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Comparison of Horizontally and Vertically Launched Airbreathing and Rocket Vehicles

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A design study was performed to define and compare the parameters of horizontal- and vertical-takeoff reusable launch-vehicle systems to identify promising configurations for further developmental emphasis. The investigation considered both two-stage rockets and single-stage airbreathing ramjet/scramjet-powered vehicles, thus representing next-generation and third-generation configurations, respectively. The payload requirement for each vehicle was 20,000 lb delivered to a 100-n mile circular Earth orbit launched easterly from Kennedy Space Center. All vehicles were first analyzed using liquid hydrogen for the entire trajectory and then reanalyzed with liquid hydrocarbon fuel for the first stage, if a rocket, or for the low-speed trajectory segment to ramjet start for the airbreathers. The vertical-takeoff airbreathing vehicles were found to have the lowest empty weights and gross takeoff weights of all of the vehicle configurations, with three-dimensional inward-turning inlets outperforming two-dimensional inlets, and the use of hydrocarbon fuel outperforming hydrogen fuel for the launch propulsive segment to ramjet start. The best horizontal takeoff vehicle is the all-hydrogen inward-turning airbreather. For the two-stage rockets, the lightest empty weight was achieved with the use of hydrocarbon fuel in the booster and hydrogen fuel in the orbiter.

Introduction

THE past few decades have witnessed a plethora of proposed launch vehicles combining many different configurations, operations, and propulsion technologies in an attempt to improve the costs and reliability of future-generation systems. One well-researched technology is the use of airbreathing engines for some or nearly all of the flight to orbit.

The principal benefit of a high-speed airbreathing engine is that the oxidizer required for combustion can be obtained from the ambient air and need not be carried by the vehicle, as must be done with a conventional rocket. However, the nature of high-speed flight within the Earth's atmosphere raises a list of well-established design challenges that must be properly considered to fairly assess the advantages and disadvantages of airbreathing vs traditional rocket engines. Indeed, a scramjet-powered launch vehicle would still require rocket power for the final part of its ascent trajectory outside of the Earth's atmosphere and would also require some additional engine or cycle component for low-speed flight. The ultimate goal of airbreathing configurations is to approach the same low cost and operational simplicity and flexibility enjoyed by other large airbreathing vehicles such as commercial airliners. To that end, many proposed airbreathing launch vehicles have been designed for horizontal takeoff and landing. It has been anticipated that a horizontal-takeoff/horizontal-landing (HTHL) system would result in less support equipment, more frequent flight rates, and increased operational flexibility, all of which would hopefully reduce the cost of an airbreathing launch vehicle over that of a more traditional vertical-takeoff/horizontal-landing (VTHL) rocket system. It is also often assumed that horizontal launch will be the preferred mode for an airbreather because aerodynamic lifting surfaces would be included anyway, and thrust requirements (and thus engine weight) for horizontal launch would be less than those for vertical. The inclusion of vertical or horizontal operational modes further increases the number of vehicle configurations available for consideration.

The present investigation is an effort to evenly view many of these possible configurations in as fair an "apples to apples" comparison as possible, subject to some reasonable assumptions and projections of available technology. The goal is not to provide a final optimized design, but rather to identify configurations that merit further development and that should be passed over. No conscious attempt has been made to advocate airbreathing vehicles over those that use purely rocket propulsion. A promising next-generation two-stage rocket configuration has been selected as the benchmark by which to evaluate any further advantages of developing the additional technology required for future airbreathing vehicles.

Design Code

All vehicles in this design study have been configured with the SpaceSIDE code developed by Astrox Corporation.[1] The code is a component-based object-oriented design package within a systems engineering software environment. SpaceSIDE uses analytical solutions and tabulated data as available rather than detailed computational fluid dynamic solutions to be speedy and flexible while still maintaining a high degree of accuracy. Use of the code's rapid design and analysis capabilities allows for the quick systematic comparison of hundreds of design parameters and input cases.

To design a hypersonic vehicle, the code uses the freestream Mach number and altitude at a chosen design point and specified bow shock strength, from which the method of characteristics and streamline tracing methods[2] are used to form the inlet surface. After the trace, the surface inviscid forces are known as is the inlet exit flow state. A quasi-one-dimensional combustor model is used to model the mixing and burning of hydrogen or hydrocarbon, and a combustor surface is defined. The nozzle flowfield is then also created using the method of characteristics. An external surface joins the inlet capture area and nozzle exit. A reference temperature method

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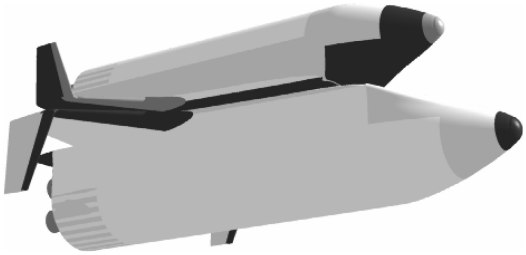

Fig. 1 SpaceSIDE TSTO rocket vehicle.

is then applied to determine the viscous forces, heat transfer, and boundary-layer displacement thickness on each surface. The aerodynamic forces are determined by integrating the pressures on each surface's gridpoints.[3] A rocket vehicle is analyzed with the same methods, but without the internal flowpath surfaces.

The code has the ability to perform analysis in a completely integrated fashion (propulsion-airframe-massproperties-aero-gravloss-heating-volumes, etc.). Individual components include either hypersonic airbreathing or rocket engines integrated into a full vehicle model; their performance is calculated over the complete mission trajectory. Vehicle sizing is done in an iterative loop. The vehicle is scaled until the volume available for the fuel is equal to the fuel volume needed based on individual component weights and densities. The code calculates the volumes and areas of all of the components and from this subtracts the volumes of payload, equipment, thermal protection system (TPS), etc. The resulting volume is multiplied by a tank packaging efficiency as a measure of how well the tank shape is able to use the available volume. The resulting value is the volume available for propellant and must equal the fuel volume required to complete the mission trajectory to "close" the vehicle. All of the components will require resizing, because the vehicle is continuously scaled to match all of these requirements simultaneously.

The entire code consists of over 200 subroutines and functions that account for approximately 12,000 executable lines of code. Several standard codes, such as Missile Datcom for aerodynamics, have been integrated into the code's suite of analysis tools. Setup time for the complete analysis of a new system requires several days, and, once the included components of the specific vehicle system are connected, the system calculations for each solution run are done in about 10 min on a standard desktop PC. The code has the ability to model 21 different commercially available rocket engines as well as airbreathing scramjet-based engines and traditional turbine engines using a variety of inlet geometries. Rocket geometries are also included, as represented in Fig. 1.

Vehicle Considerations

State of the Art

The two-stage-to-orbit (TSTO) rockets in this study have been selected to represent what was considered near state-of the-art rocket vehicles. The rocket technologies and performance metrics were chosen to represent those that are available as of this writing. By comparison, airbreathing scramjet technology is still maturing. The scramjet vehicle technologies assumed in this study were chosen to represent a reasonable extrapolation of the current technology. This extrapolation introduces more uncertainty into the airbreathing vehicle solutions than exists for the rocket vehicles. These enabling technologies primarily include the actual I_{sp} performance of a large-scale scramjet operating at higher Mach numbers and altitudes, the tank weight of conformal cryogenic tanks vs standard cylindrical tanks, and the unit weights and temperature limits of both passive and actively cooled types of TPS. The estimates used for these parameters are believed to be realistically achievable without being overtly optimistic.

Inlets for Airbreathers

A hypersonic scramjet-powered vehicle is best thought of as a flying engine. The choice of the inlet type and combustor configuration will govern the entire vehicle geometry thus influencing not only the propulsive forces of the vehicle but also its aerodynamics, surface area, and volume. Two types of inlets are considered in this present work, the two-dimensional wedge and the three-dimensional inward turning as represented in Fig. 2.

Fig. 2 Single-stage-to-orbit (SSTO) airbreathing vehicles: two-dimensional inlet and inward-turning inlet.

The two-dimensional wedge-type inlet has been well researched in various forms for the last several decades. Although not as well known, the possible performance gain of the inward-turning inlet has been bringing it more attention. The inward-turning geometry results in less wetted area in the high heating regions at the end of the inlet, through the combustor, and the entrance to the nozzle. The smaller wetted area yields an approximately 35% reduction in the amount of active cooling required by a similar two-dimensional geometry and a 50% reduction in heat transfer. The inward-turning geometry has a single combustor flowpath, which reduces the complexity and amount of actuators and seals compared to the 6–8 combustor flowpaths of the two-dimensional vehicle. The reduced cooling loads and combustor provisions result in lighter engine and thermal protection weights. Additionally, the reduced viscous losses, smaller cooling requirements, and resulting increased heat balance velocity cause an increase in effective specific impulse enabling the inward-turning vehicle to reach a higher Mach number before scramjet cutoff. All of the preceding help to close the vehicle, in a synergistic way, at lower gross and empty weights than comparable two-dimensional geometries. This study facilitates the quantification of these phenomena across different vehicle configurations.

Propellant Issues

The tradeoffs in performance caused by fuel selection are of particular note in this study. The design investigation considered two different fuels for each vehicle: liquid hydrogen (LH2) and liquid hydrocarbon (LHC) (RP-1 for rocket engines and JP-1 for turbines). The oxidizer for both fuels was liquid oxygen (LOX) when under rocket-powered flight. LH2/LOX offers the best I_{sp} performance (~455 s) of any of the typical rocket fuels; however, such performance comes at a cost. Though the high performance of hydrogen reduces the amount of propellant required, its very low density of 68 kg/m^3 requires an enormous volume to contain it, thus driving up tank and vehicle size and weight. Increased volume is tied to a corresponding increase in surface area, which imposes a further drag penalty during an airbreathing ascent trajectory. There is also a weight penalty from additional thermal protection acreage. Hydrocarbon fuel has a lower I_{sp} (~330 s) than hydrogen but is nearly 12 times as dense at 805 kg/m^3. Though more fuel mass is required to release the same propulsive energy, the high packing density of the hydrocarbon requires less volume.

Vertical and Horizontal Takeoff

A common hope for a horizontal takeoff airbreathing configuration is to reduce the operations cost of the launch vehicle. This expectation is partly based in the fact that HTHL aircraft are historically much cheaper to operate than vertically launched rockets. It must be remembered, however, that an HTHL launch vehicle will never be a pure airplane. Whether vertically or horizontally launched, the vehicles will have rockets and rocket propellant for ascent to orbit, reaction control and orbital maneuvering systems, passive and active TPS, and other systems in common. The operational gap tightens further now that horizontal integration, transportation, and assembly flow of vertically launched vehicles such

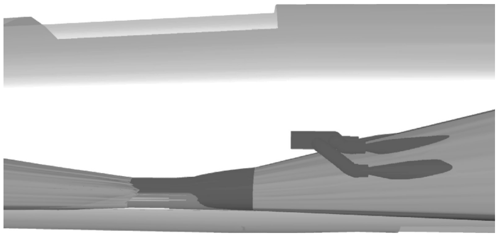

Fig. 3 Side-view detail of ascent rocket integration within hypersonic nozzle.

as the Sea-Launch Zenit-3SL have been demonstrated. The actual vertical operations for a VTHL vehicle can be reduced to fueling and the launch itself. Although both launch options imply the need for a certain amount of support hardware and personnel, it might be that the vertically launched vehicle requires more of such resources, including some sort of erecting mechanism and launchpad while the horizontal vehicle could use an airplane runway. Unlike an airliner, however, an HTHL hypersonic launch vehicle will weigh approximately four times more at takeoff than it does at landing. The wings and landing gear must both be sized for the support of the larger gross weight instead of the much smaller empty weight plus payload weight, for which they are sized for the VTHL vehicle. If the HTHL vehicle is an SSTO, that extra launch weight must be carried all of the way to orbit. On the other hand, VTHL vehicles must have takeoff rockets that are sized to provide thrust greater than weight, which means they will have a greater rocket propulsion mass to gross takeoff mass ratio than their horizontal-launch counterparts. Quantifying the tradeoffs arising from the interactions of these different configuration parameters has been a principal goal of the present study.

Rocket Integration with Hypersonic Flowpath

The labeling of the hypersonic vehicles in this study as airbreathers merely distinguishes them from the purely rocket vehicles. Any hypersonic vehicle will require some use of rockets for the final ascent to orbit after scramjet cutoff. These rockets can also be used for takeoff and ascent propulsion until ramjet start. For this investigation the rockets were integrated into the hypersonic vehicle just downstream of the combustor in the first part of the scramjet nozzle. Figure 3 is a side perspective of this arrangement for an inward-turning geometry; two-dimensional geometries were done similarly.

In the figure, the darker patches to the right are the rocket engines, and the ram/scram combustor is the darker region to the left. This arrangement allows for the rockets to make use of the scramjet nozzle for additional expansion. The rocket nozzle ports are covered during ramjet/scramjet operation. This study did not examine any air-augmentation effect arising from the placement of the rocket engines.

Configuration Setup

Wherever possible all vehicles were solved for the same set of input values, except when the particular configuration category had a unique requirement, such as a thrust-to-weight ratio greater than one for a VTHL vehicle. In those cases, all of the vehicles within that category were run with the same assumptions. A notable difference between the airbreathing and rocket vehicles are the different trajectories they fly as represented in Fig. 4.

The trajectories for airbreathing SSTO vehicles are divided into three trajectory segments: launch and acceleration to ramjet starting point, ramjet/scramjet cruise to maximum scramjet Mach number, and the rocket ascent into orbit. The TSTO rockets are divided into two trajectory segments: one for the booster stage and one for the orbiter. The major configuration parameters are listed here:

Airbreathing Vehicles[4]

1) Rockets embedded in the scramjet nozzle were used for both low-speed and orbital insertion for SSTO. One SSTO vehicle case was solved with turbojets replacing the rockets for trajectory segment 1.

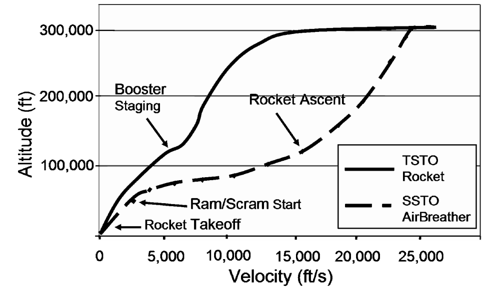

Fig. 4 SSTO airbreather and TSTO rocket ascent trajectories.

2) There is a LH2 or LHC rocket or turbine for trajectory segment 1: takeoff to ramjet start at 2500 ft/s.

3) There is a LH2 ramjet/scramjet for trajectory segment 2; scramjet cutoff when computed EISP falls below approximately 700 s [~15,500 ft/s for inward-turning inlets, ~14,000 ft/s for two-dimensional rocket-based combination cycle (RBCC), and 13,000 ft/s for two-dimensional turbine-based combination cycle (TBCC)].

4) Trajectory segment 2 is flown at a constant dynamic pressure of $Q = 2000$ psf.

5) The fifth parameter is the LH2 rocket ascent to 50/100-n mile transfer ellipse after scramjet end; trajectory 3. Orbital maneuvering system (OMS) engines circularize 100-n mile LEO orbit.

6) Vehicles make use of variable geometry in the engine cowl region for ramjet starting and for improved off-design performance.

7) TPS was matched for conditions at scramjet design point.

Rocket Vehicles[5]

1) LH2 rockets use rubberized space shuttle main engine engines with rocket installed thrust/weight of 73.5.

2) LHC rockets use rubberized RD-180 engines with rocket installed thrust/weight of 80.

3) TSTO rocket staging is at 7000 ft/s.

4) TPS design point for the booster is the staging velocity; for the orbiter the design point is the reentry condition.

5) Booster stage is recovered with a turbojet fly-back system and returned to launch site.

Payload

1) Twenty-thousand pounds were launched easterly from Kennedy Space Center to a circular 100-nm low Earth orbit.

TPS Weights

1) TPS for rockets use shuttle-type materials, maximum temperatures, and unit weights.

2) TPS for airbreathers use tailorable advanced blanket insulation (TABI) and internal multiscreen insulation (IMI).

HTHL Modeling

1) Rocket engines were sized for thrust/weight at takeoff of 0.7, which provides for good transonic capability.

2) Turbine engines (when included) were sized for thrust/weight at takeoff of 0.5 to minimize turbine sizing.

3) Landing gears were sized for takeoff: 2.97% of gross takeoff weight (GTOW).

4) Wings sized for takeoff were based on GTOW.

5) Takeoff speed $= 225$ kn.

VTHL Modeling

1) Rocket engines were sized for thrust/weight at takeoff of 1.4.

2) Landing gears were sized for landing: 4.8% of empty weight + payload weight (provides for abort scenario if accompanied by fuel dump).

3) Wings were sized for landing based on empty weight + payload weight.

4) Landing speed $= 180$ kn.

Results

Vehicle and component weight data are the primary means used in this study to report the results of the various vehicle cases. Such data detail the design of the closed vehicle and are indicative of the vehicle's response to requirements, flight conditions, and vehicle performance parameters and can therefore be successfully employed to compare and contrast the different configurations and technologies. Six basic vehicle categories were set up and solved; two SSTO VTHL RBCC airbreathers (one with two-dimensional inlet, the other inward turning), two SSTO HTHL RBCC airbreathers (one with two-dimensional inlet, the other inward turning), one TSTO rocket, and one SSTO HTHL 2D TBCC. The results of closing these different configurations for different fuel selections are detailed here.

SSTO VTHL and HTHL Airbreathers (All Hydrogen Fuel)

The RBCC airbreathing configurations were closed as purely hydrogen-fueled vehicles and were the first to be analyzed as part of this study. The sized vehicles with their corresponding GTOW are shown in Fig. 5 arranged by decreasing GTOW (the STS is depicted for scale reference).

The lightest GTOW was achieved by the vertically launched inward-turning vehicle at about 600,000 lb. The horizontal-takeoff two-dimensional inlet vehicle was over twice as heavy at 1,200,000 lb. Both HTHL vehicles are substantially heavier in GTOW than their VTHL counterparts because of the scaling up caused by the larger wing and landing-gear weight. However, the inward-turning VTHL vehicle only grew by 26% to become HTHL, whereas the two-dimensional inlet VTHL vehicle had to grow 54% to close as an HTHL vehicle. The performance gap between the two inlet types grows larger as the scale increases. The decreased flowpath drag and cooling requirement of the inward-turning design over the two-dimensional wedge inlet yield enough performance increase to allow the HTHL inward-turning vehicle to come in at a lower GTOW than even the VTHL 2D vehicle. These results show the importance of analyzing hypersonic technology in context of the integrated system. A small difference in performance of the two scramjet inlets in a laboratory test is magnified when the vehicle using the lower performance inlet must be sized and resized for the increased cooling requirement and iteratively scaled up to closure. Depicted in Fig. 6 is the GTOW of the four SSTO hydrogen vehicles broken down by payload weight, vehicle weight (empty weight), and the propellant weight required for each segment of the ascent trajectory.

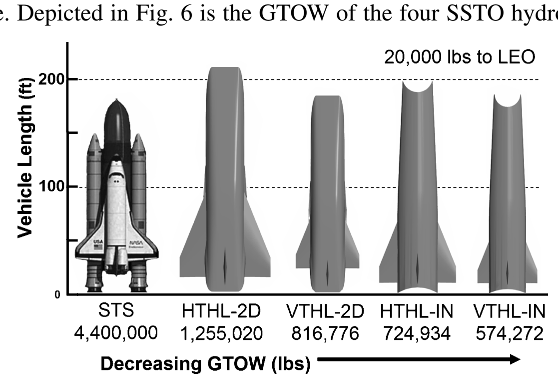

Fig. 5 SSTO airbreathing LH2-LH2-LH2 vehicles (scale comparison).

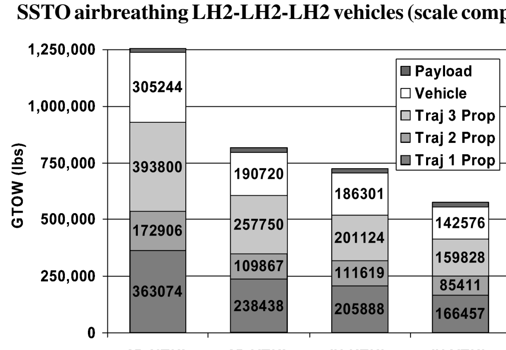

Fig. 6 Comparison of GTOW SSTO airbreathing LH2-LH2-LH2 vehicles.

Table 1 Vehicle component weights (lb), SSTO airbreather (LH2-LH2-LH2)

Vehicle type	2D HTHL	2D VTHL	IN HTHL	IN VTHL
Propulsion	59,752	47,864	36,187	34,937
Tank stack	65,514	42,520	39,103	30,708
Active TPS	33,995	26,880	17,485	15,472
Passive TPS	35,273	27,226	31,885	27,677
Wing total	30,653	9,639	14,013	6,107
Landing gear	37,275	9,618	21,531	7,384
Misc.	42,783	26,973	26,097	20,291
Empty weight	305,244	190,720	186,301	142,576

The propellant weight of the first and third trajectory segments are the combined weight of the hydrogen and liquid oxygen required for the rockets with hydrogen to oxygen weight ratio of 1:6. Trajectory segment 2 is the airbreathing part of the ascent, and the propellant weight is of the hydrogen fuel only. The data show that almost 30% of the GTOW is expended in the first few minutes of the trajectory by the rocket engines accelerating the vehicle toward Mach 2.5 and ram/scram start. This is of particular interest because once the fuel is expended it no longer weighs the vehicle down, but the tank weight and vehicle size initially required to contain that expended propellant are part of the vehicle empty weight and must be carried throughout the mission.

From Fig. 6 the hydrogen fuel used during the airbreathing trajectory segment 2 is much less than the propellant weight required for the rocket segments 1 and 3. But, because the rocket propellant weights include the weight of the oxidizer, the actual hydrogen propellant weight for segments 1 and 3 is one-sixth of the represented value. Added up, this means that approximately 60% of the onboard hydrogen is for the airbreathing trajectory. Though it does not add largely to the vehicle gross weight, the need to carry this hydrogen is the principal contributor to vehicle volume.

The empty weights are represented in Fig. 6 as the vehicle weight, and they follow the same trend as the gross weights. However, the HTHL IN inward-turning vehicle, which is approximately 90,000 lb lighter than the 2D VTHL in gross weight, is only 4400 lb lighter in empty weight because of its heavier horizontal structural components. Most of the launch operations and flight refurbishment costs, as well as the initial design and procurement costs of a launch vehicle, roughly scale with empty weight.[6] Further understanding is gained by looking at the empty weight breakdown by components as shown in Table 1.

This kind of breakdown gives quick insight into the requirements of the different configurations. The tank weights and surface areas scale up as the propellant volume increases. An increase in surface area increases the amount of area needing active and passive thermal protection. The two HTHL vehicles are readily identifiable in Table 1 by their large landing-gear weights. The value for wing totals includes the wing structure and wing TPS weight and are again conspicuous for HTHL. The values for the actively cooled TPS directly demonstrate the larger cooling requirement of the two-dimensional inlet compared to the inward turning; almost twice the amount comparing VTHL 2D to VTHL IN or HTHL 2D to HTHL IN. An interesting observation is that the weights of the propulsion systems are roughly the same across the different vehicles. The reason for this is the way the ascent rockets are sized. The VTHL vehicles, although lighter than their HTHL counterparts, have rockets that are sized for thrust to weight equal to 1.4, where the HTHL rockets are sized at 0.7. The result is that the rocket propulsion makes up a greater percentage of the VTHL empty weight, which nearly matches the lower percentage rockets of the larger HTHL vehicles.

TSTO Rockets

Although the airbreathers represent a desired future capability, an all-rocket solution might constitute a satisfactory level of

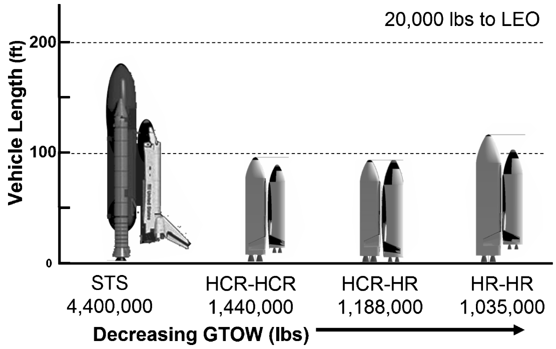

Fig. 7 Rocket vehicles (scale comparison).

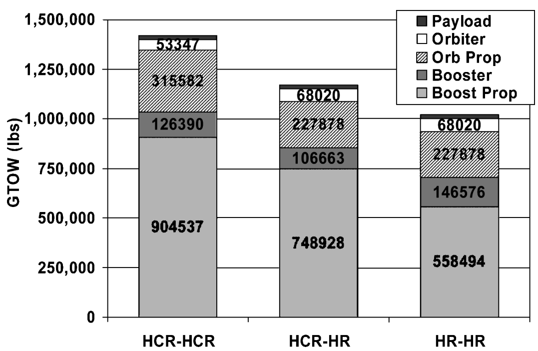

Fig. 8 Comparison of GTOW TSTO rocket vehicles.

performance that is nearer term and would require less technology development while accomplishing the same mission. The rocket results were therefore considered the benchmark against which to judge the extent of the improvement promised by the airbreathing configurations. The TSTO rockets were also the starting point for a trade study considering a different fuel type. Three TSTO rocket variations were created and sized for this study. The three configurations include hydrogen fuel in booster and orbiter (HR-HR), all hydrocarbon fuel (HCR-HCR), and a combined rocket (HCR-HR). The solutions to the three sized TSTO rockets are shown in Fig. 7.

The first thing to notice is the reduced physical size of the TSTO rockets compared to the airbreathers. This is partly because of the increased efficiency of volume when using standard cylindrical tanks as opposed to conformal tanks sandwiched into the cramped airbreathing geometries. The gross weights of the rockets, however, are larger than the airbreather gross weights. As would be expected, the higher I_{sp} of the pure hydrogen HR-HR rocket results in a smaller fuel requirement to meet the objective and therefore comes in at the lightest gross weight. The pure hydrocarbon rocket comes in at the heaviest. An interesting rocket is the HR orbiter atop an HCR booster. The HR orbiter is the same size as the other HR orbiter from the HR-HR case, as they fly the same trajectory from the same starting point and initial velocity. However, because the HR orbiter weighs less than the HCR orbiter from the HCR-HCR case, its HCR booster can be sized down a bit, thus reducing the total gross weight somewhere between the pure hydrogen and hydrocarbon cases as shown in Fig. 8.

The unforeseen outcome of the combined HCR-HR rocket was its resulting empty weight. Although the combo was the medium performer in total gross weight with a heavier gross weight HCR booster than the HR booster, the higher packing density of the hydrocarbon fuel in that HCR booster makes for a geometrically smaller booster than the hydrogen case as depicted in Fig. 7. The empty weights are shown in Fig. 9.

This is an example where using a fuel with a lower I_{sp} but a higher density might decrease the rocket empty weight and consequently the cost of the vehicle. The empty weight breakdown by component for the rocket orbiter plus the booster is found in Table 2.

Even though the fuel requirement of the HCR orbiter is larger than the HR orbiter, the fuel fits into a smaller, less complex tank. This

Table 2 Orbiter component weights (lb) TSTO rockets

Vehicle	HCR-HCR	HCR-HR	HR-HR
Propulsion	9,241	9,627	9,627
Tank stack	4,298	7,725	7,725
Passive TPS	3,384	4,888	4,888
Wing total	11,714	13,751	13,751
Landing gear	3,476	4,072	4,072
Other rocket	21,235	27,957	27,957
Orbiter empty wt.	53,347	68,020	68,020
Booster empty wt.	126,390	106,663	146,576
Total empty wt.	179,737	174,683	214,596

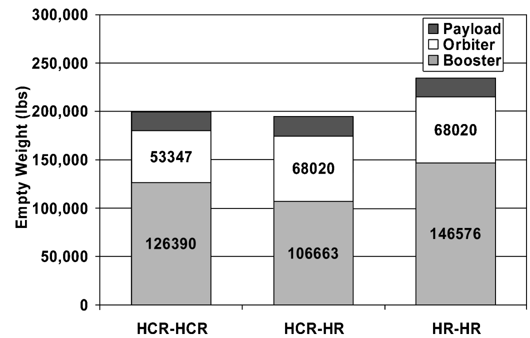

Fig. 9 Comparison of vehicle empty weights TSTO rocket vehicles.

tank volume reduction decreases the total surface area of the rocket and hence lowers the TPS weight. This weight savings coupled with the weight reduction in the tank weight allows the scaling down of the orbiter wing and landing gear making the HCR orbiter the lightest empty weight of the orbiters. It must be remembered, however, that the HCR booster was sized to carry the HCR orbiter's gross weight. Therefore, the HCR booster required for the HCR orbiter is larger and heavier than the HCR booster required for the lighter-weight HR booster. These results indicate that the greatest reduction in empty weight is achieved for gross weight reductions in the orbiter and for vehicle size (empty weight) reductions in the booster. In this particular sizing, the slight empty weight reduction of the HCR-HR rocket over the HCR-HCR rocket might not be as beneficial as having a noncryogenic-fueled HCR orbiter, so again operations issues help to define the "best" answer.

SSTO VTHL and HTHL Airbreathers (LHC for Takeoff to Ramjet Start)

The impact of using hydrocarbon fuel for the ascent rockets of the RBCC airbreathers was considered next. From the results of the TSTO rockets, it was learned that using hydrocarbon fuel in the last trajectory segment would increase the gross weight carried until that point and increase the sizing of the first and second trajectory segment components. However, reductions in vehicle empty weight could be possible by using the higher-density fuel in the first trajectory segment. The final part of the study changed the fuel usage for the first trajectory segment rockets in the airbreathers to hydrocarbon, with hydrogen use remaining during the ram/scram in trajectory 2 and for the final rocket ascent of trajectory 3. The rocket engines would not function on both hydrocarbon fuel and then hydrogen fuel; therefore, the weights of two different rocket engine sets must be accounted for in this analysis: an HCR engine set for trajectory segment 1 and an HR engine set for trajectory segment 3. The four airbreathing vehicles were resized, and the closed vehicles are depicted according to decreasing gross weight in Fig. 10.

The first change to note is that the gross weight of the HTHL IN is now greater than the VTHL 2D. The GTOW values have increased for the HTHL vehicles as was expected. The HTHL 2D grew by 164,000 lb and the HTHL IN by 92,000 lb. The real surprise is that the GTOW values for the two VTHL vehicles have decreased substantially. The VTHL IN decreased by 72,000 lb, and the VTHL 2D decreased by 114,000 lb when compared to their

Table 3 Vehicle component weights (lb), SSTO airbreather (LHC-LH2-LH2)

Vehicle	2D HTHL	IN HTHL	2D VTHL	IN VTHL
Propulsion	61,058	37,300	36,254	26,814
Tank stack	59,998	35,898	29,089	21,448
Active TPS	32,114	16,888	22,078	12,618
Passive TPS	33,439	30,545	21,793	22,278
Wing total	37,236	17,137	7,563	4,882
Landing gear	42,135	24,277	7,547	5,903
Misc.	42,313	25,975	20,092	15,368
Empty weight	308,294	188,020	144,415	109,311

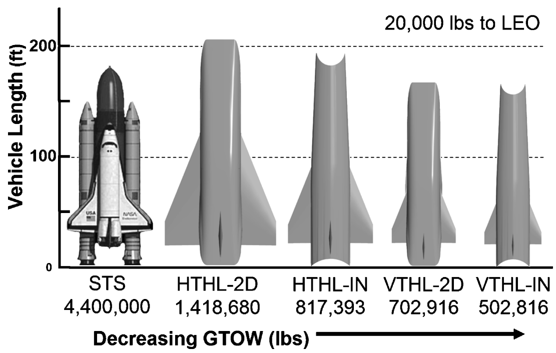

Fig. 10 SSTO airbreathing LHC-LH2-LH2 vehicles (scale comparison).

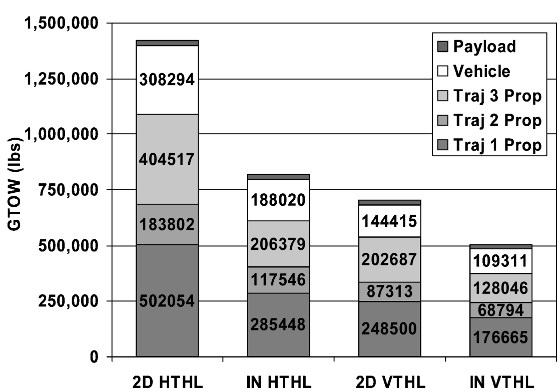

Fig. 11 Comparison of GTOW SSTO airbreathing LHC-LH2-LH2 vehicles.

all-hydrogen equivalents. A decrease in empty weight was expected, but a decrease in gross weight of this magnitude was not. Further information is provided by the gross weight breakdown shown in Fig. 11.

As should be the case, the hydrocarbon/LOX propellant weight required for the first trajectory segment is greater for all vehicles than the corresponding hydrogen/LOX required in the first set of airbreathing vehicles. However, the hydrogen propellant weight required for the airbreathing second trajectory segment has decreased for the two VTHL vehicles. This indicates that the airbreathing segment is now being done more efficiently than previously. This is a result of the decreased size of the vehicle because of a higher first segment propellant density. Both of the VTHL vehicles have benefited from an empty weight reduction of over 40,000 lb. The decrease in vehicle weight is made possible mostly by a reduction in vehicle size. A smaller vehicle benefits from reduced surface area and consequently lighter TPS weights. The smaller vehicle also decreases the amount of drag that must be overcome. These results indicate an even stronger incentive for reducing airbreather vehicle empty weight (size) than was discovered for the TSTO rockets. The weight trends can be seen in the empty weight breakdown by components shown in Table 3.

The impact of the reduced vehicle size imparts broad savings to the solution. Reductions in tank weight and active and passive TPS weights were achieved in each vehicle configuration. However, the increased GTOW of the horizontal takeoff vehicles immediately scales up their wing and landing-gear weights. This increase effectively swallows up any gains made in packaging and consequently influences empty weight by very little while still increasing gross weight of the HTHL vehicles. The HTHL 2D vehicle would become the largest aircraft to have ever flown. Horizontal takeoff can still be possible; the HTHL inward-turning vehicle is still small enough to be realistically operated from traditional runways. However, the best performer of the group is the half-million-pound VTHL inward-turning vehicle.

HTHL Turbine-Based Combination Cycle

The final configuration of this study involved an SSTO HTHL 2D vehicle in which the low-speed propulsion system is changed from rockets to afterburning turbojets. The TBCC vehicle would still require a rocket system for the final ascent to orbit, but the higher thrust required for takeoff and initial ascent would be provided by the much higher-I_{sp} turbine engines. The integration of the turbines into the hypersonic vehicle is a geometry challenge. The turbine engines must be placed where there is sufficient volume to contain them, and allowance must be made to provide them with the requisite mass capture. This study assumed an "over-under" configuration,[7] where the turbines are arranged in a parallel row located directly above the scramjet combustors. Closable inlet and nozzle doors are opened to permit mass flow. Such arrangements are more easily accommodated by the two-dimensional vehicle geometry. The convergence of the inward-turning inlet makes it challenging to efficiently package the turbines and was not attempted in this study. The six turbines themselves were sized using methods described by Raymer[8] for the resultant weight and dimensions of the engines based on the thrust required. A 20% reduction in the required weight and length were then made as suggested by Raymer to account for recent advances in turbine engine technology. A multiplier of 1.4 was applied to the data for the uninstalled turbines to account for installation. Figure 12 shows the gross weight breakdown of the sized 2D HTHL TBCC vehicle compared to the 2D HTHL RBCC vehicle with LHC for the first trajectory segment.

As expected, the use of the higher-I_{sp} turbines has greatly reduced the propellant weight requirements for the first trajectory segment (and hence the propellant volume, though packaging of the dense hydrocarbon was never a problem). However, once the turbines have ceased operation, they are part of the vehicle empty weight and must be carried all of the way to orbit. As seen in the figure, the empty weight of the TBCC vehicle is almost 240,000 lb heavier than the RBCC vehicle. This extra weight penalty requires the sizing up of the propulsion requirements for the second and third trajectory segments. At the end of the scramjet trajectory, the TBCC vehicle still weighs 1,300,000 lb, nearly twice the 700,000 lb of the RBCC vehicle at the same point in the trajectory. This means

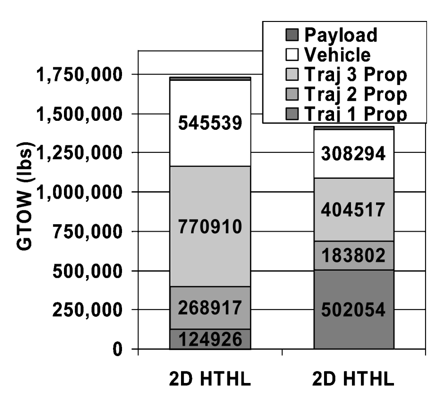

Fig. 12 Comparison of GTOW SSTO TBCC and RBCC LHC-LH2-LH2 vehicles.

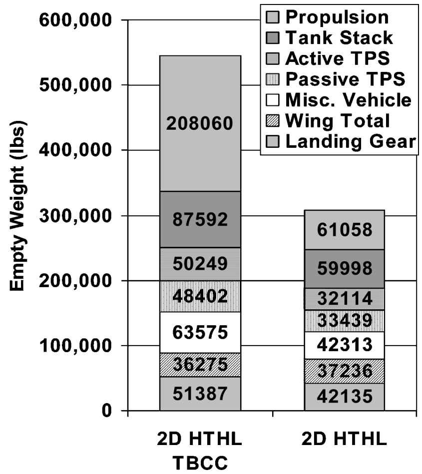

Fig. 13 Comparison of component weights SSTO TBCC and RBCC LHC-LH2-LH2 vehicles.

that the thrust and propellant requirements of the third trajectory segment rockets must be doubled. These impacts are clearly evident in Fig. 13, which details the empty weight breakdown by components.

The weights of the TBCC propulsion components are more than three times greater than for the RBCC. This increase is because of the over 100,000 lb of weight for the six turbojets, the doubling of the weight of the third segment rockets, and to the increased reaction control system and OMS requirements of a much larger on-orbit vehicle. Besides the weight penalty, the turbine engines also impact the volume of the vehicle. Each engine for this case is 9.5 ft in diameter and more than 25 ft long. This is clearly beyond the experience base of current turbines, but then so are 1,700,000-lb aircraft. Combined with the volume removed for the inlet and nozzle passageways, the turbines use upto 21,500 ft^3 of volume, approximately 20% of the usable interior volume for this vehicle. Also, the fuselage width of this vehicle had to be stretched to accommodate the combined 57 ft width of the six engine diameters. When these impacts are considered together, the use of a turbine system is a very unattractive choice for an SSTO airbreather. In fact, the empty weight of the HTHL TBCC vehicle is more than the gross weight of the VTHL RBCC inward-turning vehicle with hydrocarbon first trajectory segment!

Discussion

The results presented in this paper demonstrate the necessity of performing analyses on completely integrated vehicles. The coupling of the propulsion, airframe, aerodynamics, gravity loss, volumes, heating loads, and weights all interact to determine the performance and penalties associated with a given vehicle configuration. In many cases the results presented verify the trends that would be expected for a given configuration, such as the heavier GTOW of an all-hydrocarbon rocket over the purely hydrogen one. The value added by this analysis is that these trends are now quantitative and therefore measurable and directly comparable to other configurations. Of even greater interest is the understanding gained from the results of an unanticipated or nonintuitive interaction, as was witnessed in the data of the LHC/LH2/LH2 airbreathers.

Another valuable insight was the understanding of the coupling between vehicle size, aerodynamic drag, and the amount of required TPS. Specifically, the skin-friction drag and TPS both scale with the wetted area of the vehicle. For the heating conditions present during either the airbreathing trajectory or atmospheric reentry, all of the exposed area of a hypersonic vehicle will require some level of TPS. When the heating over a certain area exceeds the limits of current materials technology, then those areas must be actively cooled. The reduction of TPS area yields a double benefit, the first being a reduction in weight and second a reduction in the time and cost of TPS refurbishment.[9] TPS maintenance is a huge part of the space

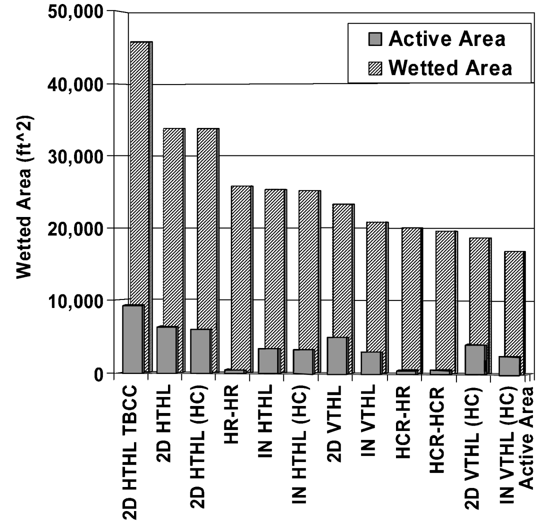

Fig. 14 Comparison of SSTO airbreathing and TSTO rocket wetted and actively cooled areas.

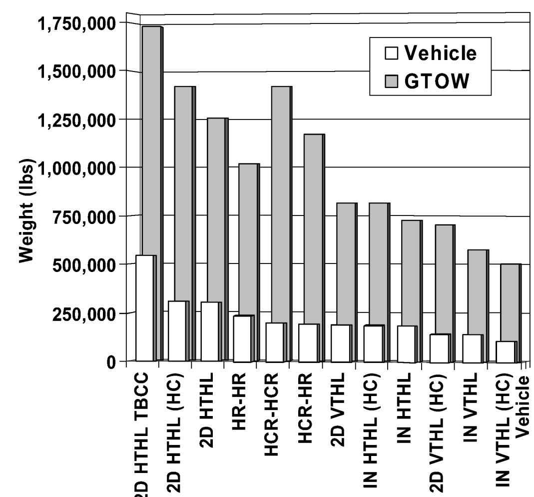

Fig. 15 Comparison of SSTO airbreathing and TSTO rocket weights.

shuttle's between-flight refurbishment costs. More advanced passive TPS materials can require less maintenance than present materials. However, the actively cooled panels on future hypersonic vehicles are a new TPS system that is likely to require a fair amount of inspection and between flight refurbishment. Figure 14 compares the wetted areas of all 12 vehicles and also represents the amount of that area that must be actively cooled.

The wetted areas of the TSTO HCR rocket combinations come in lower than all but the hydrocarbon VTHL airbreathers. The pure hydrogen HR-HR rocket, though it has the lightest gross weight of the three rockets, has the largest wetted area of the three because of its increased size. The active cooling area for the rockets is minimal as it is only required in the combustion chambers and nozzles. The airbreathers, however, need substantial active cooling through the extreme parts of the inlet and nozzle and throughout the combustor. Also shown in the preceding figure is the improvement in active cooling requirements of the inward turning over the two-dimensional airbreathers. In terms of wetted area, the TBCC and RBCC HTHL 2D airbreathers are clearly the worst performers. However, the VTHL airbreathers are actually fairly competitive with the HCR rockets in total wetted area.

The weights of the 12 vehicles considered in this report are all compared in Fig. 15 and are arranged by decreasing empty weight.

Using the empty weight as a rough measure of the approximate cost and feasibility of designing and constructing the vehicle, the "best" airbreathing configurations[10] for space access with the given payload requirement are the VTHL inward-turning airbreathers. They also enjoy the lowest values of GTOW. In general the SSTO airbreathers (with the exception of the HTHL 2D vehicles) come in with lighter empty weights and reduced GTOW compared to the TSTO rockets. However, if the expected level of scramjet technology fails to completely mature, the baseline airbreathing vehicles presented here could all grow from 5–15% in empty weight. In which case, the VTHL airbreathers and TSTO rockets would have more equivalent empty weights. The HTHL 2D baseline cases are probably already too large to be realistically managed as horizontally launched vehicles, and any increase in size would completely invalidate them from operation from existing runways. The TBCC HTHL 2D is particularly unmanageable, with an empty weight larger than the gross weight of several of the VTHL vehicles to accomplish the same mission. Though the VTHL airbreathers come in at the lightest in both weight categories, the HTHL inward-turning all-hydrogen airbreather still remains a possible choice should a horizontal vehicle be required. A horizontally operated and integrated, vertically launched VTHL benefits from both operational and performance gains and is consequently the most attractive configuration for SSTO airbreathers. But, if near-term launch capability is desired, the fully reusable TSTO rockets are very comparable with the airbreathing vehicles in terms of empty weight and are the next logical improvement over the partial reusability of current rocket launch systems. Also, empty weight pound for pound, rockets are cheaper to design and procure than airbreathing vehicles.

Conclusions

From the results of the work performed during this investigation, the following conclusions can be drawn:

TSTO Rocket Conclusions

1) HCR-HCR is the largest GTOW but smaller size choice (empty weight).

2) HR-HR is the smallest GTOW but largest size choice (empty weight).

3) Using LHC in the first stage and LH2 for second stage, HCR-HR yields the lightest empty weight (both stages together) of the three cases considered, even slightly less than the HCR-HCR case. However, the operational ease of using the same, noncryogenic fuel in both stages is an operational advantage that, for the slight empty weight increase, likely makes the pure hydrocarbon HCR-HCR rocket the best TSTO rocket choice for further attention.

SSTO Airbreather Conclusions

1) Inward-turning inlets outperform conventional two-dimensional wedge-type inlets. The increased performance comes from a smaller heating load because of less surface area exposed in high heating regions. The reduced active cooling area requirement allows the vehicle to scale down, thus reducing weights of everything from wings to landing gear as well as reducing the area requiring TPS.

2) For VTHL SSTO options, using LHC in the low-speed rocket cycle (trajectory segment 1) can yield great advantages:

a) VTHL IN SSTO for this case is lightest vehicle overall in both GTOW and empty weights, even after accounting for two (LH2 and LHC) rockets carried simultaneously.

b) The additional propellant weight caused by LHC choice has no impact on wing and landing-gear weights of a VTHL vehicle as it is expended before landing. This helps considerably in vehicle sizing.

c) The more compact fuel storage of the hydrocarbon first trajectory segment yields a smaller vehicle, which improves performance by reducing both vehicle weight and drag.

d) The empty weight of this case is less than the best rocket TSTO case, the HCR-HR, and represents the development and acquisition of a single vehicle instead of both a rocket booster and rocket orbiter.

3) Conversely, for HTHL SSTO options, using an LHC rocket in the low-speed cycle yields no decrease in empty weight but penalizes the vehicle with an increase in GTOW. This outcome cripples the HTHL 2D vehicle but only moderately increases the HTHL IN. The all-hydrogen HTHL IN is the best horizontal takeoff SSTO airbreather.

4) The TBCC HTHL 2D vehicle causes a chain reaction of negative impacts. The integration of the turbine engines uses up large amounts of volume and adds a large weight penalty all of the way to orbit. These factors drive up the scaling of vehicle empty weight, surface area, upper trajectory propulsion requirements etc. For SSTO application, the TBCC system cannot compete with the use of RBCC for takeoff and for the low-speed trajectory segment.

Summary

The understanding gained from the fuel selection trade study suggests that as a general guideline it is better to reduce the gross weight of the vehicle during later trajectory segments and to reduce the empty weight (vehicle size) for the earlier points in the trajectory. The reasoning for this is sound; carrying weight over a longer portion of the trajectory, be it propellant weight or otherwise, requires a greater energy input per pound. Propellant weight used in the first trajectory segment is quickly expended and not carried for long, but the structure size and weight required to contain it are carried along. This is why more efficient propellant packaging might be better, even if the first trajectory segment gross weight is heavier (provided that the propellant still yields sufficient performance). This is even more applicable in the case of an airbreathing vehicle, where a smaller vehicle not only means a reduction in the empty weight that is carried to orbit, but also of the drag and other losses during the airbreathing trajectory segment.

As seen in these results, a fully reusable TSTO hydrocarbon-fueled rocket is tough to beat. In terms of the metrics of empty weight, wetted area, and technology readiness, and with the incorporation of recent operational practices and infrastructure, this configuration promises excellent capability for a near-term launch vehicle. The suite of future airbreathing vehicles offers solutions that can vary widely in scale and feasibility. Several of the VTHL vehicles are competitive with the TSTO rockets in terms of the figures of merit utilized and would offer the operational benefits of a single-stage launch vehicle. The use of hydrocarbon fuel during the first rocket segment of the VTHL inward-turning vehicle yields the most promising configuration of all those studied. The only HTHL vehicle that remains competitive is the all-hydrogen inward-turning configuration.

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