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Launch Vehicle Concept with Tandem Staging and Air Collection

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A launch vehicle concept was studied for Earth-to-orbit flight using airbreathing propulsion in the booster. The orbiter is arranged forward of the booster, in a tandem arrangement, for improved aerodynamics, packaging, and staging. The booster has air collection and enrichment hardware to collect oxidizer for the orbiter during flight. The results have shown some advantages of the tandem arrangement and air collection.

Nomenclature

C_{d0} = drag coefficient at zero lift
C_L = lift coefficient
M = Mach number
T/W = thrust-to-weight ratio

Introduction

THE Space Shuttle and expendable launch vehicles have provided transportation from Earth to low Earth orbit in a manner that is satisfactory for initial exploration and some commercial applications with high value. The time has come to improve space transportation. Human exploration and development of space need more economical and reliable transportation. Commercial applications have been identified that are possible with reduced transportation costs.

The current reusable launch vehicle (RLV) program, with its X-33 flight demonstration vehicle, may lead to an operational vehicle that reduces costs considerably from those of the Space Shuttle. There is, however, at least some possibility that, after the X-33 test flights, no industry consortium will be willing to develop the operational RLV. There is also the likelihood that the RLV, if it is developed, will not provide transportation costs low enough for some potential applications.

The highly reusable space transportation (HRST) program was initiated to search for launch vehicle concepts that could reduce the transportation costs further than the baseline single-stage-to-orbit (SSTO) rocket vehicle currently being considered in the RLV program. A concept using air collection and enrichment (ACE) called tandem ACE was one of several concepts considered in the HRST program. Others include magnetic lifter launch-assist concepts, rocket-based combined-cycle (RBCC) concepts, and beamed energy.

Tandem ACE Concept

The tandem ACE concept is shown in Fig. 1. It has two basic features: The booster is located behind the orbiter (tandem), and the booster contains air collection and enrichment (ACE) hardware to collect, during flight, the oxidizer for the orbiter. The tandem ACE concept is of interest only when the booster has airbreathing (including RBCC) propulsion.

Several concepts have been considered that have been intended to improve launch vehicle characteristics by using airbreathing propulsion. These concepts usually fall into two categories. Single-stage concepts, such as the National Aerospace Plane, have usually required very optimistic structures or engine weights to achieve reasonable designs because the heavy airbreathing engines have to be carried to orbit.

Two-stage concepts, such as Saenger, usually feature airbreathing on the first stage, rockets on the orbiter, and mounting of the orbiter above or below the booster, in a parallel fashion. This mounting arrangement leads to high drag during the airbreathing flight unless the orbiter is hidden in the booster. Hiding the orbiter in the booster leads to a large booster with poor structural efficiency. Also, the orbiter wings usually do not contribute to the lift during the booster flight, leading to large booster wings. An example of the problems created by such concepts is the Access to Space study. The dry weight of the booster of the two-stage concept was more than the dry weight of the entire single-stage concept.

The tandem ACE concept avoids the difficulty of carrying heavy airbreathing engines to orbit because it is a two-stage concept with the airbreathing engines on the booster. The tandem arrangement avoids the mounting arrangement difficulties of parallel configurations for two-stage systems. There is also a benefit at staging because the interstage can be retracted, providing clean staging at high dynamic pressures. The tandem arrangement, however, leads to some difficulty for takeoff. With the tandem arrangement, takeoff from a runway could be difficult. The tandem ACE concept will probably need either a launch assist by a sled or similar ground-based system or a vertical takeoff.

Aerodynamic Analyses

The aerodynamic analyses have been conducted on a geometry similar to that shown in Fig. 1. As the booster length has changed as the work progressed, the aerodynamics have not been changed, but this effect is expected to be small and not affect the results significantly.

The zero-lift drag at subsonic speeds was calculated by considering the skin friction on several parts: booster wing, booster canard, booster vertical tail, booster fuselage, orbiter wing, orbiter fuselage, and orbiter vertical tail. The inlets were not considered because the internal drag would be included in the propulsion data, and the lower surface would be similar to the surface covered by the inlets. This approach ignores the sides of the inlets, but they would be small. For each component, the wetted area was estimated, and the Reynolds number was calculated. Based on the Reynolds number, all of the skin friction was based on turbulent flow. A skin roughness based on production sheet metal was used where a higher skin friction resulted. A form factor was calculated for each component to account for separated flow and bluntness. When interference was considered, the conclusion was that all components could be joined without added interference drag. A 5% increase was added to the results to account for leaks and protuberances. The results are shown in Fig. 2. The reference area for the coefficients was the total of the booster and orbiter wings and the booster canard. This unusual reference area was used because that is the area producing lift.

For supersonic zero-lift drag, the same calculations were applied as for subsonic flight, and wave drag was added. The Sears–Haack formula[1] was used with the maximum cross-sectional area and the

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total length as inputs. Then a correction was applied that considered the wing sweep, Mach number, and an empirical factor to account for shape deviation from Sears–Haack. The empirical factor used was 2.5, which is quite conservative. As shown in Fig. 2, the wave drag increment was significant.

Between Mach 0.9 and Mach 1.3, the zero-lift drag was estimated by adding 0.001 to the drag coefficient at Mach 1.3 for a point at Mach 1.0. This estimate resulted in a reasonable curve, as shown in Fig. 2.

Above Mach 3.0, the skin friction was calculated as for subsonic flight, but the form factors were not included. To this a Newtonian drag component was added. The Newtonian drag was based on a hemisphere of 1-ft radius and a cone frustum between the hemisphere and the total diameter of the orbiter, 20.4 ft. The half-angle slope of the conical section was assumed to be 15 deg. The Newtonian drag was increased 20% to account for the drag on the wing and tail leading edges. The leading edges will have a small radius, and the slope will be small, and so this increment should be conservative. As shown in Fig. 2, the match between the hypersonic drag and the supersonic drag was not especially close. The match could be improved by decreasing the empirical factor in the wave drag, but the drag was used as shown to be conservative.

For subsonic flight, the lift-curve slope was found to be 2.5, the aspect ratio was 1.0, and the Oswald efficiency was 0.75. A typical drag polar is shown in Fig. 3 up to an angle of attack of 8 deg.

For supersonic flight, the lift-curve slope decreased to 2.0 at Mach 1.3, 1.5 at Mach 2.0, and 1.0 at Mach 3.0. A supersonic-drag-due-to-lift equation was used. A typical drag polar is shown in Fig. 3. The same maximum angle of attack, 8 deg, was used as in the subsonic case, but the reduced lift-curve slope reduced the maximum lift coefficient. The wave drag increment is obvious.

Above Mach 3.0, the planform area was used to calculate Newtonian lift and drag increments due to angle of attack. The angle of attack was allowed to go to 20 deg. Figure 3 shows that, although the zero-lift drag at hypersonic speeds was smaller than at supersonic speeds, the drag at lift coefficients over 0.1 was higher at hypersonic

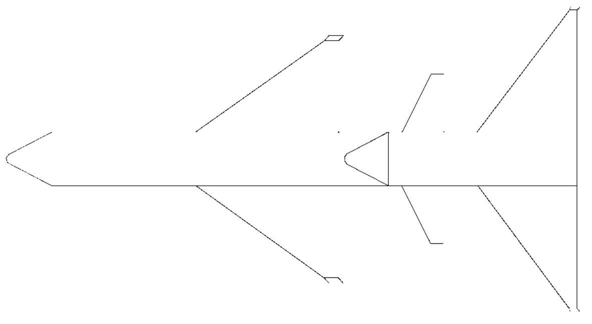

Fig. 1 Tandem configuration.

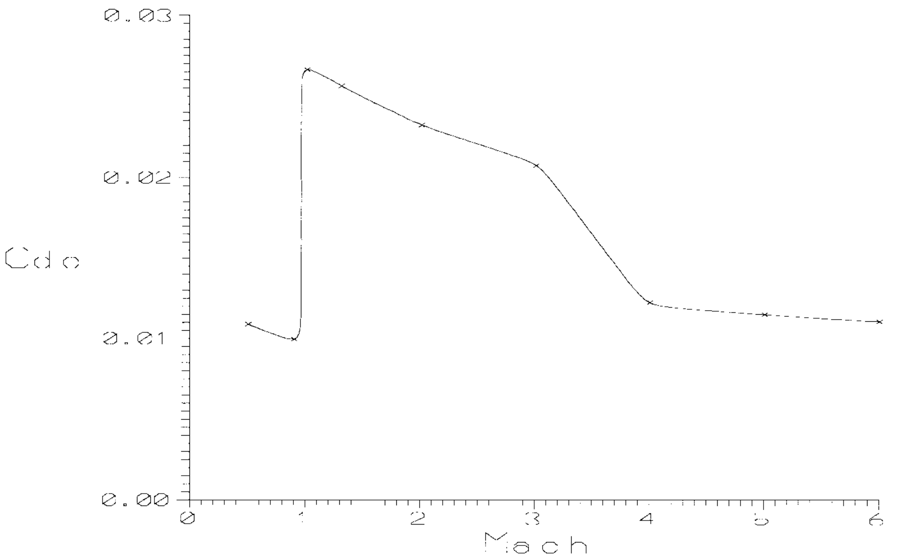

Fig. 2 Zero-lift drag.

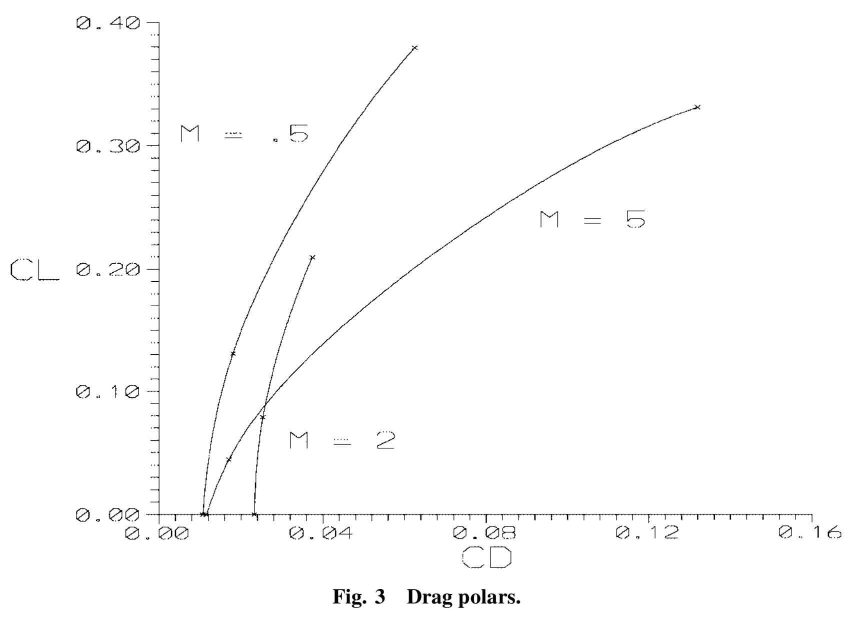

Fig. 3 Drag polars.

speeds. The high drag at hypersonic speeds is the most important factor in the aerodynamic analyses because the thrust available decreases as Mach 6.0 is approached, and there is additional drag during air collection.

Propulsion

The orbiter propulsion is a hydrogen and oxygen rocket engine similar to the Space Shuttle main engine. Although some optimization could be done on the nozzle, no changes were made from the Access-to-Space SSTO reference vehicle.

The booster propulsion chosen for tandem ACE is an air-turbo-rocket expander (ATREX) engine[2] currently being developed in Japan. The ATREX design uses hydrogen in an expander cycle to drive the compressor in the airstream. Precooling is used to improve the cycle thermodynamically, to decrease the size of the engine because the air has a higher density, and to allow the compressor blades to survive flight to Mach 6.0. The ATREX engine has been tested subscale at static and supersonic conditions.

Orbiter Trajectory

The orbiter trajectory was calculated using POST, a trajectory optimization program. Staging occurs at Mach 6.0 at a dynamic pressure of 1000 psf. The trajectory was optimized using pitch rates into a burnout condition of a transfer ellipse, as was done for the SSTO reference vehicle for a mission to the space station. Because the trajectory starts at a low flight-path angle, finding a good trajectory required starting with segments that helped the vehicle onto a higher flight path. As the optimum trajectory was approached, these phases could be deleted, leaving the entire trajectory optimized.

The mass ratio (initial mass over burnout mass) of the orbiter trajectory was 4.28 using the specific impulse for hydrogen and oxygen. A trajectory was also calculated in which the specific impulse was decreased to account for the use of liquid enriched air (LEA). In this case, the mass ratio increased to 4.61. If only LEA is used on the orbiter, the higher mass ratio would be accurate. In this work, about half of the total oxidizer is oxygen loaded on the ground. The assumption has been made that the LEA collected during flight can be loaded into the orbiter in such a way that it will not totally mix with the oxygen. Then, during the orbiter flight, the LEA can be used first. The oxygen can be used for the final part of the trajectory, where the specific impulse is most important. In this way, the mass ratio of the trajectory will be more nearly that with only oxygen. The trajectories use the LEA first and reflect the specific impulse degradation and then use the oxygen at the higher specific impulse.

Orbiter Sizing

The program CONSIZ has been used to estimate the weight of the components of the orbiter and select the proper orbiter size to meet the mission requirements. The same input file used for the Access-to-Space reference SSTO was used with a few exceptions. The orbiter wing size was increased from that of the SSTO, for a given orbiter length, such that the sized orbiter had a reference wing area of about 3500 ft^2. This wing area was selected to help balance the lift between the booster and orbiter. Several items were given as constants in the SSTO input that should change as the vehicle is reduced in size. Some of these items were changed to weight equations that were linear with orbiter dry weight, length, or gross weight.

Booster Trajectory

The booster trajectory was also calculated using POST. Only horizontal takeoff has been analyzed. The trajectory calculations were started at the end of the sled run at Mach 0.5. Because the trajectory calculations did not include data for flaps, there is a period at the beginning that is not accurate, and the altitude during this short period decreases on some trajectories. Based on other calculations, the vehicle can climb at takeoff, and the error in the trajectory is not significant. The vehicle system follows a fixed angle-of-attack trajectory segment in the subsonic flight regime until the dynamic pressure increases to 1000 psf. The trajectory then follows a dynamic pressure of 1000 psf to staging.

Booster Weights

A new computer program was written for the booster weight estimations. This program contains equations similar to those in CONSIZ or other sizing programs but does not change the input size of the vehicle. This approach was more appropriate for the booster because the weights could be more easily matched to the trajectory results.

ACE Hardware

This study did not include detailed design of the ACE hardware. Values found in the literature were used to represent the ACE hardware capability and weight.[3,4] For each pound per second of hydrogen flow, 5 lb/s of LEA could be collected. For each pound per second of LEA collected, the ACE hardware weight is 7.5 lb. This weight for the ACE hardware may be too optimistic with technology currently foreseen. A more conservative estimate would decrease the attractiveness of the ACE results.

Orbiter and Interstage Results

The results of the orbiter analyses gave a prelaunch gross weight of 572,000 lb for the tandem case. The interstage is actually connected to the booster and returns to the launch site with the booster, but the weight is not included in the booster weights. Estimating the interstage weight at 5.5 lb/ft^2 and allowing for a length of 15 ft and a margin of 10% gives 5800 lb. The interstage will retract over the booster nose by sliding straight back until it is along a cylindrical portion of the booster. The retraction mechanism will not have to withstand the orbiter weight because the interstage can lock into place, but the mechanism will have to retract when drag is pushing the interstage back. Adding another 10% for the mechanism gives a total of 6400 lb for the interstage. The total of the orbiter and interstage is then 578,000 lb for the tandem case.

Tandem (No ACE) Results

As a point of departure for the ACE work and for comparison purposes, a design with a tandem arrangement but no equipment for air collection was analyzed. One unknown was the proper thrust level for the booster. Several cases were, therefore, analyzed with different thrust levels for the same initial weight. The results are shown on Fig. 4 as a function of T/W, the sea-level static thrust divided by the system initial weight. The weight of the ATREX engines, installed, is shown to increase linearly with thrust level. Increased thrust allows greater acceleration and reduced hydrogen consumption. Reducing the hydrogen consumption reduces the tank size and weight, the thermal protection system weight, etc. The resulting booster inert weight and booster gross weight are shown for each thrust level. The difference between the booster gross weight and the initial weight is available for the orbiter and interstage. The results indicate that the best T/W is about 0.6.

Figure 4 is based on an installed ATREX engine thrust-to-weight ratio of 5, which is based on data provided by Tanatsugu. Compared to other engine designs, the weight may be somewhat higher than needed for engines of the size needed for this design. A similar comparison was made with an engine thrust-to-weight ratio of 7. With this improvement in the engine, the optimum system thrust-to-weight ratio is a little higher at about 0.7, and the same gross weight provides an additional 35,000 lb for the orbiter and interstage. Final results of the tandem case can be seen in Table 1.

Table 1 Tandem configuration

Element	Weight, lb
Gross liftoff	919,000
Booster	344,000
Orbiter	568,000
Interstage	7,000
Dry total	307,000
Booster	217,000
Orbiter	83,000
Interstage	7,000
Hydrogen used	121,000
LEA collected	0

Comparison to Parallel Staging

A design for a parallel-staging, two-stage vehicle was attempted, and the results are presented in Table 2. The orbiter is essentially the same except for the wing size. The orbiter wing could be reduced because it would not be needed for lift during the mated flight. The orbiter gross weight was reduced about 10%. If the booster and orbiter are truly parallel, the maximum cross-sectional area would be about double that of the tandem configuration, and the length could be considerably shorter. Because the Sears–Haack wave drag is proportional to the square of the ratio of the area divided by the length, this would increase the wave drag by a factor of 4–16. The Newtonian drag of the nose would also be doubled.

Table 2 Parallel configuration

Element	Weight, lb
Gross liftoff	896,000
Booster	371,000
Orbiter	518,000
Interstage	7,000
Dry total	323,000
Booster	242,000
Orbiter	74,000
Interstage	7,000
Hydrogen used	123,000
LEA collected	0

The more likely arrangement chosen was to place the orbiter behind the body of the booster, keeping the maximum area only a little more than with the tandem arrangement and with nearly the same length. This would lead to the structure of the booster carrying the weight of the orbiter and the booster body at different longitudinal locations, which would lead to bending moments that would need to be carried by the booster structure. The total length of the booster would then be similar to the length of the mated tandem design.

In any parallel arrangement, the orbiter wing would carry little lift during mated flight. To carry the total weight, the booster wing would have to be about the same as the total of the orbiter and booster wings in the tandem arrangement. The total drag of the booster wing and the orbiter wing increased, but the current analysis is not sufficiently accurate to show the increase caused by the increase in cross-sectional area. From these considerations, it seems clear that the tandem arrangement leads to a greater reduction in booster size and weight than is shown in the data presented in Table 2.

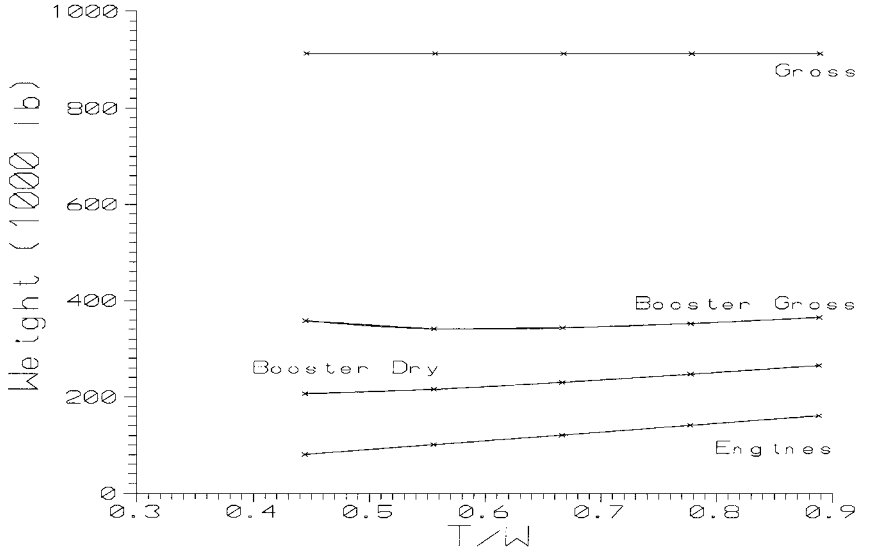

Fig. 4 Booster thrust optimization.

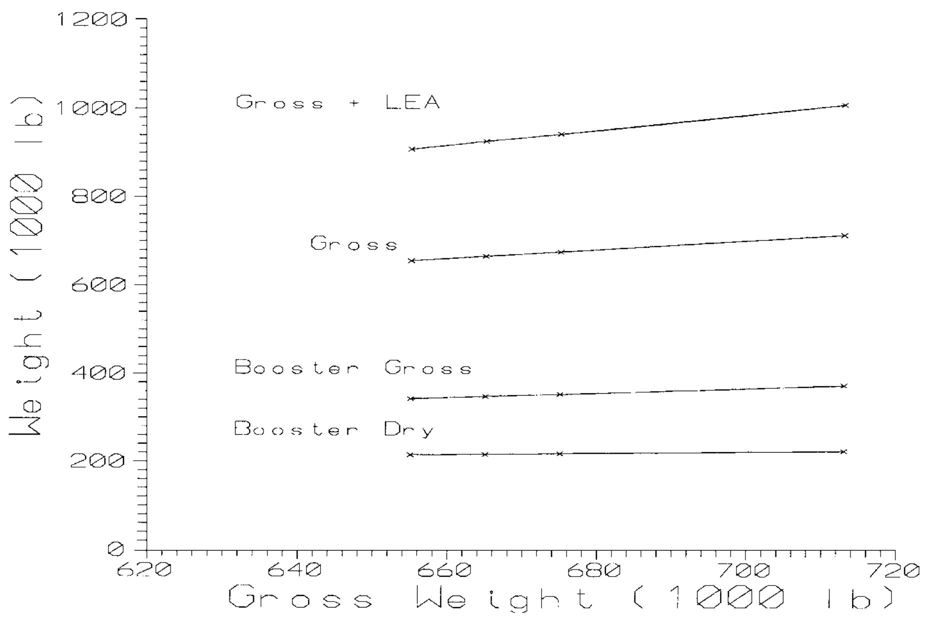

Fig. 5 Mini-ACE sizing.

Mini-ACE

The hydrogen flow rate during the booster trajectory of the tandem (no ACE) design increased during the Mach 2 to Mach 5 phase of the flight. If enough ACE hardware is put onboard the booster to use all of the hydrogen flow available at Mach 5, much of that hardware would not be used at Mach 2. The design that has been developed is one that uses only the amount of ACE hardware that can be used fully at Mach 2. This design has been named mini-ACE and is the design that should show the greatest advantage for ACE. The ACE hardware is used between Mach 2 and Mach 5. The final acceleration to Mach 6 is made without collecting air to minimize the difficulties in the speed regime with the lowest thrust and highest heating.

The mini-ACE design was calculated at several gross weights to find the gross weight that would provide the needed orbiter and interstage weight. Figure 5 shows how the various weights changed. The orbiter and interstage capability is the difference between the booster gross weight and the gross + LEA line.

Figure 1 is based on the mini-ACE design. The difference in booster length between the mini-ACE design and the other tandem designs was not sufficient to be shown in Fig. 1.

Optimized Tandem ACE

After considering the mini-ACE design, several options were considered to improve the vehicle. The engine thrust level on the vehicle was reduced. The wing areas were reduced proportionately with the gross weight reduction. The engines were throttled to approximate a cruise segment to collect more LEA. Along with an approximation of a cruise segment, the amount of hardware used was increased.

The engine thrust level was reduced to take a larger orbiter to orbit. The results can be seen in Figs. 6 and 7. This thrust reduction lowered the total dry weight and increased the amount of LEA collected and the hydrogen used. Because of the increased hydrogen consumption and concerns about takeoff, the thrust-to-weight ratio of 0.66 was selected for further work.

Because there was a reduction in gross weight, the wing areas were reduced. Wing reductions of 10, 20, and 30% were considered, as shown in Fig. 8. The wing reduction of 30% yielded the best reduction in total dry weight but could not be used because it did not have enough wing area to lift the gross takeoff weight. A reduction of 20% was selected.

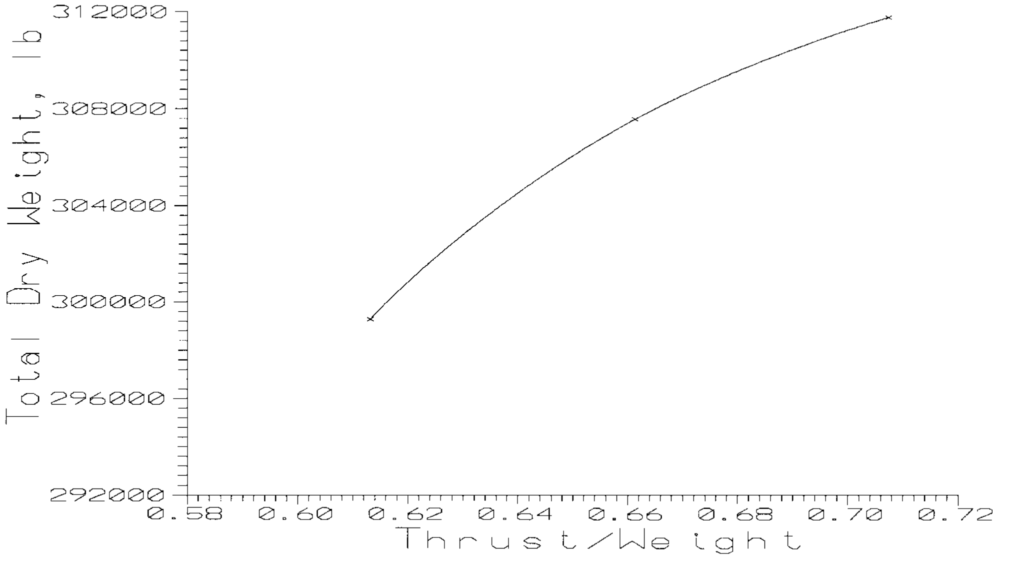

Fig. 6 ACE thrust reduction effect on total dry weight.

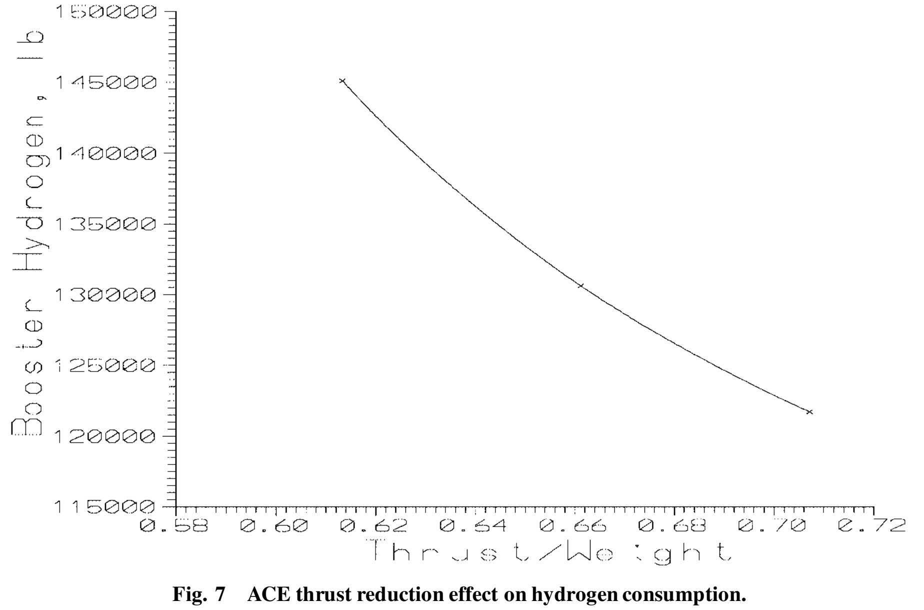

Fig. 7 ACE thrust reduction effect on hydrogen consumption.

Instead of using a cruise segment at Mach 5, throttling was used to reduce the acceleration and give a slow rise to Mach 5. Throttling occurred between Mach 4.5 and Mach 5 for the first case and between Mach 4 and Mach 5 for the second case. For each case the engines were throttled to 96, 91, and 87%. The results are shown in Fig. 9. Cruising created more LEA, but the losses due to hydrogen use and growth in dry weight outweighed the gains.

Another case considered was to increase the amount of ACE hardware available. In other words, as the hydrogen flow rate increased, so did the amount of ACE hardware being used. This approach, however, did not yield the desired results, as shown in Fig. 10. By increasing the hardware amount by 10%, more LEA was collected, but an increase in dry weight made this case undesirable. The final results of the ACE case can be seen in Table 3.

Table 3 ACE configuration

Element	Weight, lb
Gross liftoff	689,000
Booster	341,000
Orbiter	561,000
Interstage	7,000
Dry total	296,000
Booster	205,000
Orbiter	79,000
ACE equipment	5,000
Interstage	7,000
Hydrogen used	125,000
LEA collected	220,000

Stability and Trim

A major concern for the tandem ACE concept is the stability and trim capability of the mated-vehicle system and the separate stages. An analysis was conducted on the tandem vehicle (no ACE) to investigate this concern. With the original wing area, the subsonic case could be trimmed with virtually no moment on the interstage. The hypersonic case could also be trimmed but needed an orbiter incidence of 4 deg. It, unlike the subsonic case, had an interstage moment on the order of 5×10^6 ft-lb. This moment is within the boundaries of reason given the large diameter of the interstage. The subsonic case could still be trimmed with no interstage moment with the increased incidence. An attempt was made to reduce the orbiter wing while holding the booster wing and canard at the original size. With the orbiter wing reduction, the subsonic case could still be trimmed, but the hypersonic case proved very difficult. The possibility of reducing the orbiter wing was not considered further.

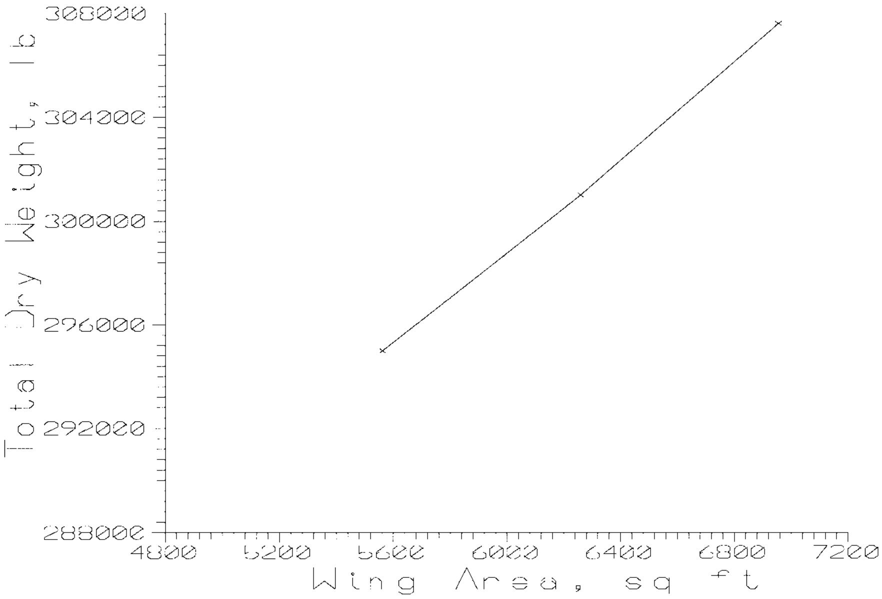

Fig. 8 ACE wing reduction.

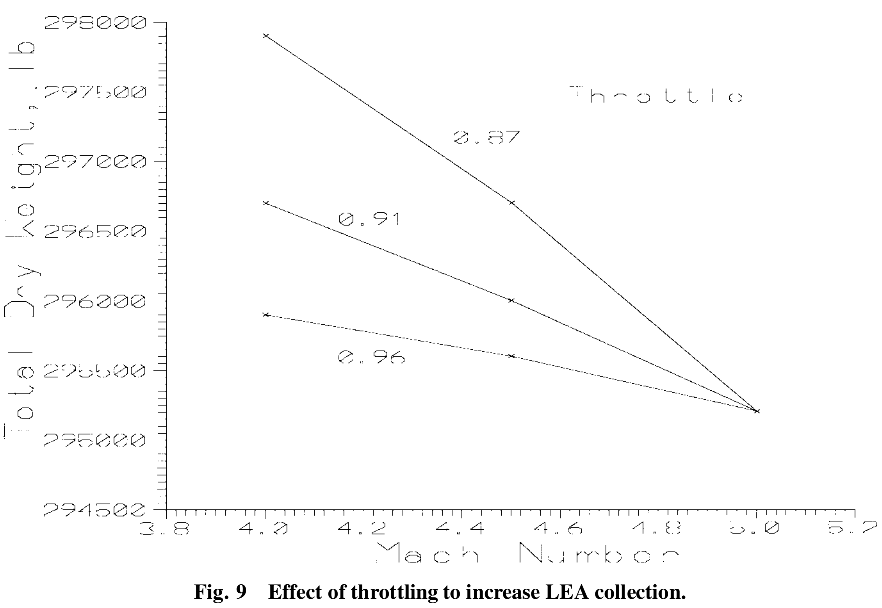

Fig. 9 Effect of throttling to increase LEA collection.

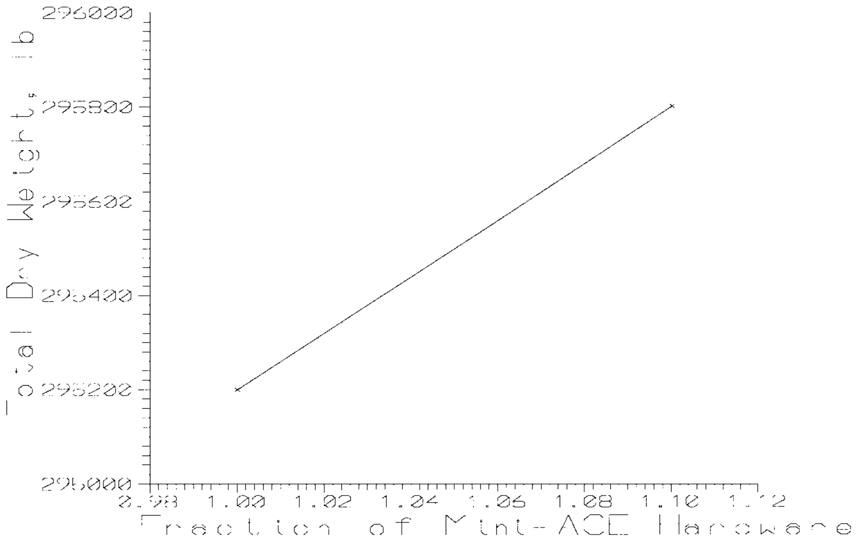

Fig. 10 Effect of increased ACE hardware.

Additional Details

Appendices to this report have been included in the final report to the highly reusable space transportation (HRST) program. These appendices provide some of the computer files used in the study. Additional details of the analyses and the results can be found by consulting these appendices.

Concluding Remarks

A design study of the tandem ACE concept for Earth-to-orbit transportation has been conducted. The tandem ACE concept has an airbreathing booster arranged in line with a rocket orbiter. The booster contains air collection and enrichment hardware to collect oxidizer for the orbiter. A tandem design with no ACE and a design with an ACE system were developed and compared. The tandem design was compared to what would be required for a parallel-staged design. The conclusions indicate that the tandem arrangement reduces the booster size and weight and the ACE system reduces gross weight with a minor decrease in dry weight.

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