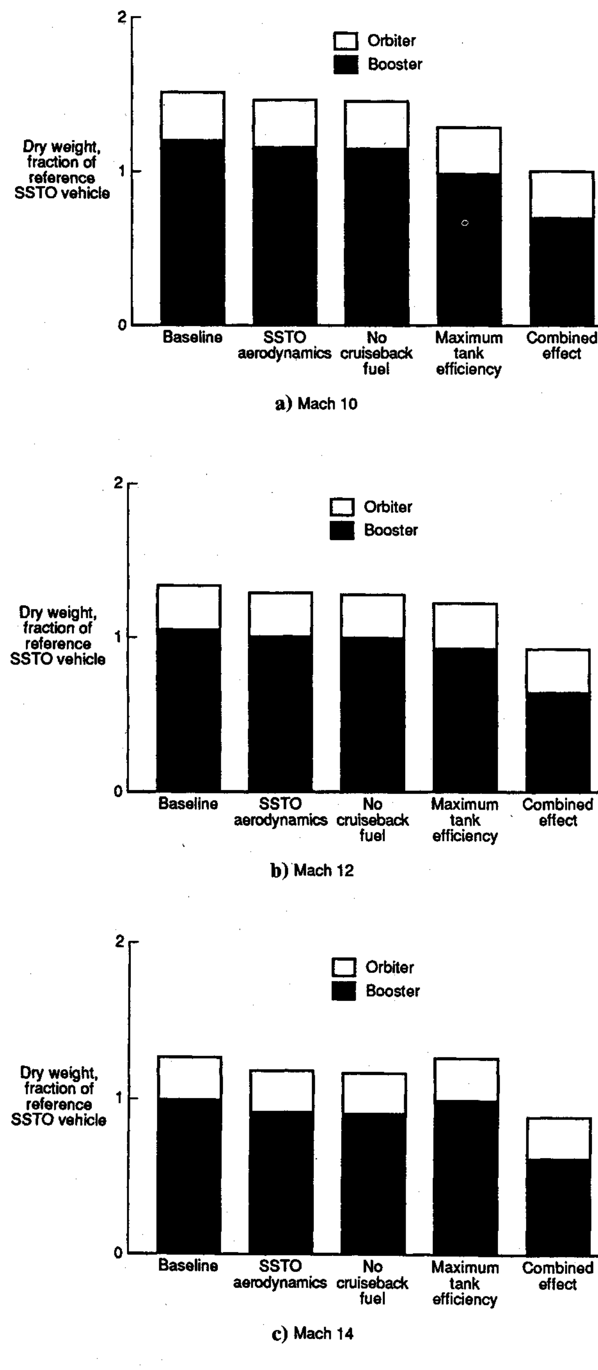

Fig. 6 Relative dry weights of ideal TSTO configurations.

would result in a total dry weight reduction of 4–7%, depending on the staging Mach number.

The weights in the columns labeled "Maximum tank efficiency" in Figs. 6a–6c were obtained by assuming the maximum possible tank efficiency (55%) for each of the booster vehicles. As indicated earlier in Fig. 5, the tank efficiencies of the Mach 10 and Mach 12 boosters are only 36% and 44%, respectively, because the booster must be wide enough for the orbiter to fit between the vertical tip fins on top, and it must be deep enough to integrate the orbiter with reasonable aerodynamic efficiency. If the booster tip fins were eliminated or the orbiter shape were altered significantly, it might be possible to achieve the maximum booster tank efficiency for all of the TSTO configurations. This would result in a total dry weight reduction of 0–14%, depending on the staging Mach number. If this were possible, the results in Figs. 6a–6c indicate that the minimum total dry weight of the TSTO configuration would occur for a staging Mach number of 12 rather than 14.

The weights in the columns labeled "Combined effect" in Figs. 6a–6c represent the results from assuming the maximum achievable tank efficiency on each booster, no cruise-back fuel, and SSTO aerodynamic coefficients and reference areas. These combined effects result in a total dry weight reduction of 29–34%, depending on the staging Mach number. Hence, the theoretical minimum dry weight of the TSTO configuration is only slightly lower than the baseline SSTO configuration, but the dry weights of the baseline TSTO configurations are still significantly higher.

Single-Stage vs Two-Stage

Airbreathing First Stage

The results from Fig. 4a indicate that the TSTO vehicle with an airbreathing first stage and a rocket-powered second stage is significantly higher in dry weight than the reference SSTO vehicle with similar technologies and design assumptions. The TSTO vehicles that stage at Mach 10, 12, and 14 are higher in total dry weight than the SSTO by 52%, 34%, and 26%, respectively. The TSTO vehicles become competitive to the SSTO vehicle with respect to dry weight only when the ideal configurations summarized in Figs. 6a–6c are considered. Historically, all U.S. and foreign launch systems have consisted of multiple stages to reduce the amount of weight that must be carried to orbit, thus producing a smaller and less costly vehicle. Hence, it is important to examine the factors that contribute to the results summarized in the foregoing.

The weight benefits from staging major launch vehicle components are well understood; however, these benefits are significantly reduced by the introduction of structural, subsystem, propulsion, and thermal protection technologies from the NASP technology program on future vehicle designs. A number of other factors contribute to the higher dry weights for the reference TSTO configurations. The most obvious factor is the weight penalty from subsystem and aerodynamic surface duplication, which is present in any multiple-stage configuration. Integration of the orbiter on top of the booster stage introduces weight penalties for structural integration and separation mechanisms and contributes to increased wave drag, base drag, and trim drag. A significant structural penalty is also introduced from the packaging inefficiency of the booster because of the size mismatch between the booster and orbiter discussed earlier at lower staging Mach numbers. Another important consideration is the weight of the cruise-back fuel and additional tankage required for the booster to return to the launch site. A final factor that contributes to the higher dry weights of the TSTO configurations is the fact that normal boiling point propellants must be utilized on the orbiter rather than slush propellants because of the relatively long time between takeoff and staging with no propellant reconditioning.

Figure 7 presents the sensitivities of the relative dry weights of the reference TSTO and SSTO configurations to increases in weight margin on structures, propulsion systems, and subsystems. These curves were generated by increasing the dry weight margin by various percentages and resizing the vehicles using CONSIZ. As the vehicles were resized, the ratios of sea level thrust T_{sl} and gross weight W_0 to aerodynamic reference area S_{ref} were held constant. Because T_{sl}/S_{ref} and W_0/S_{ref} were held constant for each vehicle, it was assumed that the mass ratio from the reference ascent trajectory could be used to size each vehicle. Figure 7 indicates a lower sensitivity to weight growth for the reference TSTO configurations. This lower sensitivity to weight growth would imply a smaller weight penalty to perform missions requiring loiter, recall, offset launch, and powered landing capabilities. The lower on-orbit weight of the TSTO orbiter would also imply a reduced sensitivity to weight growth for missions requiring orbital intercept or increased orbital maneuvering capability. However, for the mission and technology assumptions utilized in this study, the reference SSTO configuration appears to be superior to the TSTO configurations examined, especially when consideration is given to the requirement of developing, manufacturing, and operating two dissimilar vehicles for the TSTO configurations.

Rocket First Stage

Figure 4a indicates that the TSTO configuration with an airbreathing booster and rocket-powered orbiter is significantly higher in dry weight than a similar SSTO with airbreathing and rocket propulsion systems for the reasons just summarized. It is instructive to note, however, that this is not the case for exclusively rocket-powered vehicles. Fully reusable rocket-powered SSTO and TSTO vehicles have also been designed for the same mission and technology level as the vehicles in this study. The design, analysis, and comparison of these rocket-powered configurations are summarized in Refs. 7–9. The all-rocket TSTO configuration is 20% less in dry weight than the similar all-rocket SSTO configuration. Reference 8 further demonstrates that the all-rocket SSTO is significantly lower in dry weight than the similar-technology airbreathing SSTO vehicle and would probably cost less to develop and operate.

It is important to examine why the relative weights of the TSTO and SSTO configurations are different for rocket-powered boosters and the airbreathers under discussion. For the all-rocket TSTO vehicle, the additional aerodynamic drag is relatively insignificant because drag losses have a much smaller impact on the ascent performance. Because the ascent performance is not as significantly affected by aerodynamic drag, the rocket-powered TSTO vehicles can be mated offset from each other by struts, similar to the current Space Shutte Orbiter and the external tank. Hence, the structural integration and separation system penalty is less, and there is no size mismatch between the booster and orbiter, thus allowing the booster to utilize its maximum tank efficiency. The booster and orbiter rocket engines can easily be utilized in parallel from launch until staging, thus allowing the use of slush propellants on the orbiter. Finally, because the TSTO rocket systems tend to optimize at a lower staging Mach number, the boosters can be designed to return to the launch site with little or no propellant.[10]

Figure 8 presents the sensitivities of the relative dry weights of the rocket-powered TSTO and SSTO configurations to increases in weight margin on structures, propulsion systems, and subsystems. As in Fig. 7, these curves were generated by increasing the dry weight margin by various percentages and resizing the vehicles using CONSIZ. As the vehicles were resized, the ratio of sea level thrust to gross weight was held constant. Because T_{sl}/W_0 was held constant for each vehicle, it was assumed that the mass ratio from the reference ascent trajectory could be used to size each vehicle. Figure 8 indicates a lower sensitivity to weight growth for the reference TSTO configurations similar to that seen in Fig. 7. As noted earlier, the all-rocket TSTO configuration is 20% less in dry weight

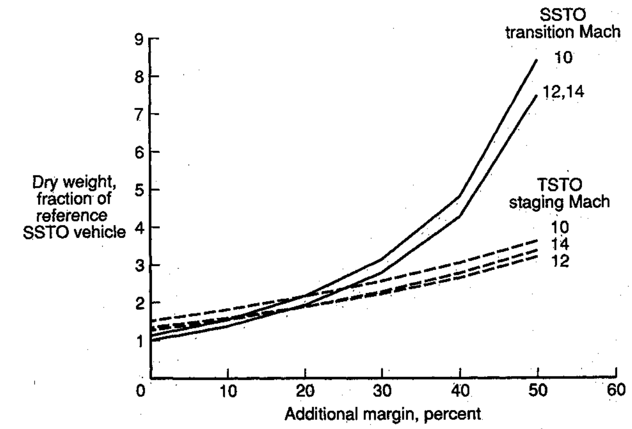

Fig. 7 Effect of additional margin on SSTO and TSTO dry weight.

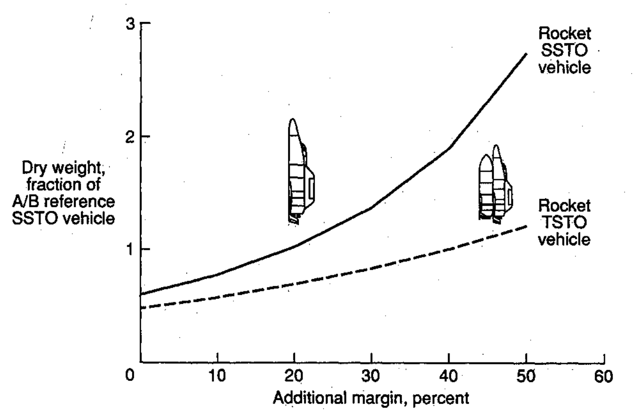

Fig. 8 Effect of additional margin on rocket SSTO and TSTO vehicle dry weight.

than the similar all-rocket SSTO configuration for the mission and technology assumptions utilized in this study. However, this advantage is probably offset by the requirement of developing, manufacturing, and operating two dissimilar vehicles.

Summary

A predominantly airbreathing SSTO vehicle was compared with three different TSTO configurations which stage at Mach numbers of 10, 12, and 14 using a number of state-of-the-art preliminary design tools. The first stage of the TSTO vehicle used the same propulsion system type and airframe shape as the SSTO vehicle except for modifications required to integrate the orbiter on top of the first stage. The TSTO configuration incorporated the same technologies, mission, and design methodology as the SSTO vehicle to allow a consistent comparison. The technologies employed on each of the vehicles were consistent with a successful NASP technology development program in the areas of structures, subsystems, and propulsion systems. The results indicated that the TSTO vehicle with an airbreathing first stage and a rocket-powered second stage was significantly higher in dry weight than the reference SSTO vehicle. The TSTO vehicles that stage at Mach 10, 12, and 14 were higher in total dry weight than the SSTO by 52%, 34%, and 26%, respectively. The factors that contributed to this higher dry weight were also examined in detail.

To determine the effect of structural and subsystem technologies on the relative weights of the SSTO and TSTO configurations, weight sensitivity trades were also performed. The TSTO configurations exhibited a significantly lower sensitivity to weight growth than the reference SSTO configuration. This lower sensitivity to weight growth would imply a smaller weight penalty to perform missions requiring loiter, recall, offset launch, and powered landing capabilities. The lower on-orbit weight of the TSTO orbiter would also imply a reduced sensitivity to weight growth for missions requiring orbital intercept or increased orbital maneuvering capability.

In an attempt to examine whether or not a more ideally integrated TSTO configuration could be competitive with an SSTO vehicle, a number of trade studies were also performed. The TSTO configurations were each redesigned assuming an ideally integrated orbiter stage that contributed no additional aerodynamic drag. They were also redesigned assuming the maximum achievable tank efficiency for the booster stage. An additional trade examined the effect of inflight refueling or downrange landing of the booster after staging to eliminate the need for cruise-back propellant. The ideal TSTO configurations that resulted from this study were found to be similar in dry weight to the reference SSTO configuration. However, when consideration is given to the requirement of developing, manufacturing, and operating two dissimilar vehicles for the TSTO configurations, the reference SSTO configuration appears to have an advantage.

References

[1]Braur, G. L., Cornick, D. E., and Stevenson, R., "Capabilities and Applications of the Program to Optimize Simulated Trajectories," NASA CR-2770, Feb. 1977.

[2]McMillin, M. L., Rehder, J. J., Wilhite, A. W., Schwing, J. L., Spangler, J., and Mills, J. C., "A Solid Modeler for Aerospace Vehicle Preliminary Design," AIAA Paper 87-2901, Sept. 1987.

[3]Divan, P. E., "Aerodynamic Analysis System for Conceptual and Preliminary Analysis from Subsonic to Hypersonic Speeds," AIAA Paper 80-1897, Aug. 1980.

[4]Simberg, R. E., "Space Transportation Comparison Study—NDV Task 11, Phase 1, Final Report," Rockwell International, Rept. NA-90-283, Downey, CA., Sept. 1990.

[5]Anon., "NASP Researchers Forge Ahead with Propulsion and Technical Advances," *Aviation Week and Space Technology,* Vol. 133, No. 18, Oct. 1990, pp. 40–41.

[6]Wilhite, A. W., "Technology and Staging Effects on Two-Stage-to-Orbit Systems," AIAA Paper 91-3181, Sept. 1991.

[7]Freeman, D. C., Talay, T. A., Stanley, D. O., and Wilhite, A. W., "Design Options for Advanced Manned Launch Systems," AIAA Paper 90-3816, Sept. 1990.

[8]Wilhite, A. W., Bush, L. B., Cruz, C. I., Lepsch, R. A., Morris, W. D., Stanley, D. O., and Wurster, K. E., "Advanced Technologies for Rocket Single-Stage-to-Orbit Vehicles," AIAA Paper 91-0540, Jan. 1991.

[9]Stanley, D. O., Talay, T. A., Lepsch, R. A., Morris, W. D., and Wurster, K. E., "Conceptual Design of a Next-Generation, Fully Reusable Manned Launch System," AIAA Paper 91-0537, Jan. 1991.

[10]Stanley, D. O., Talay, T. A., Lepsch, R. A., Morris, W. D., Naftel, J. C., and Cruz, C. I., "Parametric Trade Studies on a Shuttle II Launch System Architecture," NASA TP 3059, March 1991.

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