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Investigation of Two-Stage-to-Orbit Airbreathing Launch-Vehicle Configurations

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A conceptual design study was performed to assess and compare the parameters of two-stage-to-orbit airbreathing launch-vehicle systems in an effort to identify optimal configurations for improved access to space. The following vehicle configuration categories were considered: horizontal takeoff ramjet-scramjet boosters with upper-stage reusable rockets, horizontal takeoff turbine boosters with ramjet-scramjet upper stages, and vertical takeoff rocket boosters with ramjet-scramjet upper stages. Ramjet-scramjet upper stages utilize integrated rockets for final orbital ascent. Ramjet-scramjet booster stages make use of either integrated turbines or rockets for takeoff and acceleration to ramjet start. The payload requirement for each vehicle system is 20,000 lb delivered to a 100-n mile low Earth orbit. The vehicle solutions were evaluated utilizing several figures of merit including empty weight, wetted area, actively cooled area, gross weight, staging considerations, and design and technology traceability to future development of single-stage-to-orbit hypersonic airbreathing vehicles. The application of these criteria to the closed vehicle solutions reveals that the vertically launched rocket booster with an upper-stage ramjet-scramjet is the best two-stage airbreathing launch vehicle configuration. Of all of the two-stage vehicles investigated, those which place the hypersonic propulsion elements as part of the upper stage surpass those with first-stage placement and exhibit more design traceability with single-stage-to-orbit airbreathing launch vehicles.

I. 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 still requires rocket power for the final part of its ascent trajectory outside of the Earth's atmosphere and also requires some additional engine or cycle component for low-speed flight.

Many proposed airbreathing launch vehicles are designed as two-stage configurations. The use of multiple vehicle stages is a means to reduce the amount of weight delivered to orbit by discarding expended stages. Indeed, multiple-stage configurations have been the only successful rocket-powered launch vehicles to date. From the viewpoint of an integrated launch system, the use of staging mitigates the vehicle scaling response that would otherwise be required for the successful design closure of a single-stage vehicle, thus resulting in decreased design risk and uncertainty and possibly smaller system weights. These advantages are very attractive when a large amount of uncertainty exists in a proposed technology as is the case with hypersonic airbreathing propulsion. For these reasons, many industry and international designers have repeatedly investigated different staging configurations for airbreathing launchers. The present investigation is an effort to evenly view many of these possible two-stage-to-orbit airbreathing 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 which configurations merit further development and which should be passed over.

II. Design Code

All vehicles in this design study have been configured with the HySIDE code developed by Astrox Corporation.[1] The code is a component-based object-oriented design package within a systems engineering software environment. HySIDE uses analytical solutions and tabulated data as available rather than detailed computational fluid dynamic solutions to be speedy and flexible while maintaining a fair degree of accuracy. Utilization 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 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 grid points.[3] A rocket vehicle is analyzed with the same methods but without the internal flowpath surfaces.

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The code has the ability to perform analysis in a completely integrated fashion (propulsion–airframe–mass properties–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 in order to "close" the vehicle. All of the components will require resizing as 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, 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. Reusable and expendable rocket geometries are also included.

III. Vehicle Considerations

A. State of the Art

The rocket boosters and orbiters included in this study have been selected to represent what was considered to be 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 airbreathing 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 advanced TPS. The estimates used for these parameters are believed to be realistically achievable without being overtly optimistic.

B. 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. 1. The two-dimensional wedge-type inlet has been well researched in various forms for the past 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 of integrated heat load. The inward-turning geometry has a single combustor flowpath, which reduces the complexity and amount of actuators and seals compared to the six to eight combustor flowpaths of the two-dimensional vehicle. The reduced cooling loads

Fig. 1 Geometries of two-dimensional wedge and inward turning.

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 EISP 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. These possible advantages need to be further researched and proven in flight tests as has been done with the two-dimensional designs.

C. Propellant Selection Issues

The tradeoffs in performance as a result of fuel selection are of particular note in this study. The design investigation considered two different fuels: liquid hydrogen and liquid hydrocarbon (RP-1 for rocket engines and JP-type fuel for turbines). The oxidizer for both fuels was liquid oxygen when under rocket-powered flight. Liquid hydrogen/liquid oxygen (LH2/LOX) offers the best I_{sp} performance ($\sim$455 s) of any of the typical rocket fuels; however, such performance comes at a cost. Though the high performance of hydrogen reduces the amount of propellant required, its very low density of 68 kg/m^3 requires an enormous volume to contain it, thus driving up tank and vehicle size and weight. Increased volume is tied to a corresponding increase in surface area, which imposes a further drag penalty during an airbreathing ascent trajectory. There is also a weight penalty from additional thermal protection acreage. Hydrocarbon fuel has a lower I_{sp} ($\sim$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. Liquid oxygen is denser than both fuels at 1140 kg/m^3.

D. Vertical and Horizontal Takeoff

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[4] and landing. It has been assumed that an 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 must be remembered, however, that an HTHL launch vehicle will never be a pure and simple airplane. Whether vertically or horizontally launched, the vehicles will have integrated rockets or turbines for low-speed flight and rocket engines for orbital injection, advanced passive and active TPS, conformal propellant tanks, and extreme heating flight environments in common. The operational gap tightens further now that horizontal integration, transportation, and assembly flow of vertically launched vehicles such 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. The wings and landing gear of an HTHL vehicle 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

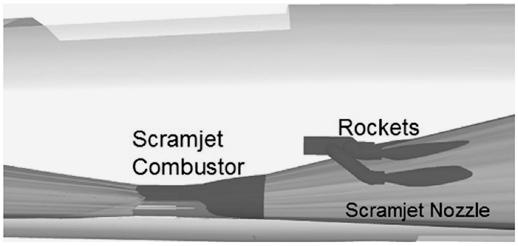

Fig. 2 Side-view interior detail of ascent rocket integration within hypersonic nozzle.

for the VTHL vehicle. Quantifying the tradeoffs arising from the interactions of these different configuration parameters has been a principal goal of the present study.

E. Rocket and Turbine Integration Within the Hypersonic Flowpath

The labeling of the hypersonic stages in this study as "airbreathers" merely distinguishes them from the purely rocket stages. Any hypersonic upper stage will necessarily require some use of rockets for the final ascent to orbit after scramjet cutoff. Similarly, a hypersonic first stage requires some low-speed propulsion cycle to achieve sufficient velocity for ramjet start. This low-speed cycle can also be done with rockets or with integrated turbojet engines. The rockets for this investigation were integrated into the hypersonic vehicle just downstream of the combustor in the first part of the scramjet nozzle. Figure 2 is a side perspective of this arrangement for an inward-turning geometry; two-dimensional geometries were done similarly. This arrangement allows for the rockets (on the right-hand side of figure) 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. The performance of integrated rockets sharing the scramjet nozzle is an area of study needing more research attention. The integration of the turbines into the hypersonic vehicle is a more difficult 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 airflow mass capture. This study assumed an "over–under" configuration,[5] in which the turbines are arranged in a parallel row located directly above the scramjet combustors. Closable turbine inlet and nozzle doors are opened to permit airflow. Such arrangements are more easily accommodated by the two-dimensional vehicle geometry as the three-dimensional inward-turning inlet would require complex geometry for the turbine inlet and nozzle doors. The convergence of the inward-turning inlet makes it more challenging to efficiently package the turbines and was not attempted in this study.

IV. 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. The payload requirement for each configuration was 20,000 lb launched easterly from Kennedy Space Center to a circular 100-n mile low Earth orbit (LEO). The general configuration parameters applicable to all vehicles are listed next with a description of each of the three configuration categories following:

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

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

3) Turbines use afterburning turbojets with (uninstalled, installed) thrust/weight ratios of (11, 8).

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

5) TPS for airbreathers use more advanced Tailorable Advanced Blanket Insulation (TABI) and Internal Multiscreen Insulation (IMI) materials.

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

7) Hypersonic trajectory is flown at a constant dynamic pressure of $Q = 2000$ psf.

8) Orbiter wings are sized for landing based on empty weight + payload weight and landing velocity of 180 kn.

9) Orbiter (rocket or airbreather) landing gear is sized for landing: 4.8% of empty weight plus payload weight (provides for abort scenario if accompanied by propellant dump).

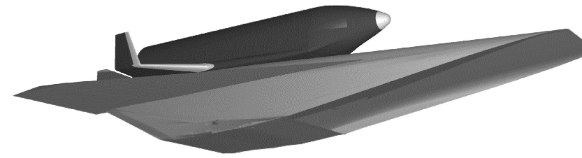

Fig. 3 HTHL ramjet-scramjet airbreather (AB) rocket-based turbine-based combination cycle/LH2-fueled rocket.

A. HTHL Hypersonic Airbreathing Booster with Upper-Stage Reusable Rocket

This configuration, shown in Fig. 3, is one of the most commonly proposed two-stage-to-orbit (TSTO) airbreathing configurationes and is composed of a hypersonic ramjet/scramjet[6] first stage with an upper-stage rocket[7] orbiter attached riding piggyback. The vehicle is horizontally processed and assembled and also takes off horizontally. Low-speed propulsion from takeoff until ramjet start is provided by either integrated turbine or rocket engines. The combined vehicle accelerates under ramjet/scramjet power until staging at some upper Mach number. The rocket orbiter is then ignited and ascends to orbit under its own power. The first stage then decelerates and reverses course to fly back to the launch site, which is now likely more than 1000 n miles distant. Other investigations have suggested recessing the upper stage within the first stage. This imparts a huge volume penalty to the first-stage booster and causes it to grow much larger. Further trade studies could be performed in this area. For the configuration of the current paper, the rocket is exposed to the same heating environment as the airbreather, which is roughly analogous to the heating envirnoment the orbiter will experience during reentry. However, much of the orbiter's leeward surface area, which is shielded by the orbiter's attitude during reentry, is here directly exposed to the high temperature flow and must be protected with additional, more capable TPS. Three versions of this configuration were solved as part of this study differing only by selection of low-speed propulsion cycle. One version utilized turbines[8]; the other two versions made use of either hydrogen or hydrocarbon rockets for takeoff and accelerations. The following configuration parameters were applied:

1) Takeoff speed = 225 kn.

2) Horizontal airbreathing boosters landing gears were sized for takeoff at 2.97% of gross takeoff weight (GTOW).

3) Turbine engines (when included) were sized using methods described by Raymer,[8] with takeoff thrust/weight of 0.7.

4) Rocket-based combination cycle (RBCC) low-speed rockets (when included) were sized for thrust/weight at takeoff of 0.7.

5) TPS design point for both vehicles is the staging velocity.

6) Rocket orbiter staging occurs when scramjet-computed effective specific impulse (EISP) falls below approximately 700 s ($\sim$10,000 ft/s).

7) LH2 rocket orbiter ascends to 50×100 n mile transfer ellipse after staging; orbital maneuvering engines circularize 100-n mile LEO.

8) All booster stages are recovered with a turbojet flyback system and returned to launch site. In the case of turbine-powered first stages, no additional turbines are included.

B. HTHL Turbojet Booster with Upper-Stage Hypersonic Airbreather

The next configuration, shown in Fig. 4, is also a horizontally launched vehicle. The first major difference in this configuration

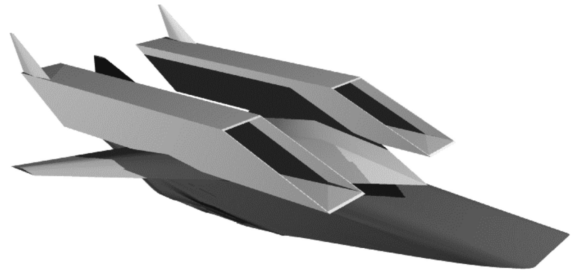

Fig. 4 HTHL turbine stage/AB-RBCC.

vs the previous one is the relocation of the hypersonic propulsion components from the first-stage to the second-stage orbiter. It is important to note in the figure that the dual-flowpath first-stage booster is shown on top, with the second-stage scramjet orbiter vehicle slung beneath it. The transfer of the ramjet/scramjet to the second stage relegates the booster to simply providing the low-speed propulsion segment from takeoff to ramjet start, which, for this configuration, is provided by traditional turbine engines. The decoupling of the low-speed propulsion cycle from the hypersonic elements removes the integration problems of accomodating both the turbine and scramjet flowpaths, and a more traditional turbine inlet geometry can now be incorporated for the booster vehicle. The booster's exposure to high heating environments is also greatly reduced. The combined vehicle system takes off and accelerates until the upper Mach limit of the booster's turbines when the second-stage orbiter is released and then accelerates under ramjet/scramjet power until point of scramjet cutoff. The orbiter will require integrated ascent rockets from the point of scramjet cutoff to orbital injection. After staging, the booster stage flies a short distance to return to the launch site. Both stages are horizontally landed, maintained, and integrated. A major benefit of this configuration is that only one vehicle is present during the high-drag and high-temperature hypersonic trajectory. Another consideration for this configuration is that the on-orbit vehicle now has a hypersonic vehicle geometry and will be required to survive a reentry trajectory. One version of this configuration was completed for this study utilizing a two-dimensional hypersonic inlet geometry for the orbiter. An inward-turning inlet geometry version could also be accomodated by this configuration, but has not yet been undertaken. Specific parameters of this configuration are listed here: 1) takeoff speed = 225 kn; 2) turbine booster landing gears sized for takeoff at 2.97% of GTOW; 3) turbine engines sized for thrust/weight at takeoff of 0.7; 4) turbine booster TPS design point is staging velocity; 5) airbreathing orbiter staging at Mach 4; 6) scramjet cutoff when computed EISP falls below approximately 700 s (~14,000 ft/s for two-dimensional RBCC); 7) airbreathing Orbiter TPS matched for conditions at scramjet design point; and 8) LH2 RBCC ascent to 50 × 100 n mile transfer ellipse after scramjet end; and OMS engines circularize 100 n mile LEO orbit.

C. VTHL Rocket Booster with Upper-Stage Hypersonic Airbreather

The final configuration considered as part of this study also places the hypersonic propulsion elements on the upper-stage orbiter, as shown in Fig. 5. In fact, the hypersonic orbiters of this configuration are of the same setup as those used by the previous configuration; the distinction lies in the different approaches employed to accelerate the airbreathing orbiters to ramjet/scramjet start. This configration uses a reusable rocket booster to provide the required low-speeed propulsion segment and, unlike the previous two configurations, is vertically launched. The rocket booster uses liquid-hydrocarbon rockets to provide propulsion from takeoff until staging. A booster flying this trajectory requires only a minimal amount of TPS. The booster is also staged at a low enough velocity for it to glide back to the launch site without a flyback system. Though the upper stage is physically larger than the rocket booster, the booster has the larger gross weight. Although launched vertically, the entire system processing flow, except for fueling, would be performed horizontally as with the other configurations in this study. Both inward-turning

Fig. 5 VTHL liquid-hydrocarbon-fueled rocket (HCR)/AB-RBCC.

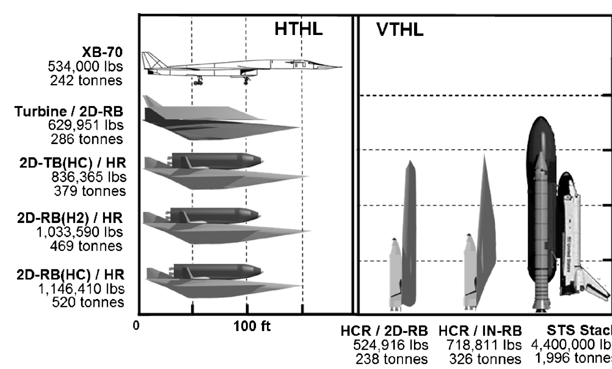

Fig. 6 TSTO vehicles: GTOW and scale comparison.

and two-dimensional inlet geometries were investigated for the orbiter resulting in two versions of this configuration in this study. The following configuraion parameters were used: 1) rocket booster engines sized for thrust/weight at takeoff of 1.4; 2) rocket booster TPS design point is staging velocity; 3) airbreathing orbiter staging at Mach 4; 4) 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 RBCC); 5) booster landing gears sized for landing: at 4.8% of empty weight; and 6) LH2 RBCC ascent to 50 × 100 n mile transfer ellipse after scramjet end and OMS engines circularize 100 n mile LEO orbit.

V. Results

The three vehicle systems just described were all created and set up within the design code. From these systems, the individual parameters and components were changed to create the six vehicles identified. Multiple solution runs were conducted to "close" each vehicle system for the case of 20,000 lb delivered to the 100 n mile circular orbit. The gross takeoff weights and lengths of these six vehicle solutions are shown to scale in Fig. 6. The supersonic XB-70 bomber and the space shuttle stack are included to provide scale reference. The gross weight of the vehicle represents the fueled weight of the vehicle. Though not as revealing a figure of merit as the empty weight, the gross weight does give quick insight into the scale of the selected vehicle. The figure quickly illustrates the magnitude of these vehicles. Even the lightest HTHL vehicle is of larger scale class than the XB-70, one of the largest and fastest turbine aircraft ever developed. Of the six vehicle systems, the three lightest are those with the ramjet/scramjet engine on the upper stage instead of the booster stage.

The weights of the various propellants are the principal constituents of the gross weight. A gross weight breakdown by vehicle and propellant weights is a powerful way to evaluate the different configurations with each other. Such a breakdown is provided in Fig. 7. The propellant amounts in the figure are divided into one of three propellant trajectory segments. Trajectory segment 1 is the low-speed cycle and represents the rocket fuel and oxidizer or turbine fuel expended during takeoff and initial acceleration. Trajectory segment 2 contains the weight of the hydrogen for the ramjet/scramjet trajectory, which is performed by either the first or second stage depending on the configuration. Trajectory 3 for all cases is the weight of the LH2 and LOX required for the rocket ascent to orbit. The individual components within each bar of the figure are arranged in a generally chronological order starting from the bottom; that is the propellants/boosters located toward the bottom of each bar are consumed/jettisoned before propellants at the top of the bar. The only exception to this trend is the flyback fuel required by the HTHL vehicle to return the booster stage to the launch site, which is consumed after staging.

As shown, the flyback propellant can become a large weight requirement if the booster returns a substantial distance to the launch site as must be done for the three HTHL configurations, which make use of ramjet/scramjet booster stages. Both the first and second trajectory segment propulsion requirements have to be sized larger to carry this additional weight along to the staging point. The impact on the HTHL all-turbine booster stage is minimal as it is staged at a much lower Mach number and is still relatively close to the launch site. The figure shows that the use of either TBCC or straight turbine propulsion yields a significant reduction in the propellant weight used during the first trajectory segment and therefore lowers the total gross weight of these TSTO configurations. The first segment propellant weights for the two HTHL RBCC vehicles are five to six times the amount for the HTHL TBCC or turbine booster. In considering these differences, it should be remembered that the propellant weight of the first trajectory segment will be quickly expended and not carried along very far by the vehicle, whereas physical propulsion components such as the turbines or low-speed rockets are part of the vehicle empty weight and will be carried until the booster is staged. Increasing the weight of a later segment increases the sizing of all previous segments that carry it. The upper stages at the top of the three left bars in Fig. 7 are the LH2 rocket orbiters. The rocket vehicle weight and trajectory 3 propellant weights are all the same for these three rocket orbiters as they are identical vehicles starting from the same staging altitude and Mach number. The upper stages at the top of the three right bars are RBCC airbreathing orbiters all starting from the same staging point at Mach 4. Two of these orbiter vehicles have nearly identical weights for second and third propellant segments and empty weight because they are essentially the same vehicle using the same two-dimensional inlet geometry and differing only slightly as a result of small differences in the weights of their required linking structures to respective and very different booster stages. The third orbiter uses the inward-turning inlet and shows a nearly 30% reduction in second

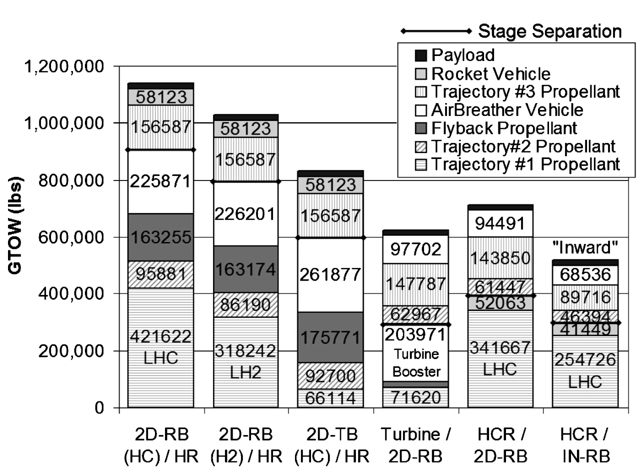

Fig. 7 Breakdown of GTOW by vehicle and propellant segments.

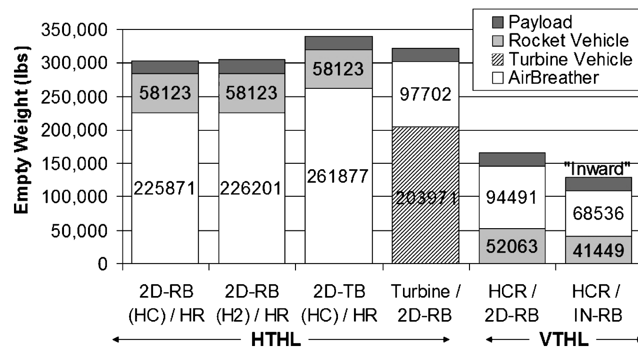

Fig. 8 Comparison of stage empty weight.

and third trajectory propellant weights and orbiter empty weight vs the two-dimensional geometry orbiters. For each of the six vehicles, the weight of the hydrogen fuel required for the ramjet/scramjet trajectory is quite small relative to the total gross thus illustrating one of the primary benefits of an airbreathing engine. This advantage is mitigated slightly by the large amounts of volume required by the hydrogen fuel.

Although the preceding propellant segments comprise a large amount of the vehicle gross weight, it is the vehicle empty weight that is the main cost driver. Most of the launch operation and flight refurbishment costs, as well as the initial design and procurement costs of a launch vehicle, scale roughly with empty weight.[9] The cost of the propellant for each flight is nearly insignificant by comparison. When comparing the empty weights as a rough measure of the approximate cost and feasibility of designing and constructing the vehicle,[10] it must be remembered that, "pound for pound," a pure rocket vehicle is likely to cost less than a more advanced and technologically uncertain hypersonic airbreathing vehicle. The empty weights for each vehicle system are shown in Fig. 8. As can be seen from the figure, the four HTHL vehicle systems (located on the left of the figure) are approximately twice as heavy in total empty weight as the two VTHL vehicle systems. For the three HTHL systems with hypersonic boosters, it is the airbreathing first stage that makes up nearly 80% of the total empty weight while the upper stage reusable rocket orbiters close much smaller. The first stage is also the major portion of the empty weight for the fourth HTHL vehicle (all turbine first stage); however, in this configuration the hypersonic airbreathing systems are part of the upper stage orbiter, which is under 100,000-lb empty weight. So, although the four HTHL vehicles have roughly the same amount of total empty weight, the empty weight of the hypersonic airbreathing vehicle itself is greatly reduced when it is part of the upper stage. This is an important result as the design, construction, and operation of the high-speed airbreathing technology is the most difficult challenge for any of the configurations in this investigation. Configurations that can reduce the scale of the airbreathing vehicle might therefore become quite advantageous. The VTHL vehicles exhibit this same advantage with their upper-stage airbreathing orbiters. Comparing all six vehicles; the VTHL configurations come in at half the total empty weight of any HTHL configuration. The VTHL airbreather stages are also 60 to 75% lighter than the airbreathing first stages of the first three HTHL configurations.

Another valuable figure of merit is the wetted area of the vehicle. The amount of wetted area impacts the vehicle's performance, weight, and operational cost. 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 first stages of TSTO configurations with lower staging Mach numbers are not present during the highest temperature regimes of the trajectory and can therefore manage with less capable TPS. The reduction of TPS area yields a double benefit, the first being a reduction in weight and second a reduction

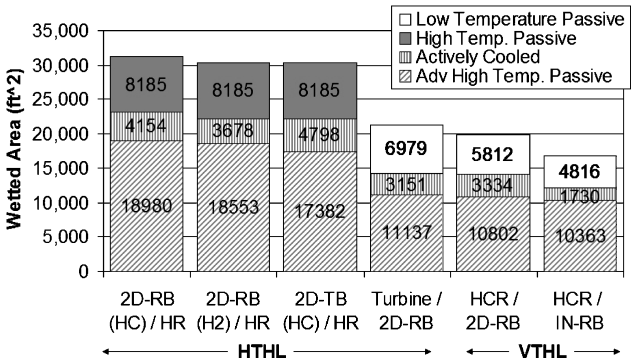

Fig. 9 Comparison of wetted area broken down by TPS type.

in the time and cost of TPS refurbishment.[11] TPS maintenance is a huge part of the space shuttle's between-flight refurbishment costs. State-of-the-art and future advanced passive TPS materials might require less maintenance than previous TPS 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. The airbreathing stages need substantial active cooling through the extreme parts of the inlet and nozzle and throughout the combustor. The lower-temperature-limit passive TPS on the boosters with Mach 4 staging is not stressed greatly during flight and might require minimal, or less frequent, TPS inspection and maintenance. Figure 9 compares the wetted areas of all six vehicles broken down into four major TPS types: high- and low-temperature state-of-the-art passive TPS, future advanced TPS, and actively cooled TPS. The hypersonic airbreathing vehicles all require advanced high-temperature passive TPS over every exposed portion of the vehicle's external surface and internal flowpath except for the flowpath regions that are actively cooled. Therefore, the larger the vehicle, as presented in the preceding figure, the larger the amounts of advanced passive TPS and active cooling required. So, the smaller and lighter upper-stage (second-stage) airbreathing orbiters (right half of figure) once again surpass the booster-stage hypersonic airbreathers (left half of figure). The three HTHL vehicles with upper-stage rocket orbiters are shown on the left half of the figure. As mentioned in the configuration setup, the entire external surface of these rockets must be protected with high-temperature passive TPS shown at the top of the bars. Conversely, the rocket boosters used as the first stage of the two VTHL configurations shown at the right of the figure are only attached up to staging at Mach 4 and therefore only require low-temperature TPS as they experience no significant heating environment. This low-temperature passive TPS shown at the top of the bars on the right is very likely to be more cost and time effective to inspect and maintain than an equivalent amount of high-temperature TPS. The same trend is seen in the TPS required for the all-turbine HTHL booster. In a effort to reduce the maintenance cost and decrease the turn time of future launch vehicles, the most promising vehicles are those whose solutions make use the least amount of high-temperature passive and actively cooled TPS. Taking these assumptions into account, the two VTHL configurations, which already have approximately half the total wetted area of the largest three HTHL vehicles, would exhibit reductions even more than that 50% in refurbishment time and cost.

VI. Discussion

Previous investigations[12] performed by the authors have ascertained that there are single-stage-to-orbit (SSTO) airbreathing configurations, which might have the potential to improve the accessibility to space by exceeding the abilities of next-generation all-rocket systems. However, as has been mentioned, there are great challenges to be overcome in the development of such an SSTO. The technology needs to be further applied and tested before embarking on such a task. The development of the vehicles in this study serves as a first step in ascertaining the functional ability of hypersonic airbreathing technology in less demanding and more forgiving TSTO configurations. With this role in mind, it would be prudent to evaluate the airbreathing stages of the three different configurations in this study with the objective of determining which arrangement provides the surest technological foundation from which to initiate an SSTO program. In brief, which airbreathing vehicle is the most similar in application to an eventual SSTO airbreather and would therefore reduce the associated design risk and technological uncertainty? There are some unknowns that would be equally answered by the successful development of any of the TSTO ramjet/scramjet systems in this study such as the sustained operation of a large-scale hypersonic propulsion system, vehicle integration issues, etc. However, there are other SSTO technological questions that are only answered by particular configurations.

One major issue is that of reentry. A scramjet vehicle is unlike any geometry that has flown a reentry trajectory. The SSTO scramjet flowpath, although designed to withstand the heating environment of its ascent trajectory, must also be able to withstand reentry environments. This might require the carriage of reserve hydrogen fuel with which to run the heat exchangers that cool the actively cooled TPS surfaces. The VTHL and HTHL TSTO configurations with upper-stage airbreathing vehicles would require these considerations in their vehicle systems design as these orbiters would also be required to perform reentry. The HTHL configuration with the hypersonic booster would not address this issue as the airbreathing components never ascend beyond the Mach 10 staging velocity.

Another issue is the high Mach-number range of operation for the scramjet engine. A successful and competitive hypersonic SSTO requires the scramjet to achieve as high a velocity as possible before switching modes to the orbital ascent rockets. In the eventual development of an SSTO, it will be important to have good data and experience with that flight regime. The HTHL configuration with the hypersonic booster only provides operational data up to its Mach 10 design point to which it is limited by the additional drag of the piggybacked upper-stage rocket orbiter. The HTHL and VTHL configurations with upper-stage hypersonic orbiters are staged at Mach 4 and accelerate up to around Mach 14 exactly as would be required by an SSTO scramjet vehicle.

These traceability issues indicate that TSTO configurations that employ upper-stage airbreathers exhibit greater design similarity with SSTO airbreathing configurations than do TSTO systems with hypersonic first stages.

VII. Conclusions

This investigation considered six vehicle systems from three different configurations of rockets, turbines, and hypersonic stages. The mission objective for all vehicles was the placement of 20,000 lb of payload to LEO launched easterly from Kennedy Space Center. These systems were solved and evaluated using several figures of merit. The vehicle solutions and observed trends are intended to facilitate an understanding of the design space for two-stage airbreathing vehicles. This study has identified several promising vehicle designs that merit further analysis with higher-fidelity aerodynamic and propulsion routines and trajectory optimization than was done in the current study. From the results of the work performed during this study, the following conclusions can be drawn for each of the three configuration categories as applied to their abilities to improve access to space.

A. HTHL Hypersonic Airbreathing Booster with Upper-Stage Reusable Rocket (Three Vehicle Designs)

1) The three vehicles analyzed with this configuration have the largest gross weights, empty weights, total wetted areas, and amounts of active cooling of the six vehicles investigated.

2) This configuration requires the largest hypersonic airbreathing stages of the three configurations analyzed.

3) Both stages of this configuration are exposed to the highest heating environment of the ascent trajectory. This increases the amount of high-temperature TPS required and will lead to higher and longer refurbishment costs and time.

4) This configuration requires a complicated high-speed separation maneuver.

5) The additional drag of the upper-stage rocket orbiter limits scramjet operation to Mach 10.

6) The airbreathing booster of this configuration is required to perform a greater than 1000-n mile flyback trajectory to the launch site. The additional propellant for that return must be carried onboard all of the way to the staging point and triggers a scaling up of the whole first-stage system.

7) The on-orbit vehicle is a reusable rocket orbiter with a similar geometry as the shuttle orbiter and will have an analogous reentry environment exposure and trajectory. This arrangement, however, does not address the design challenges that will be required for performing reentry of an on-orbit vehicle with a hypersonic geometry as would be required by an airbreathing SSTO.

8) Of the three configurations analyzed, this configuration exhibits the least amount of commonality and design traceability to eventual SSTO airbreather development.

B. HTHL Turbojet Booster with Upper-Stage Hypersonic Airbreather (One Vehicle Design)

1) Low-speed separation minimizes use of high-temperature TPS on turbine booster stage thereby decreasing the weight as well as the time and cost associated with refurbishment of that stage. The turbine vehicle itself has a large empty weight however.

2) Positioning of the ramjet/scramjet propulsion elements on the upper-stage decreases the empty weight and wetted area of this airbreathing stage. The upper-stage airbreather yields a 60% reduction in the empty weight and a 40% reduction in total wetted area vs the airbreathing booster stages of the previous configuration.

3) The airbreathing upper stage accelerates to an approximately Mach 14 scramjet cutoff, thus extending the operational depth of detail and performance data of the high-speed portions of the scramjet trajectory.

4) After staging, the turbine booster performs a short flyback return to launch site. The fuel requirement imposed by this short flight is not significant.

5) Once the booster stages at Mach 4, the upper-stage airbreather's mission profile and performance requirements are directly analogous to those required by an SSTO airbreathing vehicle. This commonality adds additional relevance and design traceability to the technology that would be acquired during the development of an upper-stage airbreathing configuration.

C. VTHL Rocket Booster with Upper-Stage Hypersonic Airbreather (Two Vehicle Designs)

1) Low-speed separation minimizes use of high-temperature TPS on rocket booster stage, thereby decreasing the weight as well as the time and cost associated with refurbishment.

2) The total empty weight of the two vehicle systems solved using this configuration was roughly half of the empty weight of any of the HTHL systems.

3) Upper-stage airbreathing orbiters for this configuration are practically identical to the airbreathing orbiters of the previous configuration and exhibit all of the same weight reductions, performance improvements, and technology traceability.

4) Difference in this configuration vs the previous one comes down to the selection of a 50,000-lb Mach 4 VTHL rocket booster vs a 200,000-lb Mach 4 HTHL turbine booster. A more detailed assessment of the operational abilities and economics of these two configurations is necessary in order to choose between them. Regardless of the choice of low-speed propulsion stage, the data show the upper-stage hypersonic airbreathing orbiter to be a superior configuration compared to a hypersonic airbreathing booster.

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