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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 08/09/96

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Project Director OLDS J R_____   School/Lab AERO ENGR_____

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Title HYPERSONIC AIRBREATHING PROPULSION TESTBED OPTIONS FOR THE X-34_____

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Options for Flight Testing Rocket-Based Combined-Cycle (RBCC) Engines

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Options for Flight Testing Rocket-Based Combined-Cycle (RBCC) Engines

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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.

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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)

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
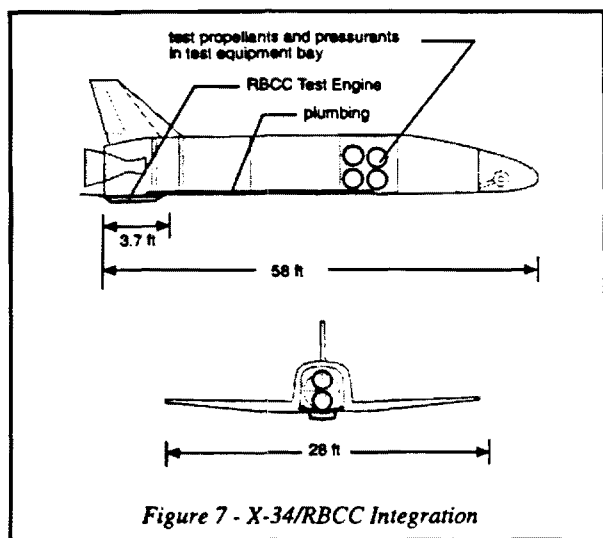
Figure 7 - X-34/RBCC Integration

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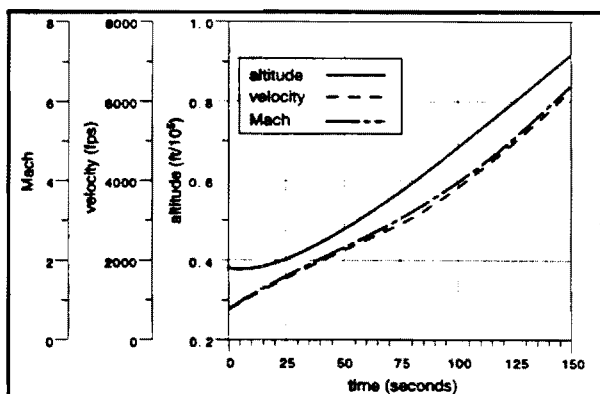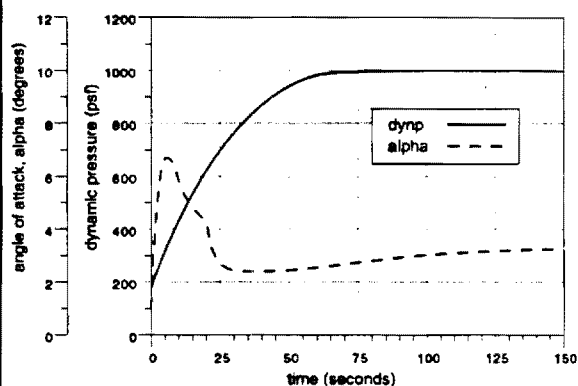
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Figure 9 - X-34 Testbed Altitude, Mach, and Velocity

Figure 11 - X-34 Testbed Engine Thrusts

Figure 10 - X-34 Testbed Dynamic Pressure and alpha

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
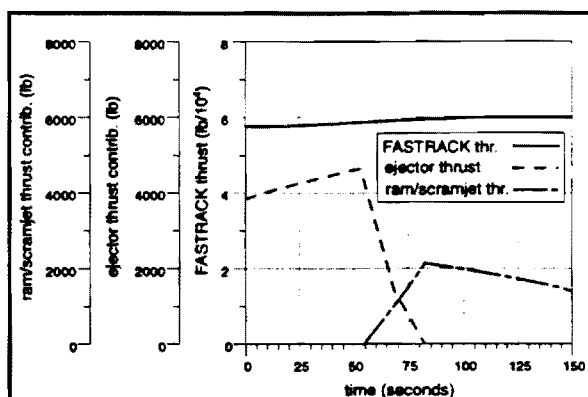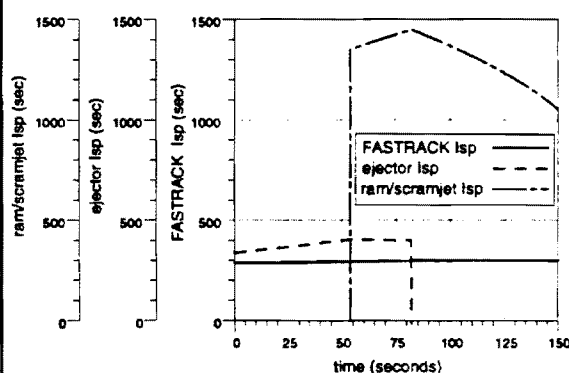
to ramjet speeds (below Mach 5) and do not allow scramjet mode testing. The choice of 1,000 psf as the baseline for the test is a reasonable compromise between achievable Mach number (6.44) and utility of the test results given the drag-related limitations of the testbed.

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

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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

90% H₂O₂   **JP-4**

MONOPROPELLANT H₂O₂, 1200 psi MAXIMUM CHAMBER
PRESSURE, 36 NOZZLE EJECTOR SUBSYSTEM

Figure 16 - Marquardt H2O2 Engine Schematic

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.

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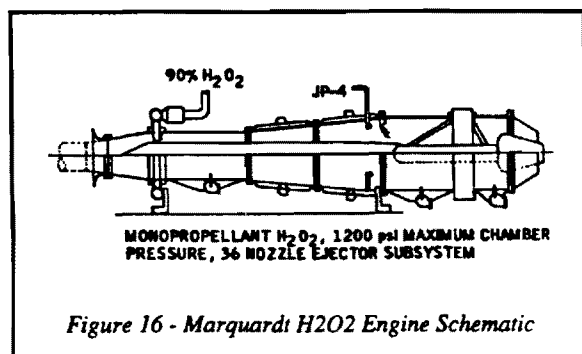
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Table 4 - W Vehicle with ESJ (Block II) Booster

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	-

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

Figure 18 - Block II W Vehicle Thrust and Isp

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

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.

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

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.

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Options for Flight Testing Rocket-Based Combined-Cycle (RBCC) Engines

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Georgia Institute of Technology
July 1, 1996

Outline

■ Brief RBCC Introduction

■ Flight Test Options

    ◆ the "new" X-34 advanced reusable technology testbed

    ◆ the W vehicle (a notional small payload RBCC TSTO vehicle)

■ Preliminary Analysis Results for Both Options

■ Conclusions and Recommendations

What is RBCC and what's so good about it?

Attractive performance for advanced space transportation...

Extensive historical ground test experience and analysis...

MONOPROPELLANT H$_2$O$_2$, 1200 psi MAXIMUM CHAMBER
PRESSURE, 36 NOZZLE EJECTOR SUBSYSTEM

RBCC Engine Background

- **Engine Highlights**
  - ◆ multiple cycles in single unit (ejector/ramjet/scramjet/rocket)
  - ◆ high trajectory averaged Isp's like airbreather
  - ◆ high engine thrust-to-weight ratio like rocket

- **Historical Development**
  - ◆ extensive concept design work in 1960's (Marquardt, Lockheed, USAF)
    - ✦ boilerplate full-sized ejector/ramjet ground tested (LOX/LH2, direct connect)
    - ✦ subscale ejector/ramjet/scramjet ground tested (up to Mach = 5-6)

- **Current Status**
  - ◆ ground test programs currently underway at NASA-LeRC and NASA-LaRC
    - ✦ tunnel and freejet tests at LeRC using storable propellants - G-IRFNA/G-MMH/JP-10
    - ✦ cooperative research with Aerojet/GASL ("strutjet" variants) and the USAF
    - ✦ tunnel tests at LaRC using LH2/LOX

Flight Test Option 1

X-34

Use the X-34 as a "Flying Wind Tunnel"

Flight Test of Dummy HRE on the X-15

X-34 Reusable Technology Testbed

RBCC Test Engine Integration

test propellants and pressurants
in test equipment bay

RBCC Test Engine

plumbing

3.7 ft

58 ft

28 ft

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X-34/RBCC Test Overview

- **X-34 Characteristics**
  - ◆ contract currently being negotiated between NASA and OSC (June 1996)
  - ◆ vehicle designed to reach Mach 8 at 250,000 ft.
  - ◆ smaller, suborbital version of previous X-34 booster design
    - ✦ gross weight ~ 45,000 lb, 58 ft. long, air launched from L-1011 aircraft
    - ✦ uses a single 60 klb LOX/RP FASTRACK engine currently in development at NASA-MSFC

- **Proposed RBCC Testbed Characteristics**
  - ◆ small thrust on test engine (about 5% of total thrust)
  - ◆ earth-storable G-MMH/G-IRFNA/JP-10 for early test and commonality
    - ✦ test propellants stored in internal test bay and pressure fed to test engine
  - ◆ test in all RBCC modes and transitions
    - ✦ X-34 required to fly a depressed, airbreathing style trajectory (q = 1000 psf)

Analysis Procedure

Converged solution required 3-4 manual iterations between the trajectory, engine, and weights & sizing models.

Sample Results for X-34/RBCC

Weights and Sizing Model

Overall Weights

Engine (instl)	281.6	lb
JP-10 Tank	17.1	lb
G-IRFNA Tank	40.5	lb
G-MMH Tank	51.8	lb
Press. System	165.6	lb
Suppt. Struct.	27.5	lb
Plumbing	125.0	lb
Instruments	50.0	lb
Other Systems	25.0	lb
Margin (15%)	117.6	lb
Testbed Inert	901.8	lb
BV Ablat.TPS	23.4	lb
BV TPS update	258.7	lb
Basic BV Inert	15095.6	lb
BV Inert	15377.7	lb
Total Inert	16279.6	lb
JP-10 Prop.	105.6	lb
G-IRFNA Prop.	484.3	lb
G-MMH Prop.	345.9	lb
Booster Prop.	29904.4	lb
Total Gross	47119.8	lb

Vehicle Parameters

JP-10 dens.	50.63	lb/ft3
G-IRFNA dens.	98.00	lb/ft3
G-MMH dens.	54.79	lb/ft3
Primary O/F	1.4	
Total Wpt	935.8	lb
JP-10/Wpt	0.113	

Booster Geometry

Wing ref. area	509.9	ft2
Body Width	7.16	ft
Vehicle length	58.00	ft
Wingspan	28.00	ft
Est. Fus. Area	1305.0	ft2

Center of Gravity
(% length from nose)

Basic BV	65.20%
BV Prop	66.90%
RBCC Engine	90.00%
Testbed Prp.	25.00%
Gross c.g.	86.53%
Sep. target c.g.	63.10%

Booster Summary

Ref. MR	2.981	
Ref. Prop. frc.	0.665	
Ref. Gross	45000.0	lb
Ref. Prop.	29904.4	lb
Basic Inert	15095.6	lb
Add'l Inert	282.1	lb
Booster Gross	45282.1	lb

Testbed Summary

JP-10 volume	2.09	ft3
IRFNA volume	4.94	ft3
MMH volume	6.31	ft3
Total prop vol.	13.34	ft3
He pressure	5000	psia
He volume	9.85	ft3
Step prp frctn	0.5092	
JP-10 wgt.	105.6	lb
IRFNA wgt.	484.3	lb
MMH wgt.	345.9	lb
Inert	901.8	lb
Testbed Gross	1837.7	lb

Dynamic pressure and angle of attack vs. time (dynp, alpha)

X-34 Testbed Dynamic Pressure Trade — Testbed Propellant and Max Test Mach Number vs. Constant Dynamic Pressure in A/B Modes (psf)

Altitude, velocity, and Mach vs. time (seconds)

Summary of X-34/RBCC Analysis

- **Overall Vehicle**
  - gross drop weight = 47,120 lb (well within capabilities of the L-1011)
  - required testbed propellant weights = 940 lb
  - required testbed propellant and pressurant volume = 23 ft^3

- **Test Conditions/Performance**
  - maximum Mach = 6.44 (for the q =1000 psf case)
    - high hypersonic drag configuration limits test q's and Mach numbers
  - total test time = 150 sec.
  - maximum heat rate of 30 BTU/ft^2-s (requires TPS mods on the X-34)

- **RBCC Test Engine**
  - testbed inert weight = 900 lb (incl. actual engine weight = 280 lb)
  - approx. engine length = 3.7 ft, engine height = 0.66 ft
    - engine clearance during takeoff and landing is a significant concern for this configuration

Flight Test Option 2

W vehicle

The W Vehicle Concept

Stage 2
All-Rocket
Payload ≥ 100kg
      (220 lbm)
To LEO
Expendable (Possible Recoverable
Following PL Separation)

Payload Locations
(2 Options)

`≥ 100kg`

Separation 2

Stage 1
RBCC–Powered
  – Ejector Mode
  – Ramjet Mode
  – Scramjet Mode

Plane   1

Pump

Turbine

To Mach ~8 (8000 FPS)
Reusable

HC/H_2O_2
RBCC Engine
Modules (~10)
Wrap-Around
Configuration

Pump-In-Tank

Separate RP Pump for RJ & SJ

Retractable Takeoff/Landing
Struts (~10)

Equipment

RP–1
H_2O_2 (90 Percent) } Propellant
RD AR2/3 Turbo pump Assembly

Rocket Engine Assembly

Thrust Chambers (~10) In Shrouded Plug-Cluster

Nozzle Skirt (Stage 2)

Turbopump Assembly

Compression Spike

Inlet

Primary Rocket
(H_2O_2 Monopropellant)

Scramburner
Ramburner (RP/JP)

RBCC Engine

Exit Nozzle

GE XLR–50 TPA Supplies All Engines
(Change LO_2 to H_2O_2) (XLR–50 aka X-405
Vanguard/VEGA Engine is 28—30 klbf SL)

Heat Shield

H_2O_2

RP–1
(Or JP)
Fuel

The W Vehicle Could Have Several Roles

■ Flight Testbed for Hypersonic Aerodynamic Research

   ◆ aerodynamic test shape in place of upper stage

■ Propulsion Testbed for RBCC Engines

   ◆ simultaneous development of airframe and engines (expanding envelope)

      ✦ Block II booster uses ejector/scramjet RBCC engines

      ✦ booster can be outfitted with ejector ramjet engines for early testing (Block I)

■ Operational TSTO vehicle in Bantam-class (220 lb to LEO for ~ $1M)

   ◆ fully or partially reusable

   ◆ low development and operations cost

      ✦ historically based H2O2/JP RBCC engines provide early start

      ✦ aluminum structure and off-the-shelf subsystem technologies baselined

   ◆ customers might include small commercial market or universities

Sample Results for Block II W Vehicle

"W" Vehicle Block II Weights and Sizing Model

Booster Stage

Overall Weights			Booster Parameters			Booster Propulsion (ESJ RBCC Engines)		
Engine (instl)	2857.4	lb	JP-5 dens.	50.0	lb/ft3	Tsls/W (instl.)		12
JP-5 Tank	65.7	lb	H2O2 dens.	87.8	lb/ft3	# of engines		12
H2O2 Tank	112.8	lb	O/F ratio	3.02		(max # engines)		24
Other Struct.	275.4	lb				T/W @ liftoff		1.25
Passive TPS	56.2	lb	JP-5 Ink. const.	0.8	lb/ft3	T @ SLS (tot)	34288.7	lb
Recovery Sys.	520.3	lb	H2O2 Ink. const.	0.8	lb/ft3	T @ SLS (ea)	2857.4	lb
Landing Struts	411.5	lb				Primary Isp	200.0 sec	
Power	75.0	lb	**Booster Geometry**			Primary T (est.)	18614.9	lb
Avionics	50.0	lb	(estimated)			Wdot H2O2 (est)	93.1	lb/s
Other Systems	100.0	lb						
Margin (15%)	678.6	lb	Cone half angle	0.175 rad		Engine dia. (est.)	1.04	ft
Dry	5202.9	lb				Engine In./dia.	6.00	
			JP-5 volume	82.08	ft3	Eng. length (est.)	6.25	ft
Upper Stage	5330.9	lb	H2O2 volume	141.02	ft3	Total Ac (est.)	10.23	ft2
Residuals	329.7	lb	Comb. prop vol.	223.09	ft3	Available Ac	27.0	ft2
Losses	82.4	lb	Internal vol.	301.17	ft3			
Staging	10945.9	lb				**Booster Summary**		
			Top radius	2.26	ft			
JP-5 Prop.	4103.8	lb	Max. radius	3.61	ft	Ascent prop.	16485.0	lb
H2O2 Prop.	12381.2	lb	Base radius	1.80	ft	Bst. (only) gross	22100.0	lb
Total Gross	27430.9	lb	Fore sect. L/aft L	2				
			Aft sect. length	3.81	ft	Step lambda	0.254	
			Stage height	11.44	ft	Mass ratio	2.506	
			Surface area	224.8	ft2	Target MR	2.506	
						MR Difference	0.0000	
			Total veh. height	24.28	ft	Prop. ml	0.601	
			Aero area	40.91	ft2			

Block II "W" Vehicle T/W Sensitivity

Total Dry Weight
Total Gross Weight

RBCC Engine T/W (Installed)

Weight (lbs)

thrust
net Isp

net Isp (sec) / thrust (lb/10³) / time (seconds)

dynp
alpha

angle of attack, alpha (deg) / dynamic pressure (psf) / time (seconds)

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Block II W Vehicle Summary Weights

Name	Weight (lb)
Booster Dry Weight (incl. 15% margin)	5,200
Booster H2O2 Propellant	12,380
Booster JP Propellant	4,100
Other Inert Weights	420
Booster Fueled Weight	22,100
Payload	**220**
Upper Stage Dry Weight (with fairing)	550
Upper Stage Propellant	4,450
Other Inert Weights	110
Upper Stage Fueled Weight	5,330
Total Gross Lift-off Weight	**27,430**

Summary of W Vehicle Analysis

- Preliminary Results Indicate H2O2 Approach is a Feasible Early Option
  - ◆ eventual X and Y vehicles will follow based on LH2/LOX RBCC variants
  - ◆ use of H2O2/JP should help limit development costs

- Bantam Mission with Block II (ESJ) Booster
  - ◆ gross weight = 27,430 lb, payload fraction= 0.8%
  - ◆ results are sensitive to installed engine T/W
    - ✦ ESJ T/W was assumed to be 12 in this work
  - ◆ recovery scenarios were not investigated and remain an issue

- Early Block I (ERJ) Booster
  - ◆ fitting the Block II booster airframe with ejector ramjets allows early testing
  - ◆ Block I booster can also be used to deliver TSTO payloads
    - ✦ max airbreathing capability is reduced to Mach 5, payload is reduced to 85 lb.

Overall Summary

- **X-34 Technology Testbed**
  - ◆ can test up to Mach 6.44 at q = 1000 psf
  - ◆ ejector/ramjet/scramjet mode transition can be demonstrated
    - ✦ G-MMH/G-IRFNA/JP-10 maintains compatibility with ground test
  - ◆ high hypersonic drag limits testing at higher q's or Mach numbers
  - ◆ test engine integration and ground clearance remains a significant concern

- **W Vehicle (early RBCC TSTO in the small payload class)**
  - ◆ can serve as a testbed during development of an operational TSTO launcher
    - ✦ H2O2/JP ejector ramjets and scramjets keep development and operations costs low (Bantam)
  - ◆ might have several constituents interested in its development
  - ◆ booster recovery remains an unaddressed concern
    - ✦ launch, landing, and abort sites, over land flight restrictions, etc.

Recommendations for Future Work

- **Update X-34 Analysis as the Concept Matures**
  - ◆ improve X-34 weight and propellant estimates
  - ◆ consider alternate mounting locations for the test engine

- **Continue to Define the W Vehicle Concept**
  - ◆ improve airframe weight and engine performance approximations
  - ◆ investigate booster recovery options

- **Consider Additional Vehicles for RBCC Flight Testing**
  - ◆ high drag of the X-34 concept limits its test capabilities
  - ◆ alternate hypersonic research vehicles should be considered (e.g. Hyper-X)