# Airbreathing Launch Vehicle for Earth Orbit Shuttle—Performance and Operation

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**Reusable launch vehicles with both airbreathing and rocket-powered first stages are analyzed and their performance, costs, and operational characteristics are compared. The results suggest that the airbreathing systems have lower gross weight and slightly lower dry weight for the same mission. Operationally, the airbreathing systems offer several advantages, such as airplane-type takeoff and landing from conventional airfields, intact abort without staging, launch into offset orbits, and substantial ferry range. The total system costs of the rocket and airbreathing systems are similar but the airbreathing system requires more development time. The technology required to develop the airbreathing launch vehicle is similar to that of any reusable shuttle vehicle with the exception of the propulsion system. A companion paper reviews recent technological progress for the airbreathing system with special emphasis on propulsion.**

## Introduction

THE desired qualities of the next-generation launch vehicle are quite demanding when compared to the capability of today's vehicles. Primarily they must have low operational cost, be capable of carrying a variety of payloads into essentially any near Earth orbit, provide an airline-type passenger environment, and have initial operating capability in the late 70's. There are a number of conceptual systems with the potential for meeting most of the objectives. One such concept is the two-stage fully reusable system using a hydrogen-fueled hypersonic aircraft as the first stage. This system has been studied in the United States[1-3] and Europe[4,5] for several years, but has been considered as unavailable for early operational use because the technological state-of-the-art was not considered sufficiently developed. However, the system does have a number of unique qualities which are appropriate to consider if the desired initial operational date is extended for a second generation vehicle is considered.

The purpose of this paper is to assess the performance, operation, and cost of an airbreathing first stage, and to enumerate its potential qualities. To give the assessment perspective, the airbreathing system is compared with two rocket-powered, two-stage, fully recoverable systems. The comparisons are made on the basis of operating cost, total system cost, gross takeoff weight, landing quality, and vehicle size. The analysis is based on a computer synthesis of the performance and costs of the vehicles for one nominal mission. A companion paper from NASA Langley[6] assesses the technological state-of-the-art of the airbreathing first stage, with emphasis on the hypersonic airbreathing propulsion system.

The three launch-vehicle systems considered use a common upper stage consisting of a rocket-powered, lifting-body configuration with a 15-ft-diam by 30-ft-long payload bay. The boosters are: a) a rocket-powered, horizontal-takeoff and landing (HTO), all-body configuration, b) the same system with vertical-takeoff (VTO) capability, and c) the horizontal-takeoff and landing airbreathing system. The HTO rocket concept was included since many of the attractive features of airbreathing systems stem from the use of the horizontal-takeoff mode.

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## Mission Description

One nominal mission was selected to evaluate the vehicle concepts. The mission consists of placing a 20,000 lb payload in a 270 naut mile orbit with an inclination of 28°. The payload bay is 15 ft in diameter by 30 ft long and is maintained at standard atmospheric conditions. If passengers are considered as part of the payload, they are accommodated within this payload volume. The upper stage is required to return the same payload to base; there is no cross range requirement.

Typically, a high utilization rate is required to make fully reusable systems cost effective. Current projections of the orbital traffic for shuttle vehicles are necessarily uncertain. In this study, a relatively high traffic level was assumed; estimates of the investment and operational costs assume 1000 flights over a 10 yr period. This amounts to an average payload capability of 2 million pounds per year.

### Booster Trajectory

The trajectories followed by the vehicles are shown on Fig. 1. All vehicles are limited to 3 $g$ axial acceleration. For the HTO vehicles, the flight begins with a ground roll to a velocity sufficient for vehicle lift-off at an angle of attack of 15°. After lift-off, the rocket-powered vehicle performs an aerodynamic pullup to a flight-path angle of 80°. This pullup is limited by either 15° angle of attack or a normal load factor of 2.0. The HTO rocket vehicle then follows the indicated trajectory to an altitude of 160,000 ft and a speed of 10,000 fps. The airbreathing-vehicle takeoff is similar, but does not include the post-lift-off pullup. The airbreathing vehicle flies to 10,206 fps at an altitude of 112,000 ft, where it performs a powered aerodynamic pullup to an altitude of 160,000 ft and a speed of 10,000 fps. This high-speed pullup is constrained by the angle-of-attack limit of 15° and a normal load factor limit of 1.25. The VTO rocket vehicle flies the trajectory shown in Fig. 1 to a speed of 10,000 fps and an altitude of 160,000 ft. At this point, where the dynamic pressure is 200 psf, all the vehicles can either launch the upper stage or coast to higher altitudes and launch at a lower dynamic pressure. This study assumes staging at 200 psf.

After stage separation, all first-stage vehicles glide to lower altitudes and execute a pullout at approximately 120,000 ft

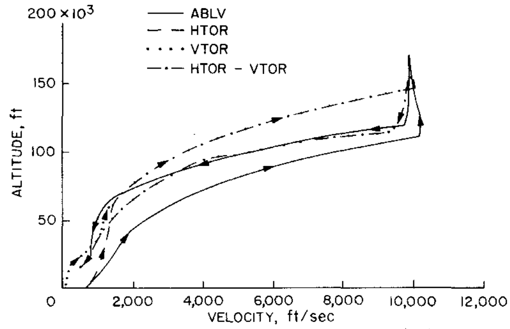


**Fig. 1 Vehicle trajectories.**

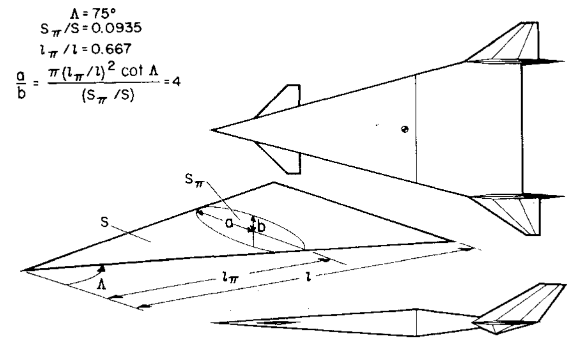


**Fig. 2 Nominal all-body configuration definition.**

followed by an unpowered turn until they are headed in the direction of the takeoff base. The airbreathing vehicle then accelerates, using its boost engines, to a speed which permits an unpowered glide to the takeoff point; typically a maximum speed of about 8300 fps is attained. The rocket-powered systems use supersonic transport engines (converted to use hydrogen fuel) to extend their glide range; the result is a slowly decelerating return flight at maximum lift-drag ratio. All systems land with turbojet power and have sufficient fuel to make a second landing approach.

### Orbiter Trajectory

The orbiter is launched at an altitude of 160,000 ft with a velocity of 10,000 fps and a flight-path angle of 7°–10°. During the initial rocket burn the orbiter flies a relatively low trajectory to approximately 250,000 ft at 26,000 fps. After a one-half orbit coast, the vehicle circularizes the orbit at 270 naut miles by using a second burn for 600 fps additional velocity. The low trajectory selected for the orbiter allows a relatively easy abort from any point along the flight path.

The orbiter entry flight is a conventional lifting-body type entry that can be made either at low angles of attack to maximize cross range or at high angles to minimize heating. Although the nominal mission specification required no cross range the configuration as defined is capable of approximately 1500 naut mile cross range.

## Vehicle Descriptions

All first-stage systems use the same basic configuration with appropriate modifications. The configuration has a delta planform and elliptical cross sections. External shape is defined by three parameters: 1) the leading-edge sweep of the body, 2) the ratio of the distance from the nose to the position of the maximum depth with respect to the body length, and 3) the ratio of cross-sectional area at the position of maximum depth with respect to the plan area. These three parameters are defined in Fig. 2, together with the shape of the fin surfaces. The configuration concept uses intersecting integral tanks (Fig. 3); that is, the tanks carry the vehicle bending and shear loads. The tank structure is aluminum skin-stringer and is pressurized to 15 psig. The aluminum structure is protected by quartz fiber insulation and external cover panels made from super alloys or titanium. The fin surfaces are made of super alloys with ceramic leading edges.

This general configuration is modified for use as an airbreathing launch vehicle by incorporating a cavity for the upper stage and adding a propulsion package as shown in Fig. 3. The hydrogen-fueled propulsion system consists of turbojets for acceleration to approximately Mach 3.5 and separate convertible scramjets for the remaining acceleration and pullup portion of the flight. Convertible scramjets operate with subsonic flow in the combustor until Mach 6; above Mach 6 all the flow through the engine is supersonic. The turbojets and convertible scramjets operate with stoichiometric fuel-air ratios during acceleration. They are regeneratively cooled by liquid hydrogen fuel to maintain reasonable metal temperatures inside the engines. The inlet is a two-dimensional, variable-geometry type and serves both the turbojet and scramjet by deflecting the flow with a variable diverter wall as shown in Fig. 3.

The turbojets exhaust into the base area under the afterbody of the vehicle. Any excess airflow delivered by the inlets during the acceleration is bypassed through the convertible scramjet engine and burned to achieve a slight thrust augmentation. Although operating the ramjet at these low Mach numbers is inefficient, it does avoid the penalty associated with spilling or bypassing the excess airflow. During ramjet or scramjet acceleration, the turbojet flow passage is shut off by the variable diverter wall in the inlet. All the airflow then passes through the convertible scramjet and is expanded as in a plug nozzle using the full area under the afterbody of the vehicle (Fig. 3). This results in a large expansion ratio which is very favorable to the ramjet or scramjet cycle.[7]

The same general body shape is modified for use as a rocket-powered first stage by incorporating plug nozzles at the rear of the vehicle (Fig. 3). In general, aerodynamic drag is less critical for the rocket-powered vehicles and it is preferable to carry the second stage in the exposed condition. The vertical takeoff version of the rocket vehicle is essentially similar to the HTO version although the loads analysis results in a slightly different weight distribution.

It is recognized that the shape used in this study may not be optimum, particularly for the rocket-powered systems. However, first-stage rocket vehicles do require good aerodynamic characteristics to return to base and to land with suitable performance. And the slender configuration used in this study is estimated to have relatively good aerodynamic performance.

The orbiter, which is common to all systems, is based on a modification of the lifting body vehicle described in the reusable orbital transport studies completed several years ago.[8] This configuration, Fig. 4, incorporates an internal payload bay, a crew compartment, and nonintegral fuel tanks. The four-tank concept carries liquid hydrogen in the outboard

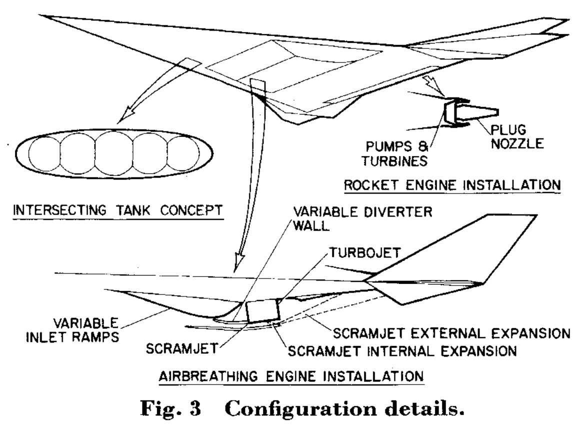


**Fig. 3 Configuration details.**

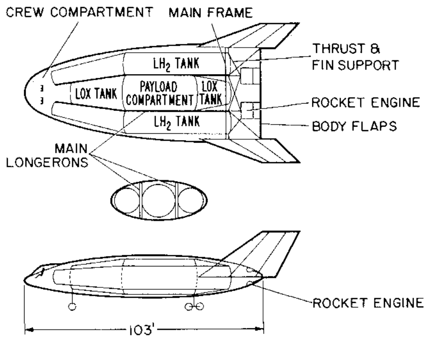


**Fig. 4 Orbiter vehicle—schematic drawing.**

tanks and liquid oxygen in the fore and aft centerline tanks. The payload bay is positioned between the oxygen tanks. All primary body structure is protected by quartz fiber insulation, which, in turn, is protected by cover panels of super alloys, coated columbium, or ceramics as required. The fin surfaces are made of super alloys and coated columbium. The propulsion system consists of two high-pressure rocket engines that provide a vehicle thrust-to-weight ratio of 1.0 at staging. Note that landing turbojets are not included.

## Methods of Analysis

An extensive computer synthesis program was used to analyze the vehicles described in this paper. This program, which has been under development for several years, is modularized as shown in the block diagram in Fig. 5. The total program is a collection of individual subroutines formulated for specific functions.

The computer synthesis starts with a geometric definition of the vehicle, proceeds with a performance and trajectory calculation, performs a weight and volume estimate, and ends with a total system cost summary. All computations for one vehicle on one mission are completed in a single computer case. This approach ensures that the results contain the multiple effects of design variables on the vehicle performance and cost. For example, if the leading-edge sweep of the vehicle is changed, the change affects the vehicle length, tail size, drag, propulsion system size, surface temperatures, structural weight, thermal protection system weight, and many other factors. Some of these effects are of primary importance while others are minor; but all are included.

The methods used to calculate vehicle performance are based on extensive in-house analyses in the various disciplines. Most methods are fully described in published reports in the area of aerodynamics,[9] loads,[10] thermal protection,[11] structures,[12–14] weights,[15,16] and airbreathing propulsion.[17] Publications are planned to further describe the methods used in structures and costs, however, the methods used in these two areas are similar to and depend upon the techniques and data described in Refs. 12, 13, and 18–20, respectively.

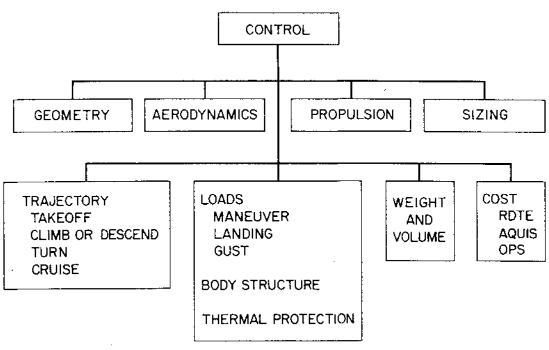


**Fig. 5 Synthesis program block diagram.**

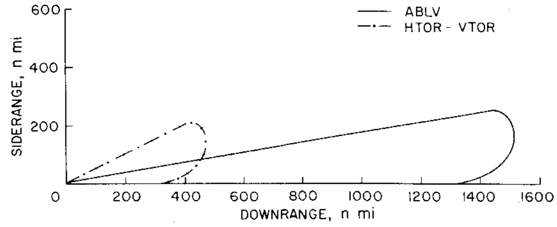


**Fig. 6 Vehicle ground tracks.**

The rocket specific impulse was assumed to be 450 sec in a vacuum and 369 sec at sea level conditions. Specific impulse levels at other altitudes were based on an interpolation with respect to ambient pressure between these values.

## Results

Weight statements for the three booster vehicles and orbiter vehicle are shown in Table 1. The HTO rocket-powered vehicle has a gross weight approximately twice that of the airbreathing system. The rocket vehicle expends 68% of its gross weight during takeoff and climb while the airbreathing system uses 21%. The specific impulse of the airbreathing engines, which ranges between 5000 and 1700 sec, is responsible for the difference. It can be seen that the dry weight of the rocket-powered system is higher than that of the airbreathing system. This difference occurs even though the airframe weight fraction (i.e., the airframe weight divided by the gross weight) is some 67% greater for the airbreathing vehicle. The higher weight *fraction* of the airbreather results from the low-density hydrogen propellant which is approximately one-fifth that of the hydrogen-oxygen mixture used in the rocket-powered vehicle.

In addition, the thermal protection system weights of the airbreathing vehicles are higher since these vehicles are subjected to high external temperatures for a longer period of time. The ground tracks of the three vehicles, Fig. 6, indicate that the slower accelerating airbreathing vehicle travels farther during the mission.

Figure 7 shows representative radiation equilibrium temperature histories. The temperature shown is a representative average of the spanwise temperature distribution midway on the vehicle forebody lower surface. The two peaks in the rocket-vehicle cases correspond to the point of maximum speed at pullup initiation and the re-entry condition after staging. For the airbreathing vehicle, the first two peaks result from the same condition as described for the rocket vehicles, while the third is caused by the reacceleration after the turn-to-base maneuver. The area under each curve represents the time-temperature integral that dictates the body insulation thickness; obviously the airbreathing system requires the thickest insulation.

As indicated in Table 1, the airbreathing vehicle has a slightly lower total propulsion system weight than the rocket

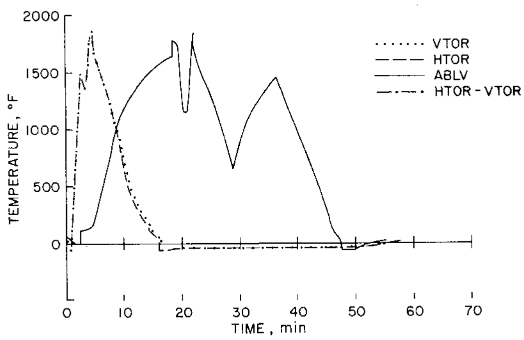


**Fig. 7 Vehicle lower surface external temperature histories midway on forebody centerline.**

**Table 1 Vehicle weight statements**

| Vehicle / Component | Airbreather Wt, lb | Airbreather % of gross wt | HTO rocket Wt, lb | HTO rocket % of gross wt | VTO rocket Wt, lb | VTO rocket % of gross wt | Orbiter Wt, lb | Orbiter % of gross wt |
|---|---|---|---|---|---|---|---|---|
| Airframe structure | 298,394 | 26.59 | 385,457 | 16.09 | 330,805 | 14.21 | 69,026 | 18.04 |
| Fuselage | 147,104 | 13.11 | 241,052 | 10.06 | 234,341 | 10.07 | 23,967 | 6.27 |
| Fuselage thermal protection | 72,148 | 6.43 | 42,869 | 1.79 | 40,643 | 1.75 | 17,323 | 4.53 |
| Fins & surface controls | 47,224 | 4.20 | 35,177 | 1.47 | 33,263 | 1.43 | 12,536 | 3.27 |
| Landing gear | 31,919 | 2.84 | 66,360 | 2.77 | 22,558 | 0.97 | 4,941 | 1.29 |
| $LH_2/LO_2$ tanks | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 10,259 | 2.68 |
| Propulsion | 123,425 | 11.00 | 141,711 | 5.92 | 141,609 | 6.08 | 8,813 | 2.30 |
| Airbreathing engines | 80,301 | 7.16 | 39,262 | 1.64 | 39,262 | 1.69 | 0 | 0.0 |
| Inlet and thrust structure | 40,584 | 3.62 | 19,603 | 0.82 | 19,603 | 0.84 | 1,374 | 0.36 |
| Fuel system | 2,539 | 0.23 | 26,809 | 1.09 | 25,987 | 1.12 | 1,564 | 0.41 |
| Rocket | 0 | 0.0 | 56,757 | 2.37 | 56,757 | 2.44 | 5,875 | 1.53 |
| Fixed equipment | 12,146 | 1.08 | 17,291 | 0.72 | 16,984 | 0.73 | 9,824 | 2.57 |
| Dry weight | 433,965 | 38.67 | 544,459 | 22.73 | 489,398 | 21.02 | 87,663 | 22.91 |
| Fuel | 306,030 | 27.28 | 235,793 | 9.85 | 231,828 | 9.96 | 37,700 | 9.86 |
| Oxidizer | 0 | 0.0 | 1,232,893 | 51.48 | 1,224,669 | 52.61 | 237,161 | 62.00 |
| Payload | 382,006 | 34.05 | 381,852 | 15.94 | 382,104 | 16.41 | 20,000 | 5.23 |
| Gross takeoff weight | 1,122,000 | 100.00 | 2,395,000 | 100.00 | 2,328,000 | 100.00 | 382,524 | 100.00 |

vehicle, although its propulsion system weight fraction is higher. The auxiliary turbojet engines essentially double the propulsion system weight of the rocket-powered vehicle. A supplemental study was performed to examine whether the HTO rocket vehicle could complete the mission more effectively without the use of airbreathing engines. In this case, the main rocket engines were used to reaccelerate the vehicle after the turn-to-base maneuver so that the vehicle could glide to the takeoff point. The results of this preliminary study indicated that the system using auxiliary turbojets resulted in the least weight and least cost.

The vehicle shapes and sizes that correspond to the weight statements of Table 1 are shown in Figs. 8 and 9. The airbreathing vehicle is approximately the same size as the rocket-powered vehicle, even though it is one-half the gross weight. The reason for the size similarity is the low density of the liquid hydrogen propellant (4.5 lb/ft$^3$).

The airbreathing vehicle carries the orbiter within a cavity on the upper surface. Studies have shown that the drag encountered by exposing the second stage during the boost phase results in a heavier and more expensive vehicle, despite the fact that the structural weight penalty for the vehicle with a cavity is approximately 30%. For the rocket vehicle the drag losses associated with an exposed upper stage are less because the vehicle does not fly a high dynamic pressure trajectory and has a higher acceleration resulting in much less time in the atmosphere. Consequently, submerging the upper stage is not advantageous for the rocket vehicle.

The horizontal takeoff airbreathing and rocket vehicles perform the same mission and are approximately the same size, but have different gross weights. High-gross weight is not a disadvantage in itself, but other quantities related to it may be adversely affected. For example, the relationship between vehicle size and weight influences takeoff and landing performance. The takeoff wing loading for the airbreathing vehicle is 76 psf and that of the rocket vehicle is 202 psf. These wing loadings result in estimated takeoff speeds, assuming a 15° angle-of-attack limitation, of 220 and 340 knots for the airbreathing and rocket vehicles, respectively. Takeoff speeds slightly above 200 knots are not unusual, but speeds in the 350-knot range exceed current technology. However, there do not appear to be any fundamental technical reasons why the technology for these speeds could not be achieved.

On a nominal mission, the vehicles return to base without the boost propellant and without the upper stage. Under these conditions the airbreathing vehicle and the rocket vehicle have wing loadings of 34 and 46 psf and estimated approach speeds of 145 and 165 knots, respectively. These speeds are considered normal by present standards and the landing quality of the two vehicles is acceptable for the nominal mission. However, one of the features of the horizontal takeoff mode is the possibility of landing under emergency conditions with all of the fuel onboard and with the second stage in place. The approach speeds are then equal to the takeoff speeds, 220 knots and 340 knots. If the first-stage oxidizer can be dumped before landing, the approach speed of the rocket-powered vehicle is reduced to about 250 knots. Whether the dumping operation or the speeds of the HTO rocket vehicle would be acceptable under emergency conditions requires further study. In any case, it appears that the takeoff and landing qualities of the airbreathing system are comparable to those of today's advanced aircraft, and suggest

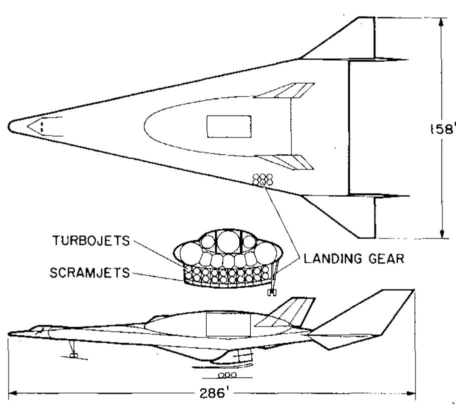


**Fig. 8 Airbreathing launch vehicle—schematic drawing.**

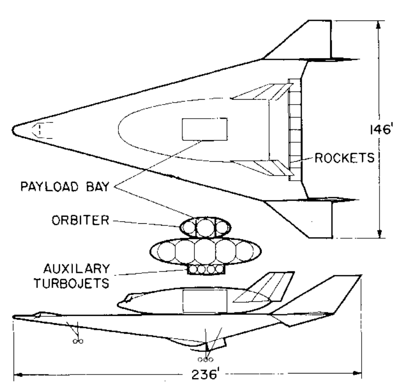


**Fig. 9 Horizontal takeoff rocket vehicle — schematic drawing.**

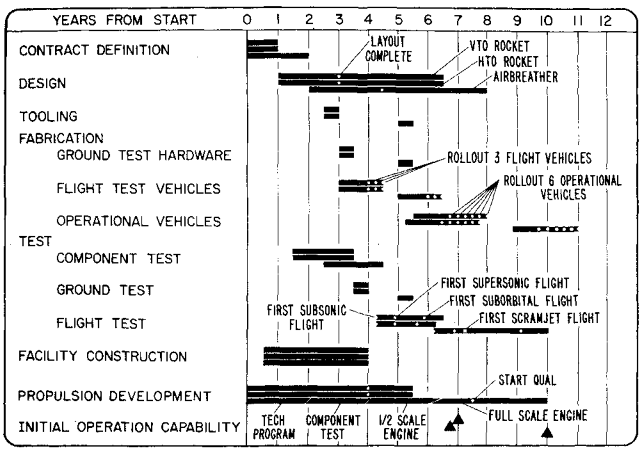


**Fig. 10 Assumed vehicle development schedules.**

that the airbreathing launch vehicle can operate like an airplane to accomplish the space transportation mission.

The vehicle gross weight and dry weight have a strong relationship to total system cost, but they are not the only important cost factors. The airbreathing launch vehicle, which has low gross weight and low dry weight relative to the rocket, requires the development of two additional propulsion systems: a turbojet and the convertible ramjet-scramjet. The costs associated with these developments might easily negate the advantage of the lower weights. A total system cost comparison is required to resolve the question.

Before examining the cost estimates, it should be pointed out that they are based on correlations, at the major subsystem level, of data from past programs. Subsystem dry weight is a major parameter with modifying factors to account for differences in material, structural concept, and system complexity. This technique is appropriate for this study, but the cost estimates may change significantly when the vehicles and the procedures to build and operate them are defined in more detail.

The total systems cost estimates are presented in Table 2. First, examine the RDT&E cost. The design engineering cost for the airframe is less for the airbreathing vehicle because the dry weight is lower. The cost of its propulsion development, however, is approximately three times that of the rocket system. It should be pointed out that the cost of the rocket engine development would be reduced if the booster and orbiter use the same rocket engine.

Supersonic transport engines were used as auxiliary turbojets for flyback capability in the rocket vehicles, since the development of a new auxiliary turbojet for the rocket vehicles was not cost-effective. For the airbreathing vehicle the situation is different, and the cost of developing a new, lightweight turbojet is cost-effective. The initial studies used six large turbojets installed in the position shown in Fig. 4. Each of these turbojets developed a thrust of 127,500 lb at sea-level static conditions. Due to their large size, development costs exceeded 1.3 billion dollars. Therefore, the propulsion installation shown in Fig. 8 was adopted to reduce the size of each turbojet. This concept, which uses 20 turbojet engines with 38,700 lb thrust each, might be considered unreasonable, but the disadvantages of this approach would have to be considered in relation to the theoretical cost savings. The savings in this case are approximately 600 million dollars.

A major item in the RDT&E phase is the flight test program. The assumed flight-test program has no historical precedent but is a modification of airplane flight-test procedures. This area requires in-depth investigation. For this study the following program was assumed. Flight tests for each configuration are divided into phases for separate horizontal takeoff flights, suborbital tests of the mated upper and lower stages and orbital qualification tests. Since all the vehicles have horizontal landing capability and turbojets for return to base, they would operate in a horizontal takeoff mode for most development testing. As discussed below, the airbreathing launch vehicle test program would require additional time to qualify the full-scale scramjet engine on the vehicle. This qualification assumes 144 flights and an additional 27 months.

Development testing the full-scale scramjet engine on the ground appears to be a prohibitively expensive procedure. The temperatures, pressures, durations, and test section area required to qualify a full-scale engine are difficult to combine in one facility and may be beyond the currently foreseeable state of the art. In any case, the enormous power requirements result in high projected costs for such a ground facility. Therefore, it is proposed that the qualification testing of the full-scale scramjet engine be accomplished by the same incremental flight testing technique used to qualify aircraft. The development of engine components and a half-scale engine module can be accomplished in ground facilities at reasonable

**Table 2 Vehicle cost statements, millions of dollars**

| | Air-breather | HTO rocket | VTO rocket | Orbiter |
|---|---|---|---|---|
| RDT&E | | | | |
| Airframe design | | | | |
| Concept formulation | 12 | 12 | 12 | 12 |
| Contract definition | 70 | 35 | 35 | 35 |
| Design engineering | 1391 | 1659 | 1481 | 947 |
| | 1473 | 1706 | 1528 | 994 |
| Avionics development | 20 | 20 | 20 | 100 |
| Propulsion development | | | | |
| Rocket | 0 | 373 | 373 | 362 |
| Turbojet | 694 | 90 | 90 | 0 |
| Ramjet/scramjet | 480 | 0 | 0 | 0 |
| | 1174 | 463 | 463 | 362 |
| Development support | | | | |
| 1st unit manufacturing | | | | |
| Airframe | (161) | (150) | (144) | (57) |
| Avionics | (3) | (3) | (3) | (6) |
| Rocket | (0) | (35) | (35) | (5) |
| Turbojet | (25) | (9) | (9) | (0) |
| Ramjet/scramjet | (8) | (0) | (0) | (0) |
| | (197) | (197) | (191) | (68) |
| Flt./grnd. test veh. (3/1) | 654 | 643 | 623 | 233 |
| Flight/ground test spares | 116 | 115 | 112 | 41 |
| Flight test operations | 497 | 263 | 274 | 88 |
| Maint./operat. trainers | 46 | 46 | 44 | 81 |
| AGE/tooling | 180 | 200 | 184 | 110 |
| Documentation | 10 | 10 | 10 | 3 |
| | 1503 | 1277 | 1247 | 556 |
| Total RDT&E | 4170 | 3466 | 3258 | 2012 |
| Initial acquisition | | | | |
| Operational vehicles (6) | | | | |
| Airframe | 590 | 544 | 523 | 236 |
| Avionics | 13 | 13 | 13 | 25 |
| Propulsion | 137 | 183 | 183 | 19 |
| | 740 | 740 | 719 | 280 |
| Spares | 191 | 206 | 202 | 36 |
| Facilities | 100 | 100 | 100 | 100 |
| Sustaining engineering | 203 | 241 | 215 | 141 |
| AGE | 111 | 111 | 108 | 42 |
| Miscellaneous | 34 | 35 | 34 | 89 |
| Total acquisition | 1379 | 1433 | 1378 | 688 |
| Recurring operations | | | | |
| Base support and crew | 487 | 594 | 583 | 360 |
| Vehicle maintenance | 1071 | 1163 | 1115 | 522 |
| Propellants | 138 | 144 | 142 | 24 |
| Facilities/AGE maint. | 73 | 73 | 72 | 53 |
| Miscellaneous | 44 | 45 | 45 | 23 |
| Total operations (10 yr) | 1813 | 2019 | 1957 | 982 |
| Total RDT&E | 4170 | 3466 | 3258 | 2012 |
| Total systems cost | 7362 | 6918 | 6593 | 3682 |

cost. The approach of qualifying the engine in flight has not been used previously, but the cost of engine qualification has never been so large. Under these circumstances, it appears that engine qualification should be patterned after aerodynamic testing which, of course, is ultimately done in flight tests.

The assumed development schedule for the three launch vehicles (Fig. 10) allows considerable extra time for the development of the airbreathing vehicle. In fact, the schedule indicates an initial operating capability in ten years for the airbreathing vehicle, approximately three years longer than required for the rocket vehicle.

The total RDT&E costs, considering all these factors, indicate that the systems are comparable and cost approximately 3.2–4.1 billion dollars to develop. The total acquisition and recurring operational costs for the vehicles are also shown in Table 2. The rocket vehicles, which are considerably heavier and have more dry weight, are more costly to procure and to operate. The total system costs, which combine RDT&E, vehicle acquistion, and systems operation costs are shown at the bottom of Table 2. All of the first-stage systems cost approximately 6.5–7.5 billion dollars. However, this preliminary analysis is not sufficiently accurate either in defining the vehicles or in estimating their costs to use in selecting the best vehicle.

The configurations used in this preliminary comparison problably favor the airbreathing systems. Rocket vehicles with first-stage shapes similar to that shown for the orbiter may be more appropriate for the VTO systems. Since vehicles with these shapes are under study by others, it would be interesting to compare them with the rocket-powered vehicles described here. This has not been done, but as pointed out earlier, it is difficult to select vehicle concepts from the results of preliminary analyses unless weight and cost differences are substantial. Since substantial differences are not expected, a more refined analysis will be required before the most efficient first-stage shuttle vehicle concepts can be identified.

## Operating Features

For the mission considered in this study, the results suggest that the airbreathing launch vehicle system will be lighter than the rocket-powered vehicles and its costs will be similar. Other rocket-powered designs may prove more promising than the one described in this paper, but it is difficult to envision a rocket-powered vehicle with performance substantially superior to the study vehicles. It is appropriate, therefore, to compare the vehicles on secondary criteria such as abort characteristics, ferry capability, cross range capability, basing advantages, and safety.

### Takeoff Mode

The takeoff mode has a significant impact on the vehicle reliability, abort characteristics, and basing concepts. The vertical takeoff mode, which is the established technique for launching space vehicles, is well suited to our current expendable launch vehicle systems. The reasons are quite apparent: it eliminates the weight of wings, eliminates the weight of landing gear and aerodynamic control surfaces, and in general, imposes virtually no penalty on an expendable rocket vehicle. These reasons are valid for expendable systems, but they are not necessarily appropriate for reusable systems. The reusable systems, if they have a horizontal landing mode, require the use of wings, landing gear, and aerodynamic control surfaces. Consequently, the motivation for using the vertical takeoff mode is not as great with reusable systems as it is with expendable systems.

Under these circumstances, the attractive features of the horizontal takeoff mode may be given more attention. One major feature is the potential to operate from many of the large airports or military bases around the world. Operation from several bases greatly simplifies the task of performing space rescue and satellite rendezvous functions. There are, of course, problems connected with operating a vehicle as large and unusual as these from existing airports. One problem may be runway stress limitations, but studies indicate that the use of multiple gear such as proposed for the supersonic transport and presently used on the large subsonic transports could solve this problem. Another problem is the noise generated by these vehicles during takeoff. Studies have shown that the airbreathing systems can operate at reduced power during takeoff and limit the noise to near that proposed for the supersonic transport program; HTO rocket-powered vehicles would have considerably higher noise levels. In addition to these two problems, there is the question of airport safety in the event of an explosion or crash of the launch vehicle near an airport. Certainly the vehicles would not be operated near populated areas until a high level of confidence had been developed through extensive use over a long period of time.

For the airbreathing system, an interesting possible solution to this problem and the runway stress problem involves taking off with only a small amount of fuel and refueling the vehicles in subsonic flight. There does not appear to be any technological reason why this could not be accomplished. In fact, it might prove to be an excellent design choice since the weights of the landing gear and a portion of the vehicle structure are determined by the maximum operating weight in the taxi condition.

### Takeoff Abort

The selection of takeoff mode has a significant impact on the design requirements for vehicle reliability and launch abort systems. The shuttle vehicle must provide a high degree of occupant safety and vehicle survivability. Crew and passenger escape capsules, which could protect the occupants in the event of a major system failure, appear to be impractical because of the weight and cost considerations. Therefore, the required safety must be provided by designing the vehicles to safely abort in the event of a major failure or by designing to preclude major failures. The latter technique involves the use of redundant systems, extensive checkout procedures and/or high reliability components. These approaches will be used to some degree on any shuttle vehicle, but extreme requirements for reliability can add significantly to cost. The three systems studied here have inherent characteristics which result in different reliability requirements. The VTO system has a time period immediately after lift-off in which multiple engine failures would be catastrophic. Following this period, the vehicle could abort the mission by dumping oxidizer, separating the stages, and landing. The procedures and costs associated with insuring safety during vertical lift-off or during an early abort have not been defined. The HTO rocket vehicle does have some capability to tolerate thrust loss during takeoff and to land at takeoff gross weights. Because the airbreathing vehicle engine sizes are determined by the transonic acceleration condition, a 40% thrust loss could be tolerated during takeoff. Also the airbreather is designed to land at takeoff gross weight. In summary, qualitative assessment of the three vehicles suggests that the reliability requirements for the airbreathing vehicle will be less stringent, but the resultant cost savings are difficult to estimate.

### High-Speed Abort

The airbreathing launch vehicle flys a lower trajectory at any given speed than the VTO rocket vehicle. The use of a low-altitude trajectory reduces the problem of aborting the mission during high-speed flight. In the event of engine failure, loss of pressurization, etc., the vehicle has the capability to terminate the flight plan and return to the base under environmental conditions no more severe than those of the nominal flight plan. For the rocket vehicles, on the other

**Table 3 Vehicle characteristics**

| | Air-breather | HTO rocket | VTO rocket | Orbiter |
|---|---|---|---|---|
| Dimensions | | | | |
| Body volume, $ft^3$ | 149,284 | 96,877 | 88,694 | 29,355 |
| Body plan area, $ft^2$ | 14,844 | 11,827 | 11,144 | 3,011 |
| Body wetted area, $ft^2$ | 33,826 | 26,738 | 25,196 | 7,013 |
| Body length, ft | 258.8 | 210.1 | 203.9 | 103.1 |
| Body span, ft | 114.7 | 112.6 | 109.3 | 44.3 |
| Operating parameters | | | | |
| Gross weight, lb | 1,122,000 | 2,395,000 | 2,328,000 | 382,524 |
| Dry weight, lb | 433,965 | 544,459 | 489,398 | 87,663 |
| Propellant weight, lb | 306,030 | 1,468,686 | 1,456,497 | 274,861 |
| T/W ratio (takeoff) | 0.70 | 1.44 | 1.48 | 1.00 |
| W/S ratio (takeoff), lb/$ft^2$ | 75.6 | 202 | 209 | 127 |
| Lift-off speed, knots | 218 | 338 | 0 | ... |
| W/S ratio (landing), lb/$ft^2$ | 34.4 | 46.3 | 44.1 | 38.4 |
| Landing approach, knots | 145 | 165 | 165 | ... |
| Cost, billions of dollars | | | | |
| Research & development | 4.17 | 3.47 | 3.26 | 2.26 |
| Acquisition | 1.38 | 1.43 | 1.38 | 0.86 |
| Operating (10 yr) | 1.81 | 2.02 | 1.96 | 0.52 |
| Total cost | 7.36 | 6.92 | 6.60 | 3.64 |

**Table 4 Vehicle operating features comparison**

| Characteristic | Comment on airbreather relative to rocket |
|---|---|
| Gross weight | Lower |
| Dry weight | Slightly lower |
| Size | Slightly larger |
| Economics | Same |
| Takeoff | HTO airplane operation, lower speeds |
| Noise | Lower engine noise |
| Abort capability | Abort at any time without staging |
| Offset orbits | 500 naut miles, equatorial possible |
| Landing | Lower speeds, present state of the art |
| Basing | Possible basing at airports |
| Ferry capability | Can carry orbiter 2000 naut miles |
| Development time | Propulsion system requires 3–4 yr longer |
| Development risk | New turbojet and scramjets required |
| Flexibility | Inherent growth potential, protected upper stage |
| Commonality | Hypersonic transport, military vehicles |

hand, the entry condition during high-speed abort may be more severe than the nominal flight conditions. In fact, the necessity of designing for such abort contingencies can significantly degrade the performance of the vehicle. This is particularly true if a change in the thermal protection system concept is required.

### Cross Range

The airbreathing launch vehicle has an inherent capability to launch into orbit planes that do not pass directly over the takeoff site. This inherent cross range capability during launch is approximately 500–1000 naut miles and can be extended by providing additional fuel tank volume in the vehicle. A 50% increase in the vehicle gross weight would provide a 2000 naut mile cross range capability prior to launching the second stage. With this capability, it is possible to operate from Texas, Florida, or California, launch the upper stage in an equatorial orbit, and return the first stage to the takeoff point. The capability to launch into orbits that are remote from the takeoff point enhances the shuttle vehicle's ability to rendezvous quickly with near Earth satellites; an important feature for military and space rescue operations.

### Ferry Capability

This capability is important if the shuttle vehicle is required to operate from more than one or two bases or if landing away from base is required. The ferry capability of the airbreathing first-stage vehicle is excellent. Ranges in excess of 2000 naut miles at hypersonic speeds are possible with an empty upper stage in place. The ferry capability of the rocket vehicle appears to be good without the upper stage but poor with it.

The ability to ferry the upper stage aboard the booster could have a significant impact on the design of the orbiter vehicle, particularly if the need for auxiliary turbojet engines on the orbiter can be eliminated. Turbojet engines have been suggested for the orbiter for three purposes: to provide landing go-around capability, ferry capability, and incremental flight test and training capability. However, such engines cause a significant penalty to upper stage performance, particularly to lifting-body configurations and therefore, it is desirable to eliminate them if possible. Detailed consideration of the need for go-around capability may well show it is not required. The landing characteristics of lifting-body vehicles[21–24] do not appear to be so poor as to require two landing attempts, and the use of an auxiliary thrust device such as a small solid rocket can provide sufficient landing flexibility for virtually all requirements. The need for ferry engines on the orbiter can be eliminated by use of the airbreathing launch vehicle as mentioned before. Another interesting approach that could be used with any booster might be to tow the orbiter with a 747 or C5A aircraft. The feasibility of this operation has already been demonstrated at a one-fifth dynamic scale by flight tests of the M2-F1 towed by a C-47 (see Ref. 25) and the required technology may well involve less design risk than the alternate methods of providing ferry capability. If the auxiliary turbojets on the orbiter are eliminated, towing also may provide a simple means of low-speed flight test and training.

### Technical Commonality

Past history indicates that the speed of aircraft has increased continuously as the technology develops. Invariably, the propulsion systems have been the pacing item for these speed increases. The next major step in aircraft speed will be keyed to the development of a propulsion system that operates in the hypersonic speed range and uses a cryogenic fuel. The convertible ramjet-scramjet using hydrogen fuel is a promising development. Attractive applications for this propulsion system include commercial hypersonic transports and hypersonic military systems. It is difficult to justify these systems at this time because of the high costs of developing facilities to test and qualify full-scale engines. If these circumstances continue, it is unlikely that usable hypersonic technology will be developed for a considerable period of time. If, however, operational scramjet technology were acquired through an airbreathing shuttle vehicle, the development of commercial hypersonic transports and/or hypersonic military systems would be greatly accelerated. Therefore, a decision to build an airbreathing shuttle vehicle could have a considerable impact on the future of high-speed aircraft.

## Summary

An analysis of three fully reusable launch vehicle configurations was conducted using a computerized synthesis program. All vehicles used a common reusable upper stage. The first-stage study configurations included a horizontal-takeoff and landing, airbreathing-engine-powered vehicle; a horizontal-takeoff and landing, rocket-powered vehicle; and a vertical-takeoff, horizontal-landing, rocket-powered vehicle. On the basis of this preliminary analysis the following conclusions are summarized.

1) The rocket-powered VTO and HTO systems had nearly equal dry and gross weight and were virtually equal in size. The gross weight of the airbreathing launch vehicle was less than one-half that of the rocket systems, but due to propellant density differences, its size was comparable. While the airbreather had a higher ratio of dry weight to gross weight (again due to its low propellant density), the dry weight of the

airbreather was still less than the dry weight of the rocket systems.

2) There are a number of desirable operational features associated with the horizontal-takeoff mode that invite further study. These features include good first-stage abort capability, the possibility of multiple basing, advantages during the test program, and in the case of the airbreather, the ability to ferry the upper stage aboard the booster. The takeoff and landing speeds for the airbreathing system under normal and abort conditions are within the present state of the art. The takeoff speed of the HTO rocket vehicle is higher than current technology allows. Landing speeds for both rocket-powered vehicles are acceptable for the nominal mission, but in the abort case, with a significant fuel load or with the upper stage in place, the approach speeds are beyond the current state-of-the-art.

3) The total system costs for all the vehicles studied are similar. The airbreathing system requires approximately three or four years longer to develop than the rocket-powered vehicles, but the costs of developing the additional propulsion systems did not make the airbreathing vehicle economically uncompetitive. This conclusion is based on two premises; that the airbreathing launch vehicle use 10–20 current-sized turbojet engines rather than a small number of very large engines, and that the scramjet propulsion system be developed at subscale in ground facilities and qualified as a full-scale engine in a flight-test program. The total cost differences between the three study vehicles are not sufficient to favor selection of one vehicle on the basis of cost.

4) The development of an airbreathing space shuttle vehicle would have a strong impact on the rate of development of military and commercial hypersonic aircraft.

A summary of the vehicle characteristics is given in Table 3. Table 4 is a qualitative summary of the vehicle performance and operating features discussed in this study and includes a comment on the characteristics of airbreathing vehicles in relation to rocket vehicles.

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