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ABSTRACT

While NASA's current next-generation launch vehicle research has largely focused on advanced all-rocket single-stage-to-orbit vehicles (i.e. the X-33 and it's RLV operational follow-on), some attention is being given to advanced propulsion concepts suitable for "next-generation-and-a-half" vehicles. Rocket-based combined-cycle (RBCC) engines combining rocket and airbreathing elements are one candidate concept. Preliminary RBCC engine development was undertaken by the United States in the 1960's. However, additional ground and flight research is required to bring the engine to technological maturity.

This paper presents two options for flight testing early versions of the RBCC ejector scramjet engine. The first option mounts a single RBCC engine module to the X-34 air-launched technology testbed for test flights up to about Mach 6.4. The second option links RBCC engine testing to the simultaneous development of a small-payload (220 lb.) two-stage-to-orbit operational vehicle in the Bantam payload class. This launcher/testbed concept has been dubbed the W vehicle. The W vehicle can also serve as an early ejector ramjet RBCC launcher (albeit at a lower payload).

To complement current RBCC ground testing efforts, both flight test engines will use earth-storable propellants for their RBCC rocket primaries and hydrocarbon fuel for their airbreathing modes. Performance and vehicle sizing results are presented for both options.

NOMENCLATURE

A_c	engine capture area (ft^2)
APAS	Aerodynamic Preliminary Analysis System
C_t	thrust coefficient (thrust/q*A_c)
C_d	aerodynamic drag coefficient
ERJ	ejector ramjet RBCC engine
ESJ	ejector scramjet RBCC engine
GASL	General Applied Science Laboratory
H2O2	hydrogen peroxide
HRE	hypersonic research engine
IRFNA	inhibited red fuming nitric acid (G = gelled)
Isp	specific impulse (seconds)
I*	rocket equation effective Isp (seconds)
JP	jet fuel (one of several hydrocarbon variants)
LACE	liquid air cycle engine
LaRC	NASA - Langley Research Center
LEO	low earth orbit (typically < 250 nmi.)
LeRC	NASA - Lewis Research Center
LH2	liquid hydrogen
LOX	liquid oxygen
M	flight Mach number
MER	mass estimating relationship
MMH	monomethyl hydrazine (G = gelled)
MR	mass ratio (initial weight/burnout weight)
MSFC	NASA - Marshall Space Flight Center
OSC	Orbital Sciences Corporation
POST	Program to Optimize Simulated Trajectories
q	dynamic pressure ($\rho V^2/2$, lb/ft^2)
RBCC	rocket-based combined-cycle
RLV	reusable launch vehicle
RP1	rocket propellant (hydrocarbon)
SLS	sea-level static
SSTO	single-stage-to-orbit
T	engine thrust (lb.)
T/W	engine thrust-to-weight ratio
TPS	thermal protection system
TSTO	two-stage-to-orbit
ΔV	velocity change (feet/second)

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INTRODUCTION

RBCC Background

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 Isp than comparable rockets. In addition, RBCC engines have higher installed engine thrust-to-weight ratios than competing turbine-based cycles or *separate* implementations of rockets and ram/scramjets (i. e. *combination* propulsion systems). A typical RBCC internal layout is shown in figure 1. Typical thrust and Isp vs. flight speed profiles for a LOX/LH2 RBCC engine are shown in figures 2 and 3.

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

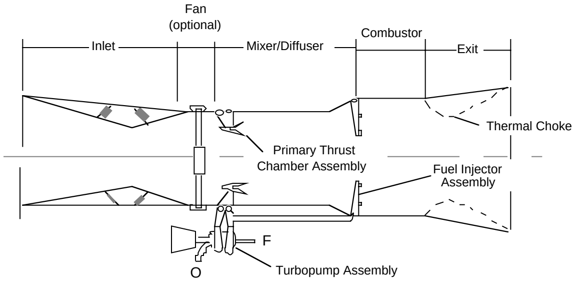

Figure 1 - Typical RBCC Engine Schematic

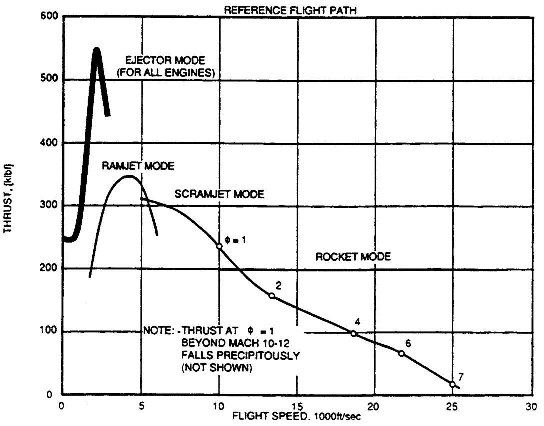

Figure 2 - Typical RBCC Thrust Profile (ref. 4)

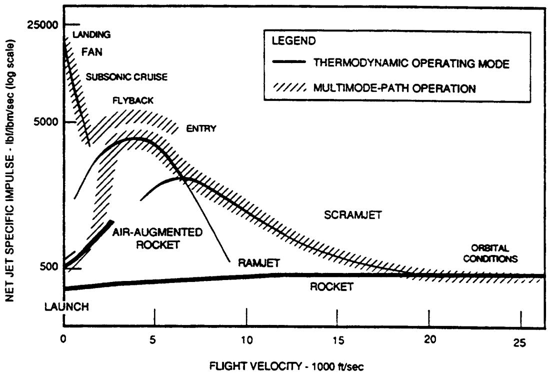

Figure 3 - Typical RBCC Isp Profile (ref. 4)

Rocket-based combined-cycle engines should not be considered a new concept. RBCC engines and vehicles based on them were studied extensively in the mid and late 1960's. In fact, when testifying before the U. S. House of Representatives Space Committee in 1967, Dr. Werner von Braun identified ScramLACE (an air-liquefaction variant of RBCC) as a "superior, more advanced concept [than liquid rockets] for a reusable launch vehicle."[2,12]

Historical work includes extensive ground testing of boilerplate and subscale RBCC engines (figure 4) in the mid-1960's by the Marquardt Corporation under U. S. Air Force sponsorship.[13-14] Various propellant combinations were tested and documented including LOX/LH2 and H2O2/JP. In addition, a contractor team lead by Marquardt (with Lockheed and Rocketdyne)

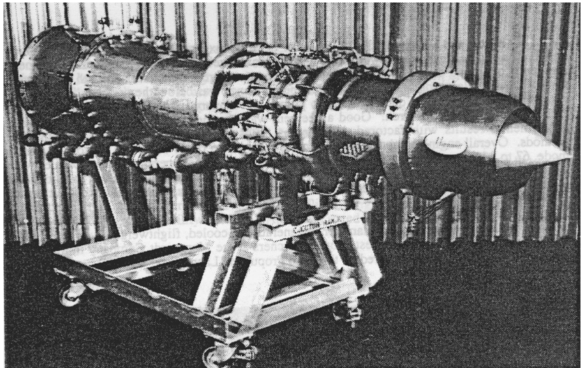

Figure 4 - RBCC Groundtest Engine (Marquardt)

conducted a significant investigation of RBCC engines for use on advanced TSTO and SSTO launch vehicles in 1966 and 1967.[15] This NASA-sponsored study examined a broad range of LOX/LH2 RBCC cycles including basic ejectors, ramjets, scramjets, supercharging fans, and air liquefaction and enrichment elements in various combinations (initially 36 options). The results of this effort are well documented in reference 15.

Based on this historical and more recent research, NASA is beginning to re-examine RBCC propulsion for advanced "next-generation-and-a-half" launch vehicles that might follow the next-generation X-33-derived RLV concepts currently being designed.

Ground Testing

Ground testing of engine concepts is a manifestation of the renewed NASA interest in RBCC. Two variants of the RBCC engine are currently undergoing ground testing. At NASA - Lewis' Plumbrook Research Station, an Aerojet/GASL/NASA RBCC ejector scramjet (ESJ) engine know as the "strutjet" is being tested. This engine utilizes gelled MMH/IRFNA for the rocket primaries and JP-10 for the airbreathing modes.[16] The U.S. Air Force is providing significant financial support for this test under it's HyTech program.

A smaller ESJ engine using gaseous O2/H2 for the primaries and H2 for airbreathing modes will soon begin testing in NASA - Langley's direct-connect scramjet test facility.[16] The test hardware was also supplied by Aerojet/GASL. Both ground test programs are expected to contribute significantly to the RBCC database of knowledge.

FLIGHT TEST OPTIONS

Flight Test Objectives

A follow-on flight test program will serve to further enhance the database of information on RBCC engines and will almost certainly be required should the engine be selected for use on advanced launch systems. 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, engine/airframe integration issues, and will validate ground testing results. The ESJ cycle is recommended for early testing because of its broad launch vehicle applicability and commonality with current ground test programs.

Advanced SSTO or TSTO vehicles in the 20,000 - 30,000 lb. payload to LEO class will almost certainly employ high energy LOX/LH2 propellants. However, earth storable propellants are suggested for the two early flight test options examined here. Earth storable propellants maintain compatibility with NASA - LeRC's ground test program, provide relatively near term test options, build on historical test program databases, and maintain compatibility with possible military 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) X-34 — A single ESJ (or optionally a ERJ) engine module could be integrated to the X-34 technology testbed and flight tested along a simulated airbreathing trajectory in all modes up to Mach numbers above 6. Testbed propellants would be carried in separate pressure-fed tanks inside the X-34 test equipment bay.

2) W vehicle — 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. This vehicle combination would eventually become an operational partially reusable launcher capable of delivering 220 lb. to low earth orbit.

X-34 TESTBED OPTION

X-34 Vehicle

The X-34 (fig. 5) is an unmanned experimental flight vehicle that is air launched from a Lockheed L-1011 carrier aircraft at around 38,000 ft and Mach 0.8. In it's present incarnation, 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. The rocket-powered vehicle will be capable of autonomously accelerating to Mach 8 at

250,000 ft. and then gliding to a horizontal recovery at a landing site downrange of the launch point. First flight will be in 1998, and the fully reusable vehicle will be capable of 25 flights per year.

NASA selected Orbital Sciences Corporation to build the current X-34 in June, 1996. Note that an earlier and larger air-launched TSTO X-34 concept (capable of delivering a payload of about 2,000 lb. to LEO) was terminated when a joint venture between NASA, OSC, and Rockwell International determined that the original concept could not meet its operational or cost goals.

Figure 5 - X-34 Technology Testbed (NASA/OSC)

The X-34 is still early in the design process and concept was sparse at the time this research was performed. Based on preliminary data, the X-34 is expected to look like a smaller version of the last X-34 booster concept generated for the original X-34 program (with similar aerodynamic coefficients). Vehicle gross weight is expected to be approximately 45,000 lb. fully fueled. Vehicle length will be 58 ft and the wingspan will be 28 ft.[17-18] The vehicle will use a single new LOX/RP1 rocket engine under simultaneous development at NASA - MSFC. The FASTRACK engine will be a low cost engine predicated on Simplex turbopumps and an ablatively cooled throat insert. The engine is expected to produce a vacuum thrust of 60,000 lb. and a vacuum Isp of 298.5 seconds with an exit area of 5.585 ft^2.

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. The reference X-34 design data used for this research appears in table 1. Much of the data is approximate.

Table 1 - Reference X-34 Design Data (some data approximated)

Geometry	
length	58 ft
wingspan	28 ft
body width	7.2 ft
theoretical wing area	510 ft^2
internal test bay vol.	50 ft^3
Weights	
propellants	29,905 lb
inert	15,095 lb
gross	45,000 lb
Engine (LOX/RP1)	
vacuum thrust	60,000 lb
vacuum Isp	298.5 sec
exit area	5.585 ft^2

RBCC/X-34 Testbed Integration

Flight testing of a scramjet aboard a rocket-powered hypersonic testbed is not without precedent. In the late 1960's, 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. 6).

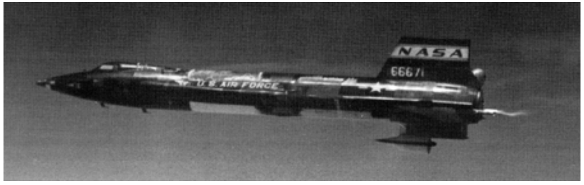

Figure 6 - X-15 with Dummy HRE (NASA)

The presently 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 (figure 7). 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. For simplicity, the engine is pressure-fed gelled MMH (G-MMH) and gelled IRFNA (G-IRFNA) primary propellants and JP-10 fuel from three separate 1,200 psia aluminum tanks stored in the X-34's 50 ft^3 internal test bay. Pressurization is provided by a single

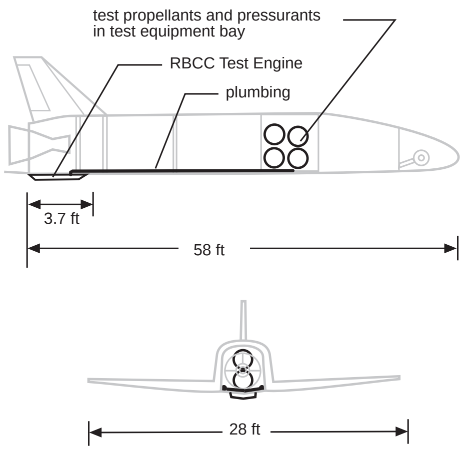

Figure 7 - X-34/RBCC Integration

5,000 psia Helium pressurant sphere. Plumbing and electrical connections will be required between the internal test bay and the externally mounted RBCC engine.

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 concept is refined. At present, the basic X-34 mounted under the L-1011 carrier aircraft is expected to clear the runway by only 1.5 feet. The addition of the RBCC test engine will reduce the ground clearance to (a possibly unacceptable) 0.84 ft. In addition, runway debris from the L-1011 nosegear could be problematic for an underslung configuration. For the present research, it is assumed that the later issue could be resolved with a simple ejectable inlet cover, but the clearance issue may require that the engine be mounted in a new location or may require a more radical and expensive solution (e.g. changing to a pylon-mounted configuration on a B-52 carrier aircraft).

RBCC/X-34 Test Scenario

For the simulations performed, the test engine's G-MMH/G-IRFNA primary was assumed to provide a "primary-only" thrust of 3,000 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, so the thrust level will not be constant nor will it be 3,000 lb. at the beginning of the test. Thrust augmentation data is provided later in this report. Testbed propellant and tankage were sized for the minimum fuel to operate the test engine in parallel with the FASTRACK engine until the main X-34 propellant was consumed. That is, the test engine operates only when the main rocket engine is also on.

The test engine will operate in ejector mode up to Mach 2.5 and transition to ramjet mode by Mach 3.5. The engine operates as a subsonic combustion ramjet up to Mach 5 at which point it will begin a smooth transition to scramjet mode. The test engine will operate as a scramjet until the vehicle reaches its maximum Mach number at burnout. At this point, 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 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 ejector ramjet (ERJ) RBCC engines. Assuming that scramjet testing is possible, a scramjet mode was included in the present study (i.e. an ESJ engine module).

Airbreathing trajectories are necessarily more depressed than rocket trajectories, 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 1,000 psf. 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 is added to the X-34 in the analysis to account for these TPS changes.

X-34 Testbed Analysis Procedure

The objective of the present analysis is to determine the amount of each type of testbed propellant required for the ESJ test, the test engine weight, the additional testbed inert weight (propellant tanks, pressurant tanks, plumbing, etc.), and the peak Mach number and stagnation point heating rate that will be reached. In addition, the sensitivities of the results to the value of the constant q boundary and vehicle aerodynamic drag were determined.

The solution requires iteration between several contributing subanalyses. Trajectory analysis was performed using 3D-POST.[21] Aerodynamic *coefficients* were determined using APAS[22] for the last X-34 booster configuration defined in the original NASA/OSC/Rockwell X-34 contract. A 2.5% penalty was imposed on all drag coefficients to account for the RBCC test engine. Actual vehicle lift and drag were then determined based on the new theoretical wing area assumed in table 1. Engine weights, tank weights, plumbing weights, etc. were determined using historical mass estimating relationships (MERs). Simplified ESJ engine performance was based on historical data and analytical predictions. The later 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. Iteration between POST and the linked spreadsheets was performed manually, but typically converged after two or three iterations. Figure 8 shows the links between the subanalyses and identifies the iteration loops. Updated X-34 and testbed inert weights from the linked spreadsheets were input into POST for each iteration. POST then generated an updated testbed propellant weight, total test time, ejector test time, peak Mach number, and peak stagnation point heating to be input into the two spreadsheets. Since the X-34 shape was not changed, the aerodynamic coefficients were not subject to iteration.

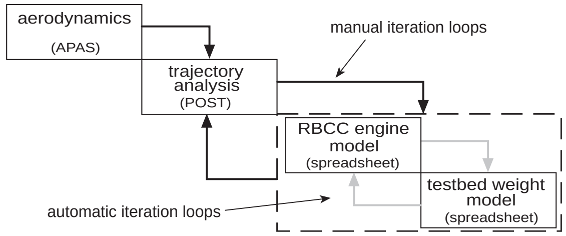

Figure 8 - Iterative Analysis Procedure

Table 2 - X-34 Testbed Baseline (q = 1000 psf)

Weights	
RBCC engine (w/inlet)	282 lb
Test eqpt. prop. tankage	109 lb
Pressurization sys.	166 lb
Other test eqpt. inert	227 lb
Test eqpt. margin (15%)	118 lb
X-34 inert (base)	15096 lb
X-34 inert (additional)	282 lb
Total Inert Weight	16280 lb
JP-10 test prop.	106 lb
G-MMH test prop.	346 lb
G-IRFNA test prop.	484 lb
X-34 propellant	29904 lb
Total Gross Weight	47120 lb
Geometry	
test prop. volume	13.3 ft^3
pressurant volume	9.9 ft^3
RBCC inlet/capture area	1.646 ft^2

Table 3 - Simplified G-MMH/G-IRFNA/JP-10 RBCC Engine Data for X-34 Flight Test

Ejector Mode	**T actual/ T primary**	**Isp**
Mach = 0	1.15	305 sec
Mach = 2.5	1.55	405 sec
Mach = 3.5	0.00	405 sec
Ramjet/Scramjet Modes	**C_t**	**Isp**
Mach = 2.5	1.20	1350 sec
Mach = 3.5	1.30	1450 sec
Mach = 10	0.55	775 sec

X-34 Testbed Analysis Results

The converged results for the baseline case of q = 1,000 psf are shown in table 2. 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 an identical trajectory). The test propellants and main propellants are simultaneously exhausted 148.8 sec. after test initiation. Including the test equipment, test propellant, and TPS changes, the X-34 gross weight increases to 47,120 lb. from 45,000 lb. — still well 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 figures 9 through 12.

The simplified thrust augmentation ratio, thrust coefficient (C_t = T/q*A_c), and Isp values used to simulate the G-MMH/G-IRFNA/JP-10 ESJ engine module are shown in table 3. Here, airbreathing mode C_t's have been determined using a *fixed capture area*

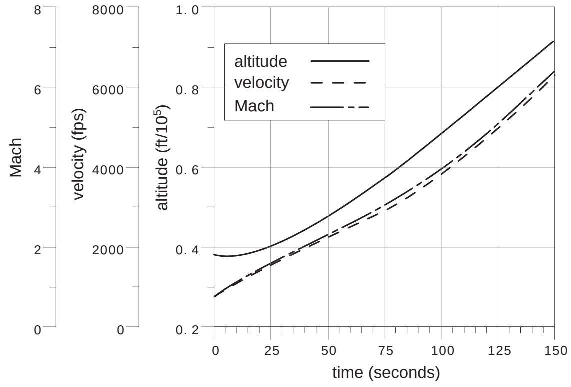

Figure 9 - X-34 Testbed Altitude, Mach , and Velocity

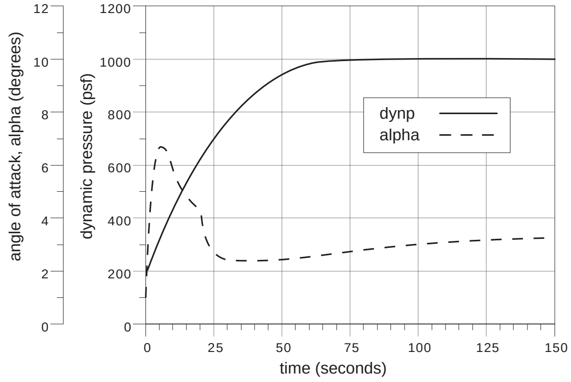

Figure 10 - X-34 Testbed Dynamic Pressure and alpha

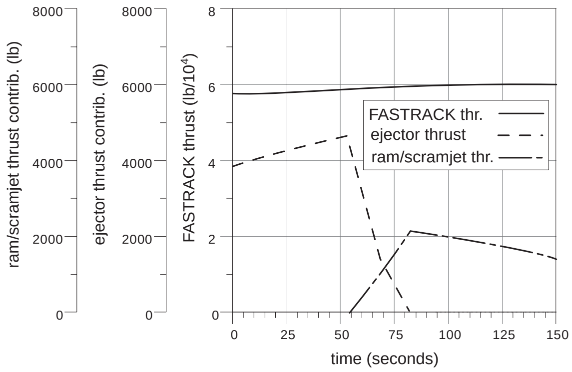

Figure 11 - X-34 Testbed Engine Thrusts

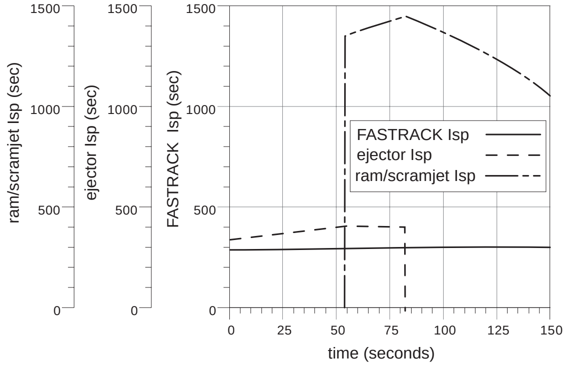

Figure 12 - X-34 Testbed Engine Isp's

(A_c) equivalent to the inlet frontal area. In this formulation, A_c does not change over the trajectory. Note that the ejector thrust ramps down to zero at Mach 3.5 (at a constant Isp) as the engine shifts to ramjet mode. The G-MMH/G-IRFNA rocket primary uses propellants at a rate of 11.11 lbm/s assuming a primary-only Isp of 270 sec. For all X-34 testbed cases, the primary-only thrust was fixed at 3,000 lb.

X-34 Testbed Sensitivity Studies

The iterative analysis procedure was used to perform sensitivity studies against changing the q boundary value and changing vehicle drag. As shown in figure 13, the peak Mach number is very sensitive to the choice constant q portion of the trajectory. Lower q values result in higher peak test Mach numbers because vehicle drag losses are reduced. However, airbreathing mode thrust is roughly proportional to q so q cannot be allowed to go too low. On the other hand, q's above 1,300 psf - 1,350 psf limit the testbed to ramjet speeds (below Mach 5) and do not allow scramjet mode testing. The choice of 1,000 psf 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 it's 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, it's configuration results in high ΔV losses due to drag that reduce it's achievable Mach number. As shown in figure 14, 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 it's hypersonic aerodynamics. These changes would also improve the quality of the airflow entering the RBCC test engine and improve the likelihood that

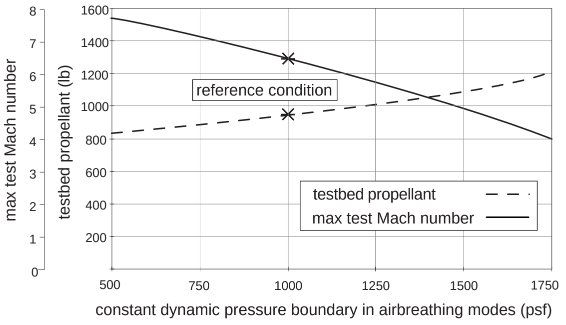

Figure 13 - X-34 Testbed q Sensitivity

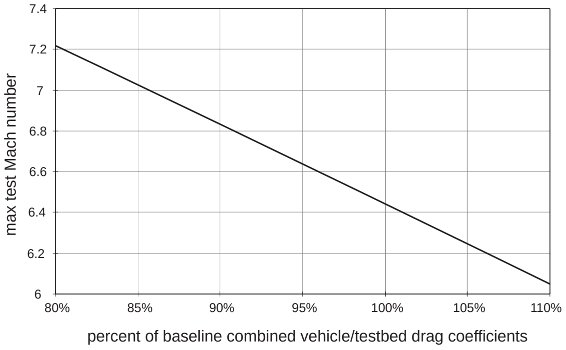

Figure 14 - X-34 Testbed Drag Sensitivity

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.

W VEHICLE TESTBED OPTION

W Vehicle

The W vehicle is a notional concept for an early, partially reusable small payload TSTO launch vehicle recently suggested by Bill Escher at NASA - Headquarters.[23-24] The concept uses a vertical takeoff and landing (VTOL) conical configuration (fig. 15). H2O2/JP ejector scramjets (ESJ) on the booster stage and H2O2/RP1 bipropellant rockets installed in an annular plug nozzle on the second stage to deliver 220 lb. of payload to a 100 nmi. circular orbit due east from the launch site. This payload-class has recently been referred to as "Bantam-class" after the Bantam low cost launch vehicle technology development program at NASA - MSFC with the same mission requirements.

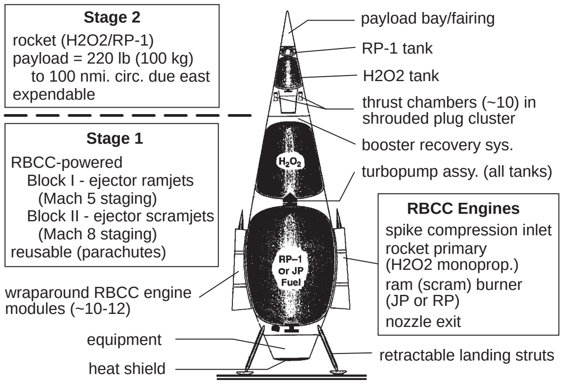

Figure 15 - W Vehicle Concept (Escher)

The W vehicle is envisioned to have several constituents for its development. A low cost (<$1M recurring cost target) operational launcher in the Bantam-class could be used to serve the small commercial payload market and the university/ government laboratory 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 (e.g. Hyper-X). The booster is recoverable, so several tests could be conducted with the hypersonic test article attached in place of the nominal second stage. Lastly, 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 H2O2/JP ERJ 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 - 30,000 lb. payload class that will use LOX/LH2 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 H2O2/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 non-cryogenic, earth-storable propellants. The ejector scramjet on the booster will be closely related to a similar design that underwent successful supercharged/ non-supercharged ground testing at The Marquardt Corporation in 1968 (fig. 16).[25] Like that engine, the W vehicle ESJ engine will use monopropellant H2O2 (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). Standalone monopropellant H2O2 engines have low Isp's by bipropellant standards. However, the oxygen rich exhaust from H2O2 decomposition provides additional oxidizer for JP combustion thereby boosting performance to more favorable values when such an engine is configured as an RBCC primary.

As previously mentioned, the initial W vehicle booster will use a non-scramjet ERJ version of the H2O2/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 Block II booster will be capable of airbreathing operation to Mach 8.

The upper stage engine will consist of a cluster of 10 H2O2/RP1 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 the configuration is approximately 100. The installed upper stage engine vacuum T/W is assumed to be 40 with a vacuum Isp of 335 sec. The upper stage operates at an H2O2/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.

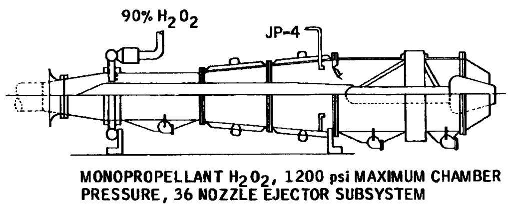

Figure 16 - Marquardt H2O2 Engine Schematic

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 will be designed and sized for ESJ engines and Bantam-class payload delivery mission from the beginning. This is considered the reference flight scenario. In the nearer-term, the booster will be fitted with ERJ engines and JP propellant and upper stage payload will be off loaded as required.

For the reference flight scenario, the TSTO will takeoff vertically from the 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 Mach 3.5 and begin to fly along a constant dynamic pressure (q) trajectory of 2,000 psf. 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 H2O2 primaries, and mixing a small amount of JP fuel with the oxygen rich primary exhaust. Rocket mode is used to pitch the vehicle up from the dynamic pressure boundary and accelerate to it Mach 8.5 where the engine will be shut down. After a 10 second coast to reduce dynamic pressure to below 800 psf, the upper stage is separated and started. The upper stage thrust-to-weight will be approximately 1.05 at staging. The upper stage accelerates directly to a 100 nmi. circular orbit assumed to be at 38° inclination. The payload fairing is ejected at an altitude of 250,000 ft. Vehicle acceleration is limited to 5.5 g's.

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, after staging the booster decelerates aerodynamically to around Mach 2 and deploys a set of multi-stage round parachutes from its top.[23] 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 touch down 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 mid-air 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 Analysis Procedure

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

The analysis procedure is similar to that described earlier for the X-34 testbed option (fig. 8). 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 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 (required stage mass ratios, atmospheric pressure at staging, and booster oxidizer/fuel mixture ratio) and ten coupling variables were passed from the spreadsheets to POST (stage gross weights, aerodynamic reference areas, engine capture area, upper stage fairing weight, H2O2 primary-only thrust and H2O2 flow rate, and upper stage vacuum thrust and exit area). The aerodynamic configuration was fixed as a 10° 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

The analysis results for the W vehicle with the Block II booster are presented in table 4 and figures 17 - 19. For this design, the mass ratio (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 2,857 lb of thrust at liftoff. The H2O2/JP mixture ratio for the booster stage is 3.02. Each of the 12 RBCC engine monopropellant primaries is sized for an H2O2 mass flow rate of 7.756 lbm/s and an equivalent primary-only thrust of 1551.2 lb (assuming a primary-only Isp of 200 sec). 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 27,431 lb. The total dry weight of both stages taken together is 5,691 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 5,803 lb.

The booster/upper stage combination generates a total ideal propulsive ΔV of 37,998 fps (including drag, gravity, thrust vector, and atmospheric back pressure losses). By itself, the booster generates an ideal propulsive ΔV of 18,024 fps and attains a final inertial velocity of 9,613 fps (starting with an initial inertial velocity of 1,202 fps). The booster average engine Isp is therefore,

$$avg.\ Isp = \frac{ideal\ \Delta V}{g_c * ln(MR)} = \frac{18,024\ fps}{32.2\ ft/s^2 * ln(2.506)} = 609\ sec$$

I* is a measure of “loss corrected” Isp including effects of drag, gravity, and thrust vector losses. Using the definition from reference 3, I* for the booster is,

Table 4 - W Vehicle with ESJ (Block II) Booster

Weights	**Booster**	**Upper Stg.**
Engine (installed)	2857 lb	145 lb
Main tankage	179 lb	43 lb
Other structure	275 lb	97 lb
Landing struts	412 lb	-
Recovery system	520 lb	-
Other dry weight	281 lb	139 lb
Margin (15%)	679 lb	64 lb
Total Dry Weight	5203 lb	488 lb
Payload	-	**220 lb**
Fairing (not above)	-	65 lb
Upper stage	5331 lb	-
H2O2 propellant	12381 lb	3914 lb
JP or RP propellant	4104 lb	533 lb
Residuals and Losses	412 lb	111 lb
Total Gross Weight	**27431 lb**	5331 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)	34289 lb	5598 lb
Engine T/W installed	12 (SLS)	40 (vac)
RBCC inlet/capture area	10.23 ft^2	-

$$I^* = \frac{actual\ \Delta V}{g_c * ln(MR)} = \frac{9,613\ fps - 1,202\ fps}{32.2\ ft/s^2 * ln(2.506)} = 284\ sec$$

The H2O2/JP RBCC engine performance data used for W vehicle analyses is listed in table 5. T actual/T primary is the thrust augmentation above the fixed H2O2 primary-only thrust (e.g. 1551.2 lb for the Block II vehicle). There is some evidence to suggest that the present ejector mode thrust augmentation factors and Isp's may be quite conservative. Escher's recently revised performance estimates indicate a primary thrust augmentation and Isp as high as 3.31 and 560 sec. respectively at Mach 2, and 5.15 and 700 sec. at Mach 3.5. [26]

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

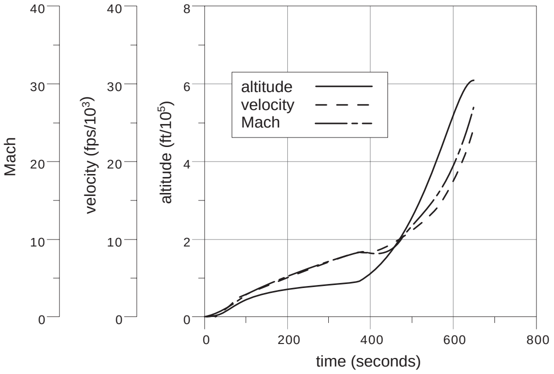

Figure 17 - Block II W Vehicle Altitude, Mach, and Velocity

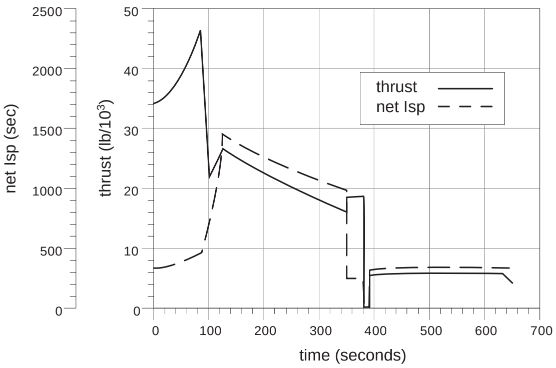

Figure 18 - Block II W Vehicle Thrust and Isp

Block I W Vehicle Testbed Analysis Results

The Block I version of the W vehicle booster will substitute 12 lighter weight ERJ engines in place of the eventual ESJ engines for earlier flight testing and very small payload delivery to LEO. All other aspects of the booster (tank sizes, recovery system, landing struts, etc.) will be designed to Block II requirements to facilitate an easy upgrade to the final Block II vehicle. Ejector ramjet engines are only capable of ramjet operation to Mach 5, so 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 H2O2/JP mixture ratio). Since the H2O2 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. The converged results of the Block I vehicle analysis are given in table 6. For this mission, any remaining H2O2 at the end of ramjet operations was used to accelerate the vehicle away from the q boundary. H2O2 is fully tanked at liftoff. With the exception of installed engine T/W and peak airbreathing Mach number (i.e. airbreathing data was only used up to Mach 5), ERJ engine performance was taken to be the same as that presented in table 5.

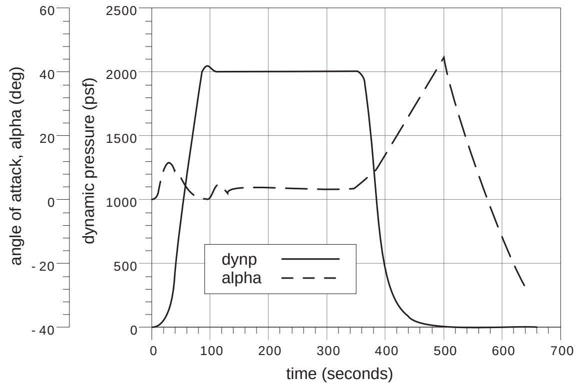

Figure 19 - Block II W Vehicle Dyn. Pressure and alpha

Table 5 - Simplified H2O2/JP RBCC Engine Data for W Vehicle Designs

Ejector Mode	**T actual/ T primary**	**Isp**
Mach = 0	1.84	335 sec
Mach = 2.5	2.63	400 sec
Mach = 3.5	0.00	400 sec
Ramjet/Scramjet Modes	**C_t**	**Isp**
Mach = 2.5	1.20	1350 sec
Mach = 3.5	1.30	1450 sec
Mach = 10	0.55	775 sec
Rocket Mode	**T actual/ T primary**	**Isp**
altitude > 60,000 ft.	1.00	250 sec

In the lower staging Mach number Block I configuration, the mass ratio (MR) of the booster stage is determined to be 2.395, the booster propellant mass fraction is 0.583, the upper stage MR 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 H2O2/JP mixture ratio increases to 11.06 after off-loading excess JP fuel. Payload to a 100 nmi. circular orbit drops to only 84 lb., but a reduced propellant load and a lighter engines reduces 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.

Table 6 - W Vehicle with ERJ (Block I) Booster

Weights	**Booster**	**Upper Stg.**
Engine (installed)	1931 lb	145 lb
Main tankage	179 lb	43 lb
Other structure	275 lb	97 lb
Landing struts	412 lb	-
Recovery system	520 lb	-
Other dry weight	281 lb	139 lb
Margin (15%)	540 lb	64 lb
Total Dry Weight	4137 lb	488 lb
Payload	-	**84 lb**
Fairing (not above)	-	65 lb
Upper stage	5195 lb	-
H2O2 propellant	12381 lb	3914 lb
JP or RP propellant	1120 lb	533 lb
Residuals and Losses	338 lb	111 lb
Total Gross Weight	**23170 lb**	5195 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)	28963 lb	5598 lb
Engine T/W installed	15 (SLS)	40 (vac)
RBCC inlet/capture area	10.23 ft^2	-

Each of the 12 ERJ engines on the Block I booster generates 2,410 lb of thrust at liftoff. Each ERJ primary generates an H2O2 mass flow rate and primary-only thrust of 6.55 lbm/s and 1,310 lb respectively.

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 ERJ engines to deliver 220 lb. payloads to the target orbit. With a gross weight of 41,000 lb., a payload mass fraction of 0.54%, 16 ERJ engines, and an upper stage weight of 13,230 lb., this concept appears unattractive compared to the ejector scramjet version (Block II) from a performance point of view. In fact, such a vehicle would probably not compete favorably with all-rocket TSTO Bantam-class concepts.

W Vehicle Sensitivity Studies

Rocket-based combined-cycle vehicles are typically very sensitive to installed engine T/W assumptions. Figure 20 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. A relatively feasible increase to a T/W of 15 could result in 10% - 15% reductions in vehicle gross weight, vehicle size, total vehicle dry weight (upper stage plus booster), and perhaps a commensurate reduction in recurring launch costs.

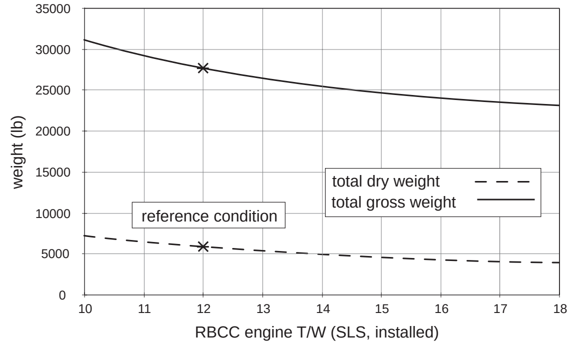

Figure 20 -W Vehicle Engine T/W Sensitivity

CONCLUSIONS

This paper reported the results of engineering analyses performed for two possible options for flight testing rocket-based combined-cycle (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 and maintains compatibility with current and historical ground test programs.

2) The (new) X-34 is capable of accelerating an 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 1,000 psf (i.e. a depressed trajectory). Possible testing at Mach numbers between 6.5 and 7.5 is limited by the high hypersonic drag of the X-34 concept. High drag also limits the q boundary to below 1,300 - 1,350 psf if the vehicle is to 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 new Hyper-X hypersonic research vehicle 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, the underslung test engine position considered in this analysis is cause for some concern. Ground clearance on takeoff and landing may be unacceptably low (less than 1 ft.) and runway debris is likely to be thrown into the inlet during takeoff. Alternate mounting positions might be possible, or as a costly alternative the X-34 could be configured to be air launched from the wing pylon of a B-52 aircraft.

4) The 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 nmi. low earth orbit with a gross weight of around 27,430 lb. and a total dry weight of 5,690 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. While 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.

RECOMMENDATIONS

The following three suggestions are presented as recommendations for continuing this work and improving the quality of the results.

1) Continue to update the X-34 testbed analysis as the X-34 concept matures. Consider alternate mounting locations that might side step the ground clearance issues. Verify the validity of using a blunt-nosed body like the X-34 to flight test scramjets.
2) Refine the W vehicle operational concept, weight estimates, and engine performance data. Investigate recovery options.
3) Evaluate additional testbed options for RBCC engines, particularly more aerodynamic hypersonic research vehicles such as the Hyper-X vehicle.

ACKNOWLEDGMENTS

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