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Two Options for Flight Testing Rocket-Based Combined-Cycle Engines

John R. Olds*
Georgia Institute of Technology, Atlanta, Georgia 30332-0150

Whereas NASA's current next-generation reusable launch vehicle research has largely focused on all-rocket single-stage-to-orbit vehicles, some attention is being given to advanced propulsion concepts such as rocket-based combined-cycle suitable for next-generation-and-a-half vehicles. Rocket-based combined-cycle engines combine rocket and airbreathing elements into a single integrated engine capable of multimode operation. Two options for flight testing early versions of a rocket-based combined-cycle ejector scramjet engine have been investigated. The first option uses a single, subscale rocket-based combined-cycle engine module mounted to the X-34 air-launched technology testbed for captive test flights up to about Mach 6.4. The second option combines rocket-based combined-cycle engine flight testing and envelope expansion with the simultaneous development of a new two-stage-to-orbit operational vehicle in the small Bantam payload class (220 lb) dubbed the W vehicle. To enable early testing and complement dual-use missile applications, both proposed flight test engines evaluated use Earth storable propellants for their rocket primaries and hydrocarbon fuel for their airbreathing modes. Research results include preliminary sizing and performance data for each concept.

Nomenclature

A_c	= engine inlet frontal area, ft^2
C_d	= aerodynamic drag coefficient
C_t	= thrust coefficient, thrust/qA_c
I_{sp}	= specific impulse, s
M	= flight Mach number
MR	= mass ratio (initial weight/burnout weight)
q	= dynamic pressure, $\rho V^2/2$, lb/ft^2
T	= engine thrust, lb
T/W	= engine thrust-to-weight ratio
V	= velocity, ft/s
ΔV	= velocity change, ft/s
ρ	= atmospheric density, slug/ft^3

Introduction

ROCKET-BASED combined-cycle (RBCC) propulsion combines elements of rocket and airbreathing propulsion into a single, integrated engine. RBCC engines are capable of operating in ejector, i.e., ducted rocket, ramjet, scramjet, and pure rocket modes. By utilizing atmospheric oxygen over a portion of the ascent trajectory, vehicles employing RBCC engines will have a higher trajectory averaged I_{sp} than comparable rockets. In addition, RBCC engines have higher installed engine thrust-to-weight ratios T/W than competing turbine-based cycles or separate implementations of rockets and ram/scramjets, i.e., combination propulsion systems. A typical RBCC internal layout for an axisymmetric configuration is shown in Fig. 1.

RBCC engines show considerable promise for future launch vehicle applications. Previous researchers have shown that RBCC equipped single-stage-to-orbit (SSTO) launch vehicles compare favorably to other advanced concepts based on performance measures such as vehicle gross weight and payload mass fraction.[1–8] In addition, their operational advantages and flexibility with an optional supercharging fan have been well documented, e.g., powered landing and go-around, loiter, self-ferry, stand-off launch, and multiazimuth launch.[9–11]

Subscale RBCC engines have been ground tested historically[12–14] and again more recently under government sponsorship. Current ground-test programs are expected to contribute significantly to the RBCC database of knowledge. However, many RBCC design issues and integrated performance characteristics can be properly evaluated only in a true flight environment. Flight testing appears to be a logical next step in the development of this class of propulsion.

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*Assistant Professor, School of Aerospace Engineering. Senior Member AIAA.

Flight-Test Options

Flight-Test Objectives

An RBCC flight test program could serve to validate the database of information collected in ground-test programs and also to further mature the concept prior to fielding an RBCC engine on an operational vehicle. In particular, a flight-test program could be used to examine engine mode transition effects, i.e., ejector to ramjet to scramjet to rocket, flight-weight hardware design issues, and engine/airframe integration issues. The ejector scramjet (ESJ) cycle is recommended for early testing because of its broad launch vehicle applicability and commonality with current ground-test programs.

Advanced reusable RBCC SSTO or two-stage-to-orbit (TSTO) vehicles capable of delivering 20,000–40,000 lb to low Earth orbit (LEO) will almost certainly employ high-energy liquid oxygen/liquid hydrogen (LOX/LH_2) propellants. However, Earth storable propellants are suggested for the two early flight-test options examined here. Earth storable propellants maintain compatibility with several ground-test programs, provide relatively near-term test options, build on historical test program databases, and maintain commonality with possible military hypersonic missile applications.

Potential Testbeds

Although many options exist and deserve to be considered, only two potential RBCC flight testbeds have been investigated in this research.

1) A single ESJ [or, optionally, an ejector ramjet (ERJ)] engine module could be integrated onto the X-34 technology testbed and captive flight tested along a simulated airbreathing trajectory in all modes up to Mach numbers near 6 or 7. Testbed propellants would be carried in separate pressure-fed tanks inside the X-34 test equipment bay.

2) An operational set of ERJ engines could be incrementally developed and tested in concert with the development of a new, small payload TSTO launch vehicle/hypersonic testbed (W vehicle). When later upgraded to ESJ engines as they become available, this vehicle combination could eventually become an operational partially reusable Bantam-class launcher capable of delivering 220 lb to LEO.

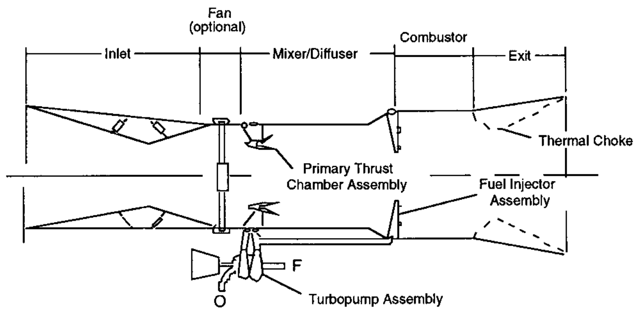

Fig. 1 Typical RBCC engine schematic.

Fig. 2 X-34 technology testbed.

X-34 Testbed Option

X-34 Vehicle

The X-34 (Fig. 2) is an unpiloted, reusable experimental flight vehicle that will be air launched from a Lockheed L-1011 carrier aircraft at around 38,000 ft and Mach 0.8 (Ref. 15). The X-34 is currently under development and is expected to be operational in 1999. The X-34 will serve as a suborbital flight testbed for demonstrating advanced reusable launch vehicle technologies such as propulsion, structures, thermal protection systems (TPS), avionics, etc. For a typical test flight, the rocket-powered vehicle will autonomously accelerate to nearly Mach 8 at 250,000 ft and then glide to a horizontal recovery at a landing site downrange of the launch point. Each of the two airframes will be capable of 25 flights per year.

X-34 concept design data were sparse at the time this research was performed. Based on preliminary data, vehicle gross weight was expected to be approximately 45,000 lb fully fueled. Vehicle length was assumed to be 58 ft and the wingspan was assumed to be 28 ft.[16,17] The vehicle will use a single new LOX/RP1 (kerosene) rocket engine under simultaneous development at NASA Marshall Space Flight Center.[18] This Fastrac engine will be a low-cost engine predicated on Simplex turbopumps and an ablatively cooled throat insert. For this research, the engine was assumed to produce a vacuum thrust of 60,000 lb and a vacuum I_{sp} of 298.5 s with an exit area of 5.585 ft^2. These parameters have since changed slightly as the design has matured. For this investigation, the X-34 propellant loading was assumed to be about 29,900 lb based on an estimated ideal propulsive ΔV of 10,500 fps and a resulting propellant mass fraction of 0.6646. A summary of the approximated X-34 design data used for this research appears in Table 1.

Table 1 Approximated X-34 design data

Parameters	Dimensions
Geometry	
Length	58 ft
Wingspan	28 ft
Body width	7.2 ft
Theoretical wing area	510 ft^2
Internal test bay volume	50 ft^3
Weight	
Propellants	29,900 lb
Inert	15,100 lb
Gross	45,000 lb
Engine (LOX/RP1)	
Vacuum thrust	60,000 lb
Vacuum I_{sp}	298.5 s
Exit area	5.585 ft^2

RBCC/X-34 Testbed Integration

The proposed RBCC test configuration consists of a single, instrumented ejector scramjet engine module with a Mach 8 capable inlet mounted below and near the aft of the X-34 (Fig. 3). This position offers symmetry of thrust and sufficient structural support, while minimizing the impact of the testbed engine exhaust on the rest of the X-34 vehicle. The rectangular inlet and engine are expected to be about 3.7 ft long, 1.0 ft wide, and 0.66 ft high. The choice to mount the test engine on the aft bottom of the X-34 could lead to takeoff and landing clearance problems, and this issue will require a more detailed investigation as the X-34 concept is finalized.

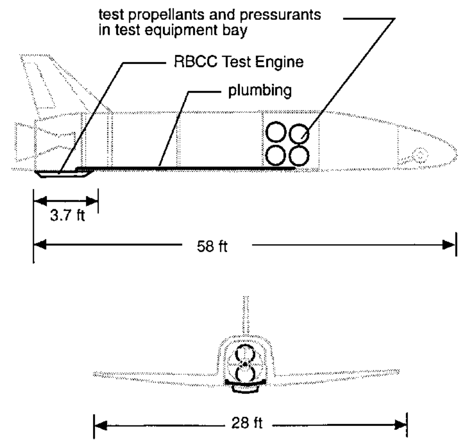

Fig. 3 X-34 with integrated subscale RBCC.

For simplicity, the engine is pressure-fed gelled monomethyl hydrazine (G-MMH) and gelled inhibited-red fuming nitric acid (G-IRFNA) primary propellants and hydrocarbon fuel [jet propellant-10 (JP-10)] from three separate 1200-psia aluminum tanks stored in the X-34's 50-ft^3 internal test bay. Pressurization is provided by a single 5000-psia helium pressurant sphere. Engine cooling is assumed to be a combination of heat sink cooling and limited water cooling in critical areas. Plumbing and electrical connections will be required between the internal test bay and the externally mounted RBCC engine.

Airbreathing trajectories are more depressed than rocket trajectories, and so the X-34 will be required to fly a high dynamic pressure q trajectory for the test. Beginning at Mach 3.5 (ramjet mode), the vehicle will fly along a constant q boundary trajectory initially chosen to be 1000 lb/ft^2. Because of the higher q, some changes will be required to the X-34's TPS to account for higher than nominal surface forces and heat loads. Typically, TPS blankets would have to be reinforced, and an ablative TPS might be required along the wing leading edges and nosecap. Additional inert weight has been added to the X-34 in the testbed analysis to account for these TPS changes.

Flight testing of a scramjet aboard a rocket-powered hypersonic testbed is not without precedent. In the late 1960s, plans were made to test the Langley Hypersonic Research Engine (HRE) aboard the X-15 experimental aircraft.[19,20] Although an operational HRE never flew, the X-15 was flown twice with a dummy version of the HRE installed below its bottom ventral (Fig. 4).

RBCC/X-34 Test Scenario

The objective of the present analysis was to determine the amount of each type of testbed propellant required for the ESJ test, the test engine weight, the additional testbed inert weight required (propellant tanks, pressurant tanks, plumbing, etc.), and the peak Mach number and stagnation point heating rate that could be

Table 2 Simplified G-MMH/G-IRFNA/JP-10 RBCC engine data for X-34 flight test

Mach no.	Thrust	I_{sp}, s
	Ejector mode	
0	$T_{actual}/T_{primary} = 1.15$	305
2.5	$T_{actual}/T_{primary} = 1.55$	405
3.5	0	405
	Ramjet/scramjet modes	
2.5	$C_t = 1.20$	1350
3.5	$C_t = 1.30$	1450
10	$C_t = 0.55$	775

Fig. 4 X-15 with dummy HRE.

expected from this configuration. In addition, the sensitivities of the results to the value of the constant q boundary and vehicle aerodynamic drag were to be determined. For the simulations performed, the test engine's G-MMH/G–IRFNA primary was assumed to provide a primary-only thrust of 3000 lb (about 5% of the thrust provided by the main X-34 rocket engine). Note that the RBCC engine experiences varying amounts of thrust augmentation throughout the test flight due to the ingestion and combustion of atmospheric oxygen, and so the thrust level will not be constant and will exceed the 3000 lb primary-only thrust even at the beginning of the test. Testbed propellant and tankage were sized for the minimum fuel to operate the test engine in parallel with the Fastrac rocket engine until the main X-34 propellant was consumed. That is, the test engine was operated only when the main rocket engine was also on.

Simplified RBCC performance used for this research is given in Table 2. Here, airbreathing mode C_t have been determined using a fixed cowl area A_c equivalent to the inlet frontal area. In this formulation, A_c does not change over the trajectory. At full throttle in the ejector mode, the G-MMH/G-IRFNA rocket primary uses propellants at a rate of 11.11 lbm/s assuming a primary-only I_{sp} of 270 s. For all X-34 testbed cases, the primary-only thrust was fixed at 3000 lb ($T_{primary}$ in Table 2). The test engine was assumed to operate in ejector mode up to Mach 2.5 and fully transition to ramjet mode by Mach 3.5. As shown in Table 2, the ejector thrust was linearly ramped down to zero at Mach 3.5 (at a constant I_{sp}), whereas the ramjet mode used an additional multiplication factor (not shown) to linearly ramp up to full power at Mach 3.5. The engine was operated as a subsonic combustion ramjet up to Mach 5 at which point it began a smooth transition to scramjet mode. The test engine was then assumed to operate as a scramjet until the vehicle reached its maximum Mach number at burnout.

It should be noted that the blunt nose and flat underbody of the X-34 are not ideal for scramjet operation and testing. Scramjets are typically designed with a well-compressed inlet flow and an aft expansion surface. More detailed inlet flow analysis work is recommended to determine if scramjet testing on the X-34 is worth pursuing. If not, then the X-34 still holds promise for flight testing ERJ RBCC engines. Assuming that scramjet testing is possible and desirable with limited compression, a scramjet mode was included in the present study, i.e., an ESJ engine module.

X-34 Testbed Multidisciplinary Analysis Procedure

The solution requires iteration between several contributing subanalyses. Trajectory analysis was performed using 3D-POST[21] for the portion of the trajectory when the engines are on. Aerodynamic coefficients for the range of flight conditions of interest were determined using APAS.[22] A 2.5% penalty was imposed on all drag coefficients to account for the added drag RBCC test engine. Actual vehicle lift and drag were then determined based on the theoretical wing planform area assumed in Table 1. RBCC engine weight, tank weights, plumbing weights, and so forth were determined using historical parametric mass estimating relationships (MERs) suitable for conceptual design analysis. Simplified ESJ engine performance was based on historical data and analytical predictions (given in Table 2). The latter two subanalyses were implemented as linked spreadsheets on a Macintosh personal computer, and their internal iterations were performed automatically. POST and APAS were run on a Silicon Graphics workstation. Base X-34 and updated testbed inert weights from the linked spreadsheets were input into POST for each iteration. POST then generated new testbed propellant weights for each type of propellant, vehicle MR, total test time, ejector test time, peak Mach number, and peak stagnation point heating to be input into the two spreadsheets. This process was repeated until all internal variables (typically propellant weights) converged. Iteration between POST and the linked spreadsheets was performed manually, but typically converged after two or three iterations. Figure 5 shows the links between the subanalyses and identifies the iteration loops. Because the X-34 shape was not changed, the aerodynamic coefficients were not subject to iteration.

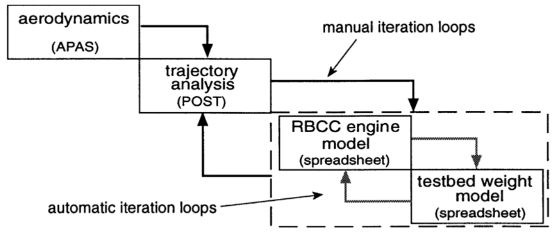

Fig. 5 Iterative analysis procedure.

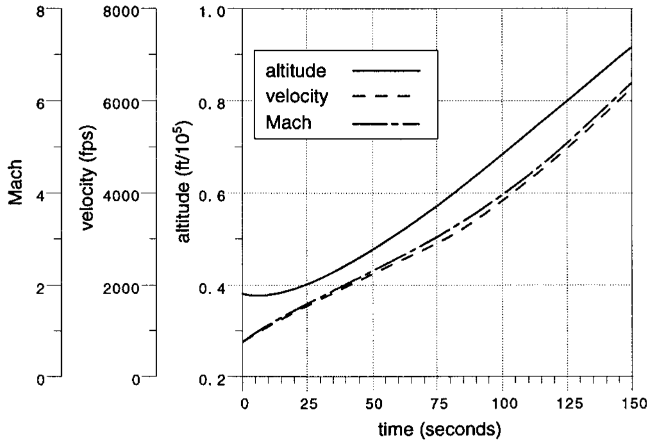

Fig. 6 X-34 testbed altitude, Mach, and velocity.

X-34 Testbed Analysis Results

The converged results for the baseline case of $q = 1000$ lb/ft^2 are shown in Table 3. For this case, the vehicle is expected to reach a maximum Mach number of 6.44 and experience a maximum stagnation point heat rate of 30 Btu/ft^2-s. (Stagnation point heating is for a reference 1-ft-radius sphere flying along an identical trajectory.) The test propellants and main propellants are simultaneously exhausted 148.8 s after test initiation. When the test equipment, test propellant, and TPS changes are included, the X-34 gross weight increases to 47,120 lb from 45,000 lb, still within the lift capability of the L-1011. Test propellants and pressurants will require just over 23 ft^3 of internal volume in the X-34 test bay and should be packageable within the 50 ft^3 available. Power-on trajectory profiles for this baseline case are provided in Figs. 6 and 7.

X-34 Testbed Sensitivity Studies

The iterative analysis procedure just described was used to perform sensitivity studies against changing the q boundary value and changing vehicle drag. As shown in Fig. 8, the peak Mach number is very sensitive to the choice of q over the constant q portion of the trajectory. Lower q values result in higher peak test Mach

Table 3 X-34 testbed baseline (q = 1000 lb/ft^2)

Parameters	Dimensions
Inert weight roll up	
RBCC engine (w/inlet)	280 lb
Test equipment propellant tankage	110 lb
Pressurization system	165 lb
Other test equipment inert	225 lb
Test equipment margin (15%)	120 lb
X-34 inert (base)	15,100 lb
X-34 inert (additional)	280 lb
Total inert weight	16,280 lb
Gross weight roll up	
Total inert weight	16,280 lb
JP-10 test propellant	110 lb
G-MMH test propellant	350 lb
G-IRFNA test propellant	480 lb
X-34 propellant	29,900 lb
Total gross weight	47,120 lb
Geometry	
Test propellant volume	13.3 ft^3
Pressurant volume	9.9 ft^3
RBCC inlet frontal area	1.646 ft^2

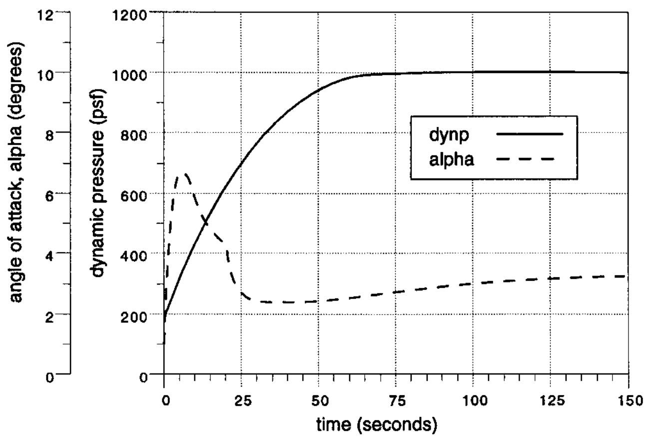

Fig. 7 X-34 testbed dynamic pressure and alpha.

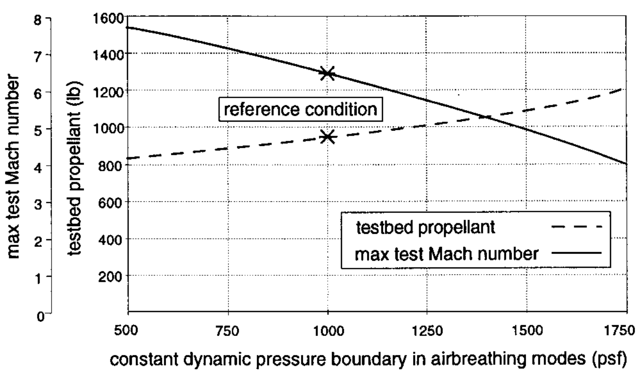

Fig. 8 X-34 testbed q sensitivity.

numbers because vehicle drag losses are reduced. However, airbreathing mode thrust is roughly proportional to q, and so a low q would not result in useful test data. On the other hand, q above 1300–1350 lb/ft^2 limit the X-34 testbed to ramjet speeds (below Mach 5) and do not allow scramjet mode testing. The choice of 1000 lb/ft^2 as the baseline for the test is a reasonable compromise between achievable Mach number (6.44) and utility of the test results given the drag-related limitations of the testbed.

With its blunt nose, thick wings, and low slenderness ratio, the X-34 is not particularly well suited to airbreathing-style ascent trajectories. When flying a depressed trajectory, its configuration results in high ΔV losses due to drag and a reduced maximum Mach number. As shown in Fig. 9, a 20% across-the-board reduction in the baseline drag coefficients could increase the peak Mach number by nearly 0.85. Although expensive, it may be possible to permanently or temporarily, e.g., an external glove, modify the external moldlines of the X-34 to improve its hypersonic aerodynamics. These changes would also improve the quality of the airflow entering the RBCC test engine and improve the likelihood that useful data could be collected for scramjet engines. However, a more practical conclusion is that if higher Mach number ESJ testing is a requirement then research vehicles more suitable to hypersonic flight should be examined as possible testbeds. NASA's Hyper-X concept is a potential high Mach number testbed for RBCC as are new concepts being developed under NASA's Future-X program.

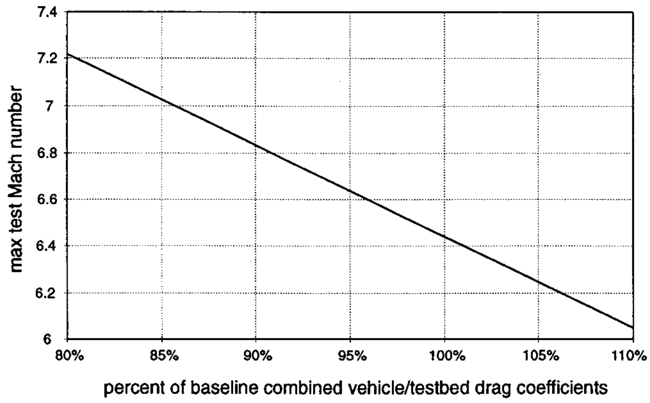

Fig. 9 X-34 testbed drag sensitivity.

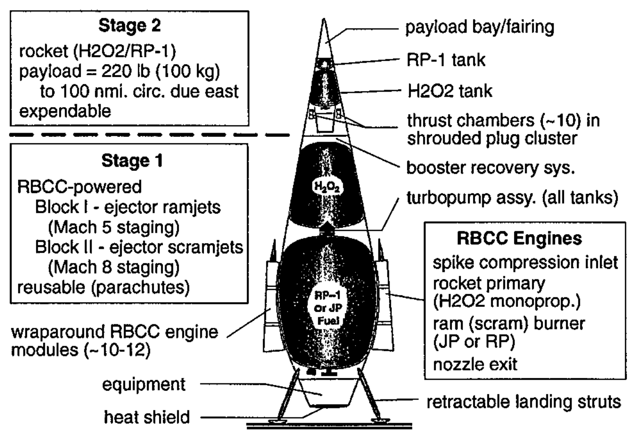

Fig. 10 W vehicle concept.

W Vehicle Testbed Option

W Vehicle

The W vehicle[23] is a notional concept for an early, partially reusable, small payload TSTO launch vehicle originally suggested by Escher. The concept uses a vertical takeoff and landing (VTOL) conical configuration (Fig. 10). Hydrogen peroxide/hydrocarbon (H_2O_2/JP) ejector scramjets on the booster stage and H_2O_2/RP1 bipropellant rockets installed in an annular plug nozzle on the second stage deliver 220 lb of payload to a 100-n mile circular orbit due east from the launch site. This payload class has recently been referred to as bantam class.

The W vehicle is envisioned to have several constituents for its development. First, a low-cost (<\$1.5 million recurring cost target) operational launcher in the bantam class could be used to serve the small commercial payload market and the university space research market. Once operational, the scramjet-equipped booster stage could serve as a flying wind tunnel for hypersonic testing by various high-speed vehicle research programs. The booster is recoverable, so that several tests could be conducted with the hypersonic test article attached in place of the nominal second stage. Last, the development of the W vehicle as an operational system allows for early flight testing of ERJ and ESJ RBCC engines as a parallel development and testing program. The name W vehicle is derived from this role.

By initially using H_2O_2/JP ERJ engines and eventually ESJ engines on an operational launch system, the W vehicle will serve as a pathfinder for future advanced SSTO (or TSTO) launch vehicles in the 20,000–40,000-lb payload class that will use LOX/LH_2 RBCC engines. An experimental flight demonstrator for this larger, cryogenic engine concept will likely be termed an X vehicle. Following tradition, a full- or subscale prototype version of the operational SSTO will be called a Y vehicle. When considered a part of the same developmental family, the Earth-storable H_2O_2/JP ESJ testbed vehicle is logically termed the W vehicle (W preceding X and Y).

To facilitate early development and keep costs low, the W vehicle will rely on lower technology construction techniques (aluminum tanks and structure), off-the-shelf subsystems (avionics and turbopumps derived from existing hardware), and noncryogenic, Earth storable propellants. The H_2O_2/JP ejector scramjet on the booster will be closely related to a similar design that underwent successful supercharged and nonsupercharged ground testing in 1968 (Ref. 24). Like that engine, the W vehicle ESJ engine will use monopropellant H_2O_2 (typically 90% or 95%) rocket primaries and JP fuel for airbreathing modes (note that the hydrocarbon fuel could probably be changed to RP1 or one of a variety of JP variants if desirable for propellant commonality with the upper stage). Stand-alone monopropellant H_2O_2 engines have low I_{sp} by bipropellant standards. However, the oxygen-rich exhaust from H_2O_2 decomposition provides additional oxidizer for JP combustion thereby boosting overall engine performance to more favorable values when used an RBCC primary.

As already mentioned, the initial W vehicle booster will use a nonscramjet ERJ version of the H_2O_2/JP engine. This booster configuration will be identified as block I. Relying on ramjets, the block I booster will only be capable of airbreathing operation to Mach 5. As flight experience is obtained, the ERJ engines will be replaced with scramjet-capable ESJ engines. This follow-on block II booster will be capable of airbreathing operation to Mach 8.

The upper stage engine will consist of a cluster of 10 H_2O_2/RP1 rocket thrusters mounted in an annular plug nozzle configuration. The outer wall of the plug nozzle also serves as the interstage adapter. The expansion ratio for this engine configuration is approximately 100. The installed upper stage engine vacuum T/W is assumed to be 40 with a vacuum I_{sp} of 335 s. The upper stage operates at an H_2O_2/RP1 mixture ratio of 7.35. Payload is mounted in the nosecone fairing section of the upper stage. Optionally, the payload could be mounted inside the inner wall of the plug nozzle.

W Vehicle Flight Scenario

The W vehicle will be a hypersonic aerodynamic and propulsion testbed, as well as an operational, small payload TSTO launch vehicle. As such, it will be required to fly a variety of mission and test profiles: suborbital hypersonic tests, flights with a dummy upper stage, low payload orbital delivery missions, envelope expanding engine checkouts, etc. For the purposes of this research, it is assumed that the block II booster with the ESJ RBCC engines and a LEO payload delivery requirement of 220 lb will drive the final vehicle configuration and size. That is, the W vehicle tanks and airframe will be designed and sized for the eventual ESJ engines and bantam-class payload delivery mission from the beginning. In the nearer term, the booster will be fitted with ERJ engines, and excess JP propellant and upper stage payload will be off loaded as required.

For the reference flight scenario (the block II ESJ configuration), the TSTO W vehicle will takeoff vertically from a Wallops Island, Virginia, launch site with an initial thrust-to-weight of 1.25 and accelerate to Mach 2.5 in ejector mode. Guidance will be accomplished with differential throttling. The RBCC engines will completely transition to ramjet operation between Mach 2.5 and 3.5 and begin to fly along a constant dynamic pressure q trajectory of 2000 lb/ft^2. The ESJ engine will begin a smooth transition to scramjet mode at Mach 5 and continue to accelerate to Mach 8. At Mach 8, the engine will change to rocket mode by closing its inlet, reigniting the H_2O_2 primaries, and mixing a small amount of JP fuel with the oxygen-rich primary exhaust. This rocket mode is used to pitch the vehicle up from the dynamic pressure boundary and accelerate it to Mach 8.5, where the engine will be shut down. After a 10-s coast to reduce dynamic pressure to below 800 lb/ft^2, the upper stage will be separated and started. The upper stage thrust-to-weight will be approximately 1.05 at staging. The upper stage accelerates directly to a 100-n mile circular orbit assumed to be at 38-deg inclination. The payload fairing is ejected at an altitude of 250,000 ft. Vehicle acceleration is limited to 5.5 g.

For the reference flight scenario, the upper stage is considered expendable. To save hardware costs, the booster is planned to be reusable. As envisioned by Escher,[23] after staging the booster decelerates aerodynamically to around Mach 2 and deploys a set of multistage round parachutes from its top. The booster will slowly descend in a tail-first attitude. Landing struts will be deployed, and the RBCC engines will be briefly pulsed to obtain a near zero touchdown velocity.

The booster recovery scenario received only cursory treatment in the present research and should undergo a more thorough investigation. A number of reusability issues for test flights and launch missions remain outstanding: launch and landing site locations, landing precision requirements, abort sites, overland flight restrictions, etc. Water recovery and midair booster snatch via an aircraft or a helicopter have been suggested as additional alternatives. It has also been suggested that the upper stage be reentered and reused.

W Vehicle Multidisciplinary Analysis Procedure

The objective of the present research was to determine the W vehicle weights, propellant requirements, and other performance parameters for a conceptual block II booster and the reference flight scenario. In addition, the performance of the vehicle with the block I (ERJ) booster was desired. RBCC vehicles are very sensitive to installed engine T/W, and so sensitivities of vehicle weight to changing RBCC T/W was also determined. The installed engine sea-level static T/W of the ESJ engines were assumed to be 12 (a T/W of 15 was assumed for the ERJs).

The analysis procedure is similar to that described earlier for the X-34 testbed option (Fig. 5). POST and APAS were used for trajectory and aerodynamic subanalyses, respectively. Weight models of the booster and upper stage were created as linked spreadsheets on a Macintosh personal computer using historical parametric MERs. Simplified RBCC engine performance was derived from historical and analytical data. Iteration between POST and the linked spreadsheet weight modules was performed manually and typically converged within three to four iterations. Four coupling variables were exchanged from POST to the spreadsheets (both required stage MRs, atmospheric pressure at staging, and booster oxidizer/fuel mixture ratio) and 10 coupling variables were passed from the spreadsheets to POST (both stage gross weights, both aerodynamic reference areas, RBCC engine inlet frontal area, upper stage fairing weight, H_2O_2 primary-only thrust and H_2O_2 flow rate, and upper stage vacuum thrust and exit area). The aerodynamic configuration was fixed as a 10-deg half-angle cone and was scaled photographically. Once established by APAS, the aerodynamic coefficients were assumed to be fixed.

Block II W Vehicle Testbed Analysis Results (ESJ)

The analysis results for the W vehicle with the block II booster are presented in Table 4 and Figs. 11–13. For this design, the MR of the booster stage was determined to be 2.506, the booster propellant mass fraction is 0.601, the upper stage MR is 6.508 (counting the fairing in the initial weight but not in the burnout weight), and the upper stage propellant mass fraction is 0.834. Each of the 12 ESJ engines on the booster generates about 2860 lb of thrust at liftoff. The overall tanked H_2O_2/JP mixture ratio for the booster stage is 3.02. Each of the 12 RBCC engine monopropellant primaries is sized for an H_2O_2 mass flow rate of 7.756 lbm/s and an equivalent primary-only thrust of 1551.2 lb (assuming a primary-only I_{sp} of 200 s). Peak heating occurs prior to staging at Mach 8.23 and is 70.3 Btu/ft^2-s to a 1-ft-radius reference sphere. Gross liftoff weight is 27,430 lb. The total dry weight of both stages taken together is 5695 lb. The overall payload mass fraction is 0.8%. The exit area of the plug nozzle on the upper stage is 12.07 ft^2, and the upper stage engine vacuum thrust is 5800 lb.

The booster/upper stage combination generates a total ideal propulsive ΔV of 38,000 fps (including drag, gravity, thrust vector, and atmospheric back pressure losses). By itself, the booster generates an ideal propulsive ΔV of 18,025 fps and attains a final

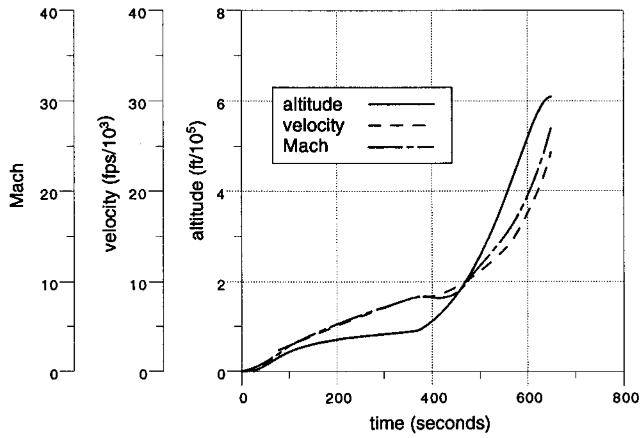

Fig. 11 Block II W vehicle altitude, Mach, and velocity.

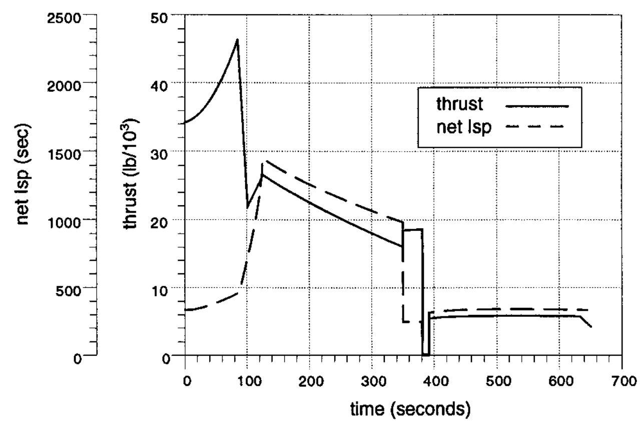

Fig. 12 Block II W vehicle thrust and I_{sp}.

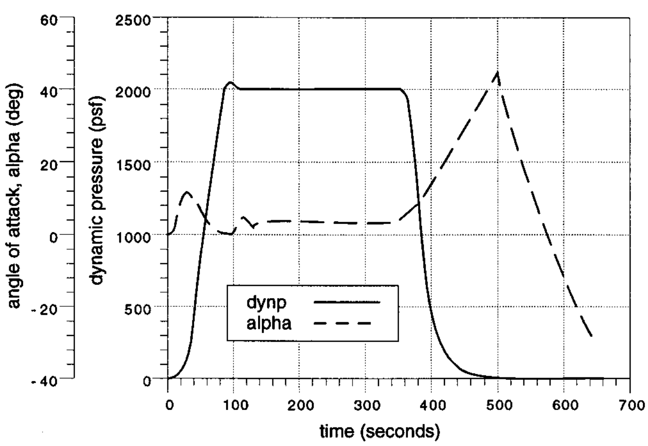

Fig. 13 Block II W vehicle dynamic pressure and alpha.

inertial velocity of 9,615 fps (starting with an initial inertial velocity of 1,200 fps). The H_2O_2/JP RBCC engine performance data used for W vehicle analyses is listed in Table 5. $T_{\text{actual}}/T_{\text{primary}}$ is the thrust augmentation above the fixed H_2O_2 primary-only thrust (T_{primary} is 1551.2 lb for the block II vehicle).

As in the X-34 testbed option, airbreathing mode thrust coefficients are normalized by a fixed A_c chosen to be equal to the engine inlet frontal area of all booster engines. Engine inlet frontal area was fixed at 25% of the maximum booster cross-sectional area. A_c does not change over the trajectory, but does change as the booster is resized from iteration to iteration.

Block I W Vehicle Testbed Analysis Results (ERJ)

The earlier, block I version of the W vehicle booster will utilize 12 lighter weight ERJ engines in place of the eventual ESJ engines. All other aspects of the booster (tank sizes, recovery system, landing struts, etc.) will be designed to block II requirements to facilitate

Table 4 Block II W vehicle booster (with ESJ)

Parameter	Booster	Upper stage
	Dry weight roll up	
Engine (installed)	2,860 lb	145 lb
Main tankage	180 lb	45 lb
Other structure	270 lb	100 lb
Landing struts	410 lb	——
Recovery system	520 lb	——
Other dry weight	280 lb	140 lb
Margin (15%)	680 lb	65 lb
Total dry weight	5,200 lb	495 lb
	Gross weight roll up	
Total dry weight	5,200 lb	495 lb
Payload	——	220 lb
Fairing (not above)	——	65 lb
Upper stage	5,330 lb	——
H_2O_2 propellant	12,380 lb	3,910 lb
JP or RP propellant	4,110 lb	530 lb
Residuals and losses	410 lb	110 lb
Total gross weight	27,430 lb	5,330 lb
	Geometry	
Stage height (est.)	11.44 ft	12.84 ft
Internal volume (est.)	301.2 ft^3	69.9 ft^3
Surface area (est.)	225 ft^2	93 ft^2
	Engine	
Initial thrust (total)	34,290 lb	5,600 lb
Engine T/W installed	12 (init.)	40 (vac)
RBCC inlet frontal area	10.23 ft^2	——

Table 5 Simplified H_2O_2/JP RBCC engine data for W vehicle designs

Mach no.	Thrust	I_{sp}, s
	Ejector mode	
0	$T_{\text{actual}}/T_{\text{primary}} = 1.84$	355
2.5	$T_{\text{actual}}/T_{\text{primary}} = 2.63$	400
3.5	0	400
	Ramjet/scramjet modes	
2.5	$C_t = 1.20$	1350
3.5	$C_t = 1.30$	1450
10	$C_t = 0.55$	775
	Rocket mode (altitude > 60,000 ft)	
	$T_{\text{actual}}/T_{\text{primary}} = 1.00$	250

an easy upgrade to the final block II vehicle. Ejector ramjet engines are only capable of ramjet operation to Mach 5, so that a block I W vehicle will use less JP fuel than a block II version, i.e., a block I vehicle will have a higher H_2O_2/JP mixture ratio. Because the H_2O_2 tank size is fixed at block II requirements, excess JP will be off loaded. The lower staging Mach number will also result in a lower payload capability for the fixed upper stage. For this mission, a small amount of remaining H_2O_2 at the end of ramjet operations was used to accelerate the vehicle away from the q boundary. H_2O_2 is fully tanked at liftoff. With the exception of installed engine T/W and peak airbreathing Mach number, i.e., airbreathing data were only used up to Mach 5, ERJ engine performance was taken to be the same as that presented in Table 5.

In the lower staging Mach number block I configuration, the MR of the booster stage has been determined to be 2.395, the booster propellant mass fraction is 0.583, the upper stage MR requirement increases to 7.608 (counting the fairing in the initial weight but not in the burnout weight), and the upper stage propellant mass fraction becomes 0.856. The booster H_2O_2/JP mixture ratio increases to 11.06 after off loading excess JP fuel. Payload to a 100-n mile, circular orbit drops to only 85 lb, but a reduced propellant load and lighter engines reduce the initial gross weight of this configuration to 23,170 lb. At 0.36%, the payload mass fraction is less than half that of the eventual block II configuration. Each of the 12 ERJ engines on the block I booster is required to generate 2410 lb of thrust at liftoff.

For comparison, a clean sheet W vehicle was analyzed assuming that ejector scramjets would never become available, and the program would have to rely solely on H_2O_2/JP ERJ engines to deliver the full 220-lb payload to the target orbit. With a gross weight of 41,000 lb, a payload mass fraction of 0.54%, 16 ERJ engines, and

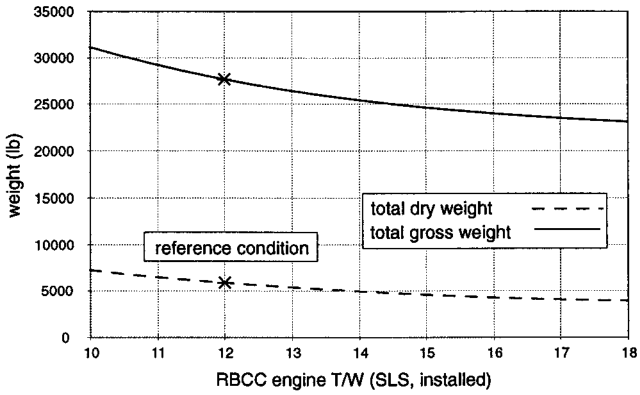

Fig. 14 W vehicle engine *T/W* sensitivity.

an upper stage weight of 13,230 lb, this concept appears relatively unattractive compared to the ejector scramjet version (block II) from a performance point of view.

W Vehicle Sensitivity Studies

RBCC vehicles are typically very sensitive to installed engine T/W assumptions. Figure 14 shows the sensitivity of the block II W vehicle to changes in installed ESJ T/W. Recall that the baseline vehicle assumed an ESJ T/W of 12. Holding payload constant and resizing the vehicle, a relatively feasible increase to a T/W of 15 could result in 10–15% reductions in vehicle gross weight. Reductions in vehicle size, total vehicle dry weight (upper stage plus booster), and perhaps a commensurate reduction in recurring launch costs would also follow.

Conclusions

This paper reported the results of engineering analyses performed for two possible options for flight testing RBCC engines: the X-34 and a new small TSTO vehicle development known as the W vehicle. Specific conclusions include the following:

1) Both concepts appear capable of serving as RBCC testbeds based on conceptual level preliminary analysis. The test engines can be operated in and transitioned to all modes (ejector, ramjet, scramjet, and rocket if desired) during the test flights. Use of Earth-storable propellants on both test concepts accelerates testing possibilities, promotes dual-use of RBCC technology for missile applications, and maintains compatibility with several current and historical ground-test programs.

2) The X-34 was found to be capable of accelerating a small captive G-MMH/G-IRFNA/JP-10 RBCC ejector scramjet test module to hypersonic speeds of about Mach 6.4 along a dynamic pressure boundary of 1000 lb/ft^2, i.e., a depressed trajectory. Testing at higher Mach numbers (between 6.5 and 7.5) is prohibited by the high hypersonic drag of the X-34 concept. High drag also limits the q boundary to a maximum of 1300–1350 lb/ft^2 if the vehicle is to even reach scramjet test velocities. Drag reducing modifications to the X-34 shape would help, but such modifications are expected to be expensive. In addition, the quality of the RBCC inlet flow in scramjet mode is likely to be poor for the blunt-nosed X-34 shape. As an alternative, a more aerodynamic testbed such as NASA's Hyper-X hypersonic research vehicle or a new candidate from the Future-X program could be considered.

3) The internal test bay volume of the X-34 at 50 ft^3 is adequate to contain the required RBCC test propellants and pressurization system, and the gross weight of the testbed configured X-34 (47,120 lb) does not exceed the lift capability of the L-1011 carrier aircraft. Although the X-34 TPS system would have to be modified for high q and high heating rate hypersonic flight, it does not appear to be an insurmountable problem. However, limited ground clearance resulting from the underslung test engine position considered in this analysis is cause for some concern and should be investigated in more detail.

4) The TSTO W vehicle concept is an attractive vehicle capable of serving multiple purposes in advanced space transportation: a flying wind tunnel for hypersonic research, a flight testbed for RBCC propulsion, a near-term evolvable bantam-class launch vehicle for small commercial and research community payloads. Based on present results, the block II ejector scramjet version of the W vehicle can deliver a payload of 220 lb to a 100-n mile LEO with a gross weight of around 27,430 lb and a total dry weight of 5,695 lb. The total vehicle height is slightly more than 24 ft.

5) Recovery/reusability of the booster stage of the W vehicle still requires significant feasibility analysis. Although potentially attractive for reducing recurring costs, there are several concerns that should be addressed: launch, landing, and abort sites; landing precision requirements; overland flight restrictions, etc.

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J. A. Martin
Associate Editor