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Rocket Based Combined Cycle (RBCC) Propulsion Workshop
Proceedings Final Report

Submitted to

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August 28, 1992

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August 28, 1992

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Dear Eric,

The following two enclosures in camera ready form constitute the final output delivery as specified in contract number NAS8-38609 D.O. 10:

o   Rocket Based Combined Cycle (RBCC) Propulsion Technology Workshop Proceedings Executive Summary

o   Rocket Based Combined Cycle (RBCC) Propulsion Technology Workshop Proceedings Final Report

I would appreciate a copy of the final distribution list for my records.

It has been a pleasure working with you and we at the Propulsion Research Center are looking forward to future association with you. Your professional guidance in performing this contract is greatly appreciated.

Clark W. Hawk, Ph D PE
Director

Encl a/s

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       Ms Sue Weir
cc   without enclosures
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1.0 Abstract

This RBCC propulsion technology workshop was sponsored by NASA-OAST's Transportation and Platforms Division under its Earth-to-Orbit Propulsion Technology Program. This workshop took place at the University of Alabama in Huntsville during the week of March 23-27, 1992.

The goal of the Rocket Based Combined Cycle (RBCC) Propulsion Technology Workshop, was to impart technology information to the propulsion community with respect to hypersonic combined cycle propulsion capabilities.

The major recommendation resulting from this technology workshop was: Conduct a systems-level applications study to define the desired propulsion system and vehicle technology requirements for LEO launch vehicles. All SSTO and TSTO options using the various propulsion systems (airbreathing combined cycle, rocket-based combined cycle, and all rocket) must be considered. Such a study should be accomplished as soon as possible. It must be conducted with a consistent set if groundrules and assumptions, and before any major expenditures on a RBCC technology development program occur.

2.0 Introduction

The goal of the Rocket-Based Combined Cycle (RBCC) Propulsion Technology Workshop was to assess the RBCC propulsion system's viability for Earth-to-Orbit (ETO) transportation systems. This was accomplished by creating a forum (workshop) in which past work in the field of RBCC propulsion systems was reviewed, current technology status was evaluated, and future technology programs in the field of RBCC propulsion systems were postulated, discussed and recommended.

Extensive tutorial activities were accomplished prior to and at the beginning of the workshop. Prior to the workshop, a written tutorial summarizing past work in the field and current relevant research was distributed to workshop participants.[1] At the workshop, these tutorial activities were extended and expanded through some twenty-six fifteen minute briefings by specially selected expert presenters. The tutorial activities met two needs. First, since workshop participants came from a variety of technical disciplines, the tutorial activities served to provide necessary knowledge to those participants whose background was not in combined cycle propulsion. Second, since much of the research relevant to RBCC propulsion systems was conducted in the 1960's, the tutorial activities

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provided a review of past technology programs in the field and informed the participants of technology programs currently underway.

Current technology status was evaluated by four topical breakout groups. Each of the groups was responsible for analyzing a particular aspect of RBCC propulsion systems. A brief description of each group's responsibilities follows.

2.1 Mission and Space Transportation Options (Group 1)

Breakout Group 1 examined various launch vehicle concepts to determine their suitability for incorporating RBCC propulsion system alternatives and the advantages that RBCC propulsion systems would bring to LEO vehicles. In addition, the team determined propulsion system technology drivers for the particular vehicles.

2.2 Vehicle Integrated RBCC Propulsion Systems (Group 2)

Breakout Group 2 defined propulsion technology requirements for RBCC powered launch vehicles. The group defined criteria for the time frame of application to guide in defining technologies to be developed.

2.3 RBCC Vehicle Design, Development and Test Definition (Group 3)

Breakout Group 3 identified the steps needed to develop and validate low cost, mission-based vehicle systems focused on the RBCC propulsion concept. This was accomplished by identifying required critical technology areas for development, assessing needs in the design methods and tools, and addressing ground and flight test facility requirements relative to operations and design certification.

2.4 Spaceflight Fleet Applications and Operations (Group 4)

Breakout Group 4 traced the life cycle of an RBCC powered vehicle from its testing phase through its certification and to its operation phase. The group formulated test approaches, designed a certification process, developed an operations scenario, and discussed life cycle costs (LCC).

3.0 RBCC Propulsion Systems

Rocket-Based Combined Cycle (RBCC) propulsion systems are a family of engine concepts, rather than a single, unique propulsion system. RBCC propulsion systems integrate airbreathing propulsion and rocket propulsion into a single engine assembly. Therefore, there is a single propulsion system operating in various engine modes (cycles). RBCC propulsion systems can be used for single-stage-to-orbit (SSTO) or two-stage-to-orbit (TSTO); operate with or without a supercharging fan subsystem; and utilize an air liquefaction subsystem if desired.

Many of the concepts relevant to RBCC engines were first studied in the mid-1960's by a team led by the Marquardt Corporation[2]. The study objectives were:

1) To systematically appraise the significance of Rocket-Based Combined Cycle engines to potential advanced launch vehicle missions in the period, post 1975

2) To determine the technology ramifications of RBCC engines with particular emphasis on delineating critical or pacing technology requirements

3) To systematically and comprehensively document technical data which would be useful for further studies involving RBCC engines, with emphasis on vehicle/mission applications.

Marquardt examined thirty-six candidate engine concepts. After initial screening, twelve were chosen for further analysis, and the two most promising were selected (for the relatively near and far term, respectively): the Supercharged Ejector Ramjet, and the ScramLACE. Details of these systems will be given later.

This study, however, dealt almost exclusively with two-stage-to-orbit systems in which the first stage utilized RBCC engines and the second stage was all-rocket. The study showed increased performance (payload/TOGW) over all-rocket-powered vehicles for fully recoverable, orbital launch systems (about 4 times the ratio of payload/TOGW for the Supercharged Ejector Ramjet, and about 8 times for the ScramLACE) Marquardt determined that the more attractive combined cycle propulsion systems are characterized as ejector or advanced air-augmented rocket systems which are capable of ramjet operation following the initial acceleration phase.

These air-augmented concepts were revisited by the Astronautics Corporation of America (ACA) in 1986[3] This study "focused on the analysis of past work in the field of rocket-based combined cycle engine systems, the selection of five RBCC engines for further evaluation and investigation of design approach alternatives which integrate these concepts into a vehicle design." The five RBCC engines selected were: the Ejector Scramjet; the Supercharged Ejector Scramjet; the ScramLACE; the Supercharged ScramLACE; and the Recycled Supercharged ScramLACE. A brief description of each follows.

3.1 Ejector Scramjet

The Ejector Scramjet (ESJ) (Figure 1) is the simplest design of the five (the other four are variations of the Ejector Scramjet). The ESJ is designed with variable inlet, fixed combustion geometry and fixed exit geometry. The use of thermal choke eliminates the need for physically variable exit geometry which is required in the ramjet mode to control the inlet shock position.

In the ejector mode, the engine operates at high thrust for liftoff and acceleration to the Mach 2 or 3 range. The rocket primary thrusters are at full thrust using hydrogen/oxygen propellants, and the afterburner is operating at local stoichiometric conditions at full flow. The engine transitions to ramjet mode at about Mach 3 for supersonic to hypersonic acceleration. The rocket primary thrusters are off while the ramjet combustor operates at near stoichiometric conditions.
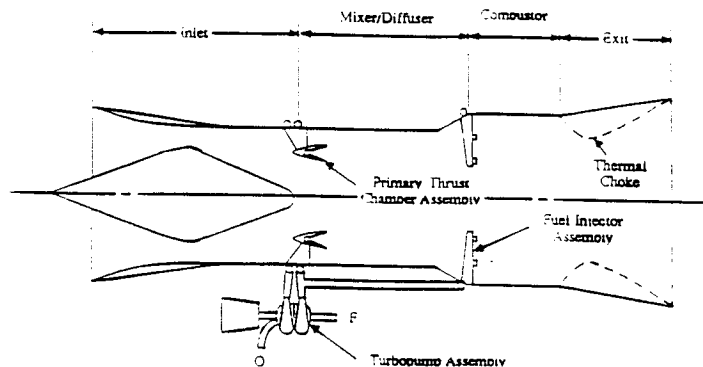
Figure 1: Ejector Scramjet

In the range of Mach 6-8, the engine transitions to the scramjet mode. Hydrogen fuel is injected in the forward part of the duct, now flowing supersonically. Combustion takes place in the constant area and diverging duct section. Exhaust gas expansion initiates in the nozzle and completes on the aft-body of the vehicle.

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At some flight Mach number, depending upon vehicle and mission requirements, the engine transitions to rocket mode with the inlet being physically closed. The rocket primaries operate again on hydrogen/oxygen propellant, and the exhaust gases expand in the divergent portion of the duct and finally on the vehicle aftbody.

3.2 Supercharged Ejector Scramjet

The Supercharged Ejector Scramjet (SESJ) is configured similarly to the ESJ except for the addition of a supercharging turbofan (Figure 2). The advantages of this design include an increased ejector mode effective specific impulse, the availability of a fan-ramjet mode, and sharply decreased fuel consumption in flyback, landing, go-around and self-ferry modes when the fan is operated alone as a high bypass ratio turbofan.

Obviously, these advantages are gained at the expense of additional weight and complexity. These complications include the fan itself, the turbomachinery required to drive the fan system, and the machinery required to remove the fan from the flowpath during scramjet operation. These factors increase vehicle complexity and increase vehicle inert weight.
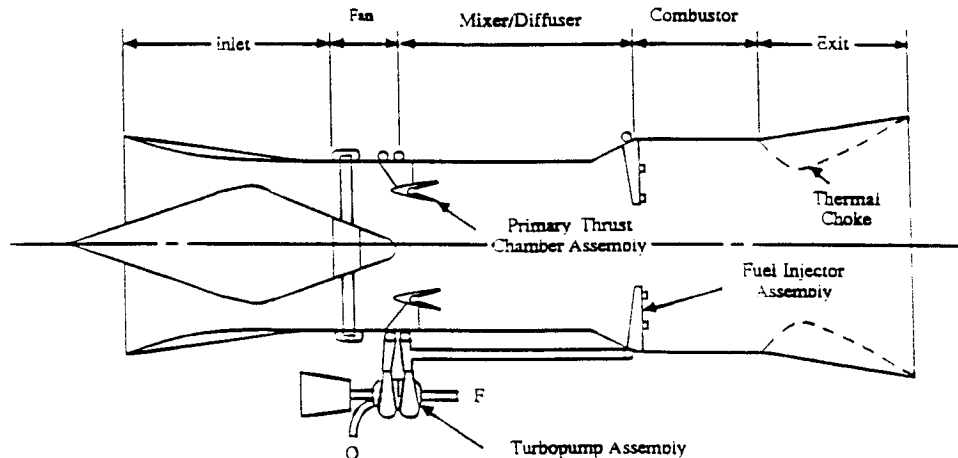
Figure 2: Supercharged Ejector Scramjet

Initially, the system operates similarly to the Ejector Scramjet with the exception that the fan is operating at full power. In the fan-ramjet/ramjet mode, the engine transitions from supercharged-ejector mode to fan-ramjet mode in which only the fan and the ramjet systems are operating. As engine inlet recovery temperature rises and the pressure contribution of the fan drops as flight velocity further increases, the fan system is shut down and stowed out of the flowpath. The engine then transitions to scramjet mode, followed by rocket mode for orbital insertion as in the case of the ESJ. In the descent, go-around, landing and self-ferry modes of

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flight, the fan is unstowed and can be operated with or without plenum burning to provide high specific impulse and sufficient thrust for subsonic loiter/landing of the vehicle.

3.3 ScramLACE

The ScramLACE (Figure 3) is the Ejector Scramjet with the tanked liquid oxygen replaced in flight with liquid air produced by an on-board air liquefaction system. The Liquid Air Cycle Engine (LACE) subsystem only operates during the ejector portion of the flight, and then the engine operates identically to the ESJ. Operation of the air liquefaction system is initiated and liquid air is supplied to the rocket primaries which operate on hydrogen/liquid air throughout the ejector mode. The system operates extremely fuel-rich because the hydrogen required to cool and liquefy the air exceeds that needed for combustion.

The primary advantage of the air liquefaction subsystem is that it reduces the amount of liquid oxygen that the vehicle must carry and thus increases the effective specific impulse of the engine. The disadvantages of the air liquefaction system are the additional weight and complexity it introduces to the propulsion system.
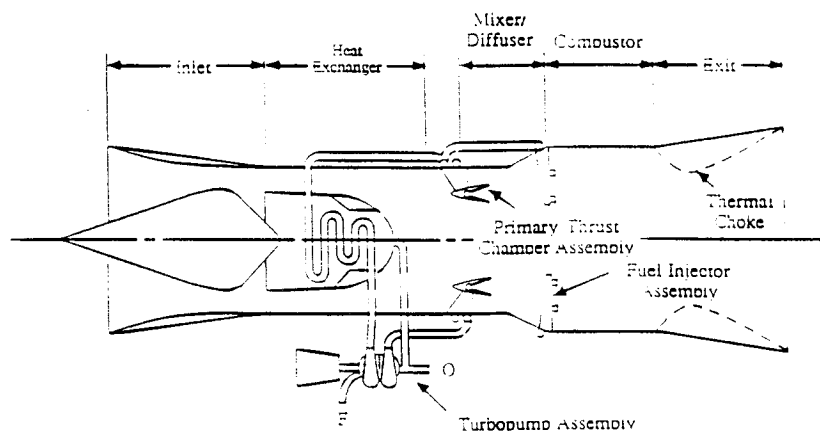
Figure 3: ScramLACE

3.4 Supercharged ScramLACE

The Supercharged ScramLACE (Figure 4) is the ScramLACE engine described above with the addition of a supercharging fan. At liftoff, both the fan and air liquefaction subsystems are fully operating. The air liquefaction subsystem shuts down as the engine transitions to ramjet mode. The fan continues to operate at full power in the ramjet mode until its pressure contribution drops. The fan is then stowed out of flowpath. The engine continues on in scramjet mode and then rocket mode for orbital

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insertion. The Supercharged ScramLACE has the advantages and disadvantages of both the fan subsystem and the air liquefaction subsystem previously discussed.
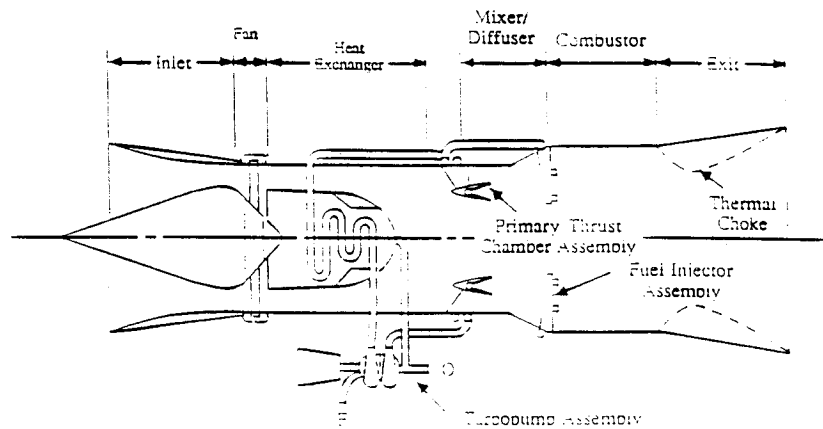
Figure 4: Supercharged ScramLACE

3.5 Recycled Supercharged ScramLACE

A disadvantage of the ScramLACE engine is that it operates at a non-optimum fuel-rich level because the hydrogen required for air liquefaction is greater than that needed for combustion. The Recycled Supercharged ScramLACE returns a portion of the excess hydrogen to the hydrogen tank where "slush" hydrogen (a 50/50 mixture of liquid and solid hydrogen) resides. This process results in the recycling of hydrogen at approximately 120 R to the main hydrogen tank where the greater thermal sink of the slush hydrogen is required to recool the hydrogen. The engine is then able to operate at near optimum mixture ratios in the ejector mode. Additionally, the greater density of the slush hydrogen results in reduced tanking and structural requirements.

The Recycled Supercharged ScramLACE provides the highest specific impulse of the five choices, but it is attained at the price of added complexity. The production of slush hydrogen, however, is emerging as a developed technology due to the work being done in support of the NASP Technology Maturation Program.

4.0 Major Findings/ Conclusions

1. Initial investigations by workshop participants suggest that the best near-term (IOC 2005) application for a combined-cycle engine is a propulsion system for the booster element of a low risk, fully reusable,

TSTO launch vehicle. The combined cycle engine suggested for this role was a turboramjet. The enhancement of the existing "Himate" joint NASA/Air Force study of this type of combined cycle engine for TSTO application, including the addition of an applications assessment, could be an affordable way to broaden NASA's Earth-to-Orbit propulsion technology program beyond the realm of pure rocket engines.

2.	RBCC propulsion technology development is not dependent upon SSTO for justification. The RBCC powered SSTO vehicle received relatively low ratings during workshop discussions primarily due to a perceived high development risk and potential cost growth. More depth of study with a consistent set of groundrules and assumptions is required to show the benefits of RBCC powered SSTO LEO launch vehicles relative to all rocket powered SSTO LEO launch vehicles. The following two questions need to be answered:

- Is SSTO economically feasible?

- Can advancing RBCC propulsion technology for SSTO LEO launch vehicles ever overcome existing rocket technology for these vehicles?

However, RBCC propulsion systems should not be discounted. TSTO vehicles utilizing RBCC propulsion systems have potential performance advantages over all-rocket systems. Additionally, the applicability of RBCC propulsion systems to TSTO vehicle concepts allows for the evolution of a propulsion system to SSTO capabilities by first applying RBCC engine technologies to TSTO vehicle concepts.

3.	Among the most critical unknown factors in RBCC powered SSTO vehicle design is the performance of the scramjet mode at high Mach number. Scramjet performance may degrade with increasing Mach number at a much greater rate than has been conventionally assumed.

4.	The integral rocket, unique to RBCC propulsion, requires further technology development. At take-off, mixing and mixing enhancements of the air-augmented rocket mode need development. When the rocket primary thrusters are used for orbital insertion, the transition from scramjet mode to all-rocket mode will result in a rocket chamber design that is outside the current rocket technology database. Unknown technology issues associated with the integral rocket include the following:

- Combustion stability

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- Injector/plume interaction

- Acoustic environments in the inlet and diffuser region
  after inlet closure

- Control of mixture ratios during inlet closure while
  maintaining vehicle thrust, chamber pressures, and
  heat fluxes.

5.   The development of new testing facilities or the upgrading of existing facilities will be required for the development of RBCC propulsion technology. Facilities will be needed for component technology development and for full scale flight-type engine modules. While no new facility requirements for research and component technology development for the Mach 0-8 range exist, a high priority requirement exists for the near term research and component technology development test facilities in the Mach 8-18 range. Another high priority requirement exists for near term upgrades to existing large scale, long duration clean air facilities for engine developments in the Mach 0-8 range. Finally, a requirement exists for large scale, long duration, real gas facilities for engine development tests in the Mach 8-18 range.

6.   Operational considerations (eliminating the standing army) must play an important role in the design of any new LEO launch vehicle. The initial non-recurring investment required to provide reliability, fault-tolerance, safety, and dependability should not be compromised to "sell" a program; this comes at the expense of operations efficiency. Traditionally, the costs for high usage systems are dominated by operational expenses (standing army). To reduce life-cycle cost, operations engineers and user representatives must be included early in the vehicle design phase.

7.   Launch and recovery operations need to be airline type. The goal should be to minimize ground operations and turn around by using a hangar type facility for planned maintenance or repair actions. The vehicle concept should eliminate or at least minimize hazardous ground operations which increase turn around time due to safety requirements.

5.0   Recommendations

1.   Conduct a systems-level applications study to quantify the benefits and costs associated with RBCC systems and to define the desired propulsion system and vehicle technology requirements for LEO launch vehicles. All SSTO and TSTO options using the various propulsion systems (airbreathing combined cycle, rocket-based combined cycle, airbreathing

plus rocket combinations, and all rocket) must be considered. Such a study should be accomplished as soon as possible. It must be conducted with a consistent set of groundrules and assumptions, and before any major expenditures on a RBCC technology development program occur.

Several design options of the RBCC propulsion system need to be considered. Among them are: liquid air systems, slush hydrogen, SSTO vs. TSTO, horizontal vs. vertical takeoff, turbomachinery systems to enhance low speed performance, cooling concepts/thermal protection systems, and axisymmetric vs. 2D inlet/nozzle concepts.

2.   Make the NASP technology base available to the R&D community. Extensive RBCC studies, conducted in a NASP information-rich environment, are needed to validate the benefits of RBCC propulsion. Archival data from early hypersonic programs should also be reexamined with an eye towards applying advances in subsystem technology (materials, CFD, controls) to update the results from previous programs.

3.   Experimentally determine realistic high Mach number (8 to 18) scramjet performance to be used in future RBCC powered SSTO LEO launch vehicle studies.

6.0 Report of Topical Breakout Group 1
Mission and Transportation Infrastructures for RBCC Propulsion System

Group Leaders:	Mr. Jim Berry	Rocketdyne
	Mr. Leo Burkhardt	NASA/LeRC
	Mr. Vince Weldon	Boeing
Working Group:	Mr. Terry Abel	General Dynamics
	Mr. Dana Andrews	Boeing
	Dr. Bob Budica	Marquardt
	Capt. Lou Carreiro	USAF Wright Lab
	Mr. John Copper	McDonnell Douglas
	Mr. Walt Dankhoff	W.J. Schafer & Assoc.
	Mr. Michael Hayes	Rockwell International
	Mr. Bill Haloulakos	McDonnell Douglas
	Mr. C.F. Huffaker	NASA/MSFC
	Mr. Russell Morrison	Rocketdyne
	Mr. John McIver	Boeing
	Mr. Richard Norris	USAF Wright Lab
	Mr. William Powell	NASP/JPO
	Mr. John Olds	N.C. State University
	Mr. Jim Sanders	Retired
	Mr. Joseph Szedula	General Dynamics

6.1   Introduction

Breakout Group 1 examined various launch vehicle concepts to determine their suitability for incorporating RBCC propulsion system alternatives and the advantages that RBCC propulsion system would bring to LEO vehicles. In addition, the team determined propulsion system technology drivers for the particular vehicles.

The launch vehicles were divided into three classes: near term, mid term and far term with the following definitions:

- Near Term with an IOC of 2005
- Mid Term with an IOC of 2010
- Far Term with an IOC of 2015

Two classes of LEO launch vehicles were determined to be prime candidates for RBCC propulsion system concepts - near term HTOL two-stage-to-orbit (TSTO) vehicles with airbreathing first stage and all-rocket second stage, and far term SSTO vehicles.

6.2 Vehicle Selection and Assessment Process

The first step in the vehicle assessment process was to define the requirements and goals which the vehicles were expected to meet or strive for. These are shown in Table 1. Only two of the items were considered requirements, a payload to low polar orbit of 10K lbs. and a total system capacity of 500K lbs. to orbit per year. The other items were considered goals which nearer term systems may not fully meet, but far term systems would be expected to meet. These requirements and goals were taken from those defined by the Space Propulsion Strategic Planning Support Working Panel of the Space Propulsion Synergy Group.[4]

Table 1: Launch Vehicle Requirements and Desired Attributes

REQUIREMENTS	
Capability/Flight	10K lb polar LEO
Capacity/Year	. 500K lb/year
Desired Attributes	
Crew/Vehicle Safety	.9995
Mission Reliability	.99
Affordability	< $500/lb
Availability	.95
Responsiveness	7 days

One change was selected to the desired attributes/requirements. This was a reduction of the mission reliability goal from 0.999 to 0.99. This change was thought to be more consistent with the crew/vehicle safety goal of 0.9995 using a vehicle which would not have to experience many launch holds, but could merely return to base if something went wrong. Such a vehicle is the only type of system which could approach airline-type operations and achieve the low mission costs required to encourage expanded space activities. Such a system would need to be fully reusable, or nearly so, another bound which helped focus group activities.

A set of evaluation factors, listed in Table 2, was selected as a measure of how well each vehicle met the stated goals. The factors, as well as weights applied to them, were selected by consensus vote of the group. For each evaluation factor a vehicle was selected which best met that criteria. All other vehicles were then rated relative to that vehicle. For example, in the near-term category, the TSTO all-rocket system was determined to have the highest level of technology maturity and was therefore given 13 points for that evaluation factor. The technology maturity of the other vehicle concepts were then ranked against that of a TSTO all-rocket system. This resulted in a score of 4 for the Delta Clipper.

Table 2: Evaluation Factors

Safety	18
Operations and Support	16
Technology Maturity	13
Procurement Costs (Development)	13
Mission Reliability	8
Operational Readiness • Availability • Responsiveness	8
Margins/Sensitivity	8
Evolutionary Payoff	8
Environmental Impact	8

Vehicles were selected for evaluation from known launch vehicle studies with an eye toward getting a representative cross section of vehicle and propulsion types. The near, mid, and far term IOC categories were selected to be consistent (with minor changes) with time frame categories reported by NASA/Langley and mostly the same types of vehicles were inserted into these categories as was accomplished by NASA/Langley[5] .
The candidate vehicle concepts, with their assigned IOC's are shown in Figure 5.

Concept/ Propulsion Cycle	Takeoff/ Landing	Stages	IOC
Beta II, Turbojet/Ramjet booster + SSME powered orbiter	HTHL	2	2005
Subsonic Air-Launched Turboramjet second stage + rocket powered orbiter	HTHL	AL + 2	2005
Near-Term AMLS, SSME derived rockets	VTHL	2	2005
AN-225/Interim Hotol, Air Launched, RD-120 derived Rocket	HTHL	AL +1	2010
SSTO AMLS, Variable Mixture Ratio Staged Combustion Rocket	VTHL	1	2010
Delta Clipper, Dual-Position Bell Expander Cycle Rocket with Deep Throttle	VTVL	1	2010
Aerospike VTHL, Expander Aerospike Rocket	VTHL	1	2010
Sled-Launched HTHL, Lightweight SSME	HTHL	1	2010
Turboramjet/Scramjet Booster + Rocket Orbiter	HTHL	2	2010
ALES, Air-Liquefaction/Separation/ Collection Booster + Rocket Orbiter	HTHL	2	2010
Sled-Launched Air-turborocket	HTHL	1	2010
Hotol-K, Sled-Launched precooled Air-turborocket	HTHL	1	2010
RBCC, LOX Ejector/Ramjet/Scramjet/ Rocket	VTHL	1	2015
Airbreathing (slush) Low-Speed System/Ramjet/Scramjet	HTHL	1	2015
RBCC (slush), LOX Ejector/Ramjet/ Scramjet/Rocket	VTHL	1	2015

Figure 5: Candidate Vehicle Concepts/Timeframes

There was not a clear consensus on the timeframes for some of the vehicle concepts. The near-term sub-group considered two of their concepts (the

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Delta Clipper VTVL SSTO rocket and the interim HOTOL subsonic air-launched rocket) to be mid-term and handed them off to the mid-term sub-group. Others considered those and many of the mid-term concepts more consistent with IOC's of 2000-2005.

6.2.1 Near Term

As discussed above, the near-term sub-group deferred two vehicle concepts to the mid-term sub-group due to the perception of high development risks for those vehicles for an IOC of 2005. The remaining near-term concepts were ranked essentially equal. These include:

a) The Beta II TSTO/HTHL with air-breathing (turbojets/ramjets) first stage and all-rocket second stage.

b) A three-stage HTHL with first stage an uprated existing subsonic airplane, turbojet/ramjet second stage with a tandem mounted all rocket third stage.

c) TSTO/VTHL with all rocket first and second stage and no crossfeed in order to enhance safety/reliability.

Recommended technologies for the selected near term concepts are:

- Robust, near state-of-the-art high temperature, lightweight materials and low risk mass fractions.

- Non-rocket-based combined cycle propulsion, such as integral turbojet/ramjet engines, which could benefit both HTHL options.

6.2.2 Mid Term

For the mid-term (IOC 2010), nine vehicle concepts were assessed. The rankings resulted in two distinct groupings. The five all-rocket-powered vehicles (four SSTO's and an air-launched all-rocket vehicle) scored much better than the four airbreathing concepts. The primary discriminators in order of importance were:

1) Operational readiness and support costs
2) Procurement costs
3) Technology maturity

The airbreathing concepts did not fare well because of the lack of confidence in the maturity of the propulsion technology. Additionally, the

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perception of poor operational efficiency of the two-stage concepts reduced their scores.

Recommended technologies for the mid-term concepts were:

- Design for efficient operations:
    Health management systems
    Reliable cryogenic turbomachinery
    Minimized support complexity (Reduce the standing
        army)

- Rocket engine improvements:
    Higher sea level thrust/weight
    Improved trajectory I_{sp} from dual-position or
        aerospike nozzles
    Vacuum deep throttling to eliminate need for orbital
        maneuvering engine
    Sea level deep throttling for pre-lift-off throttle-up
        and vertical landing

6.2.3   Far Term

The far-term sub-group assessed three vehicles: two RBCC SSTO VTHLs, one fueled by liquid hydrogen, the other by slush hydrogen; and a HTHL non-rocket-based combined cycle SSTO fueled by slush hydrogen. No clear discriminations were made among these options.

A far term (IOC 2015) finding was that RBCC propulsion system benefits for SSTO are not clear. More depth of study is required to show benefits relative to the all-rocket mid-term SSTO options. However, clear discriminators in favor of RBCC powered SSTO vehicles do appear to exist such as:

- Ascent cross range to enhance launch window access capability

- Powered go-around capability for improved safety

- Actively cooled structures for enhanced re-entry cross range

- Hypersonic cruise spin-off potential

A fundamental issue appears to exist: Can advancing RBCC propulsion system technology for LEO SSTO launch vehicles overcome advancing all-rocket SSTO technology? From the standpoint of safety and reliability the

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answer may be yes; for example, if a RBCC engine allows a safer rocket system. This issue must be addressed in conjunction with the NASP technology development effort.

For the selected far term (IOC 2015) RBCC concepts the following propulsion goals were selected:

- Increased T/W at sea level;

- Reduced complexity;

- Design for efficient operations;

- Improved materials (high temp., low density);

- Improved high end thrust and specific impulse.

6.3 Representative RBCC Vehicle Concepts/Implications

This section examines RBCC propulsion systems as they could be applied to SSTO LEO launch vehicles. A mission profile is suggested, a trajectory analysis is performed, and a representative design is presented.

After taking off vertically, the RBCC-powered SSTO vehicle pitches over into a relatively horizontal trajectory to take advantage of its air-entrainment capability (ejector rockets in cowl). After completing its ejector rocket mode, typically at about Mach 3, the vehicle flies via its modular ramjet, followed by scramjet power to a high Mach number, such as Mach 15. The forward cowl doors are closed and orbital insertion is accomplished via all-rocket power. Subsequently, the vehicle reenters with the forward cowl doors closed. Following completion of the entry phase, the forward cowl doors are opened, and the fans are used for cruise-back, subsonic loiter and powered landing. Should circumstances dictate a mission abort during ascent, the vehicle can cruise, supersonically and at high altitude, back to its launch site. Its high efficiency fan (powered by a turbojet gas generator in each cowl module) permits this capability.

Representative Design

Work was undertaken at Boeing prior to the workshop to analyze the type of vehicle described above. In order to provide an independent assessment of the RBCC propulsion approach as applied to a SSTO LEO launch vehicle, Boeing chose not to use the configuration published in Air Augmented Rocket Propulsion Concepts, except as a data reference. Boeing selected the

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Recycled Supercharged ScramLACE as the propulsion system based on the high I_{sp} (about 2700 sec) available for the supercharged LACE ejector mode which would reduce required take off weight. It was also decided to make/store LO_2 for the burn to orbit after scramjet shut-down to further reduce this weight. A scramjet shut-down Mach number of 15 was selected due to recent reports of scramjet difficulties in reaching higher Mach numbers with adequate thrust.[6]

A trajectory run using Boeing's OTIS program was accomplished which defined required thrust and specific impulse profiles. The vehicle did not converge to an acceptable thrust/drag profile until a full wrap-around configuration (shown in Figure 6) was adopted. The trajectory then showed a marginal positive thrust "pinch point" (thrust versus drag) at Mach 15, indicating that a lower scramjet termination Mach number should probably be implemented. This was not accomplished due to lack of time.

Figure 6 also shows a representative engine module for the RBCC propulsion concept described above. This figure shows most of the main propulsion related features. Twenty of these modules, sized to provide a total fan area of 180 sq ft, are mounted around the vehicle's periphery. As shown on Figure 6, the cowl is locally bulged to enclose the relatively small main landing gear enabled by the relatively light take-off weight (464K lbs) of the vehicle. The vehicle contains 245K lbs. of 50-50 slush H_2 and makes 179K lbs. of LO_2 subsequent to the LAIR/ejector phase ending at Mach 3. The vehicle's dry weight is about 190K lbs. and its propellant mass fraction is only about 0.55 at take-off. This mass fraction, although relatively low, would be quite difficult to obtain due to the large capture area driver size (for the weight and drag of the vehicle) and it's heavy full-periphery air-breathing propulsion system.

To provide a sanity check for the Figure 6 concept, it was compared to a conical single stage design by NASA/Langley[7]. The Langley conical air-breather SSTO is somewhat shorter than the Figure 6 concept (about 220 ft. versus 290 ft.) and is also lighter (about 157K lbs. versus 190K lbs.). Since both vehicles have about the same cone angle (similar geometry), small mid body wings, and about the same body platform to wing platform ratio, it is permissible to compare them on the basis of dry weight to body length ratio for a preliminary consistency check. For the Figure 6 concept, this ratio is 190K lbs./290 ft. or 655 lbs./ft. For the Langley concept this ratio is 157K lbs./220 ft. or 714 lbs./ft. These values are within 9% of each other indicating similar analysis results and a slightly higher technology level for the Figure 6 approach (each foot of body length averages 9% less weight). This is primarily due to a presumably higher efficiency propulsion

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system, i.e., one which includes a supercharger fan for flyback, loiter and powered landing purposes.
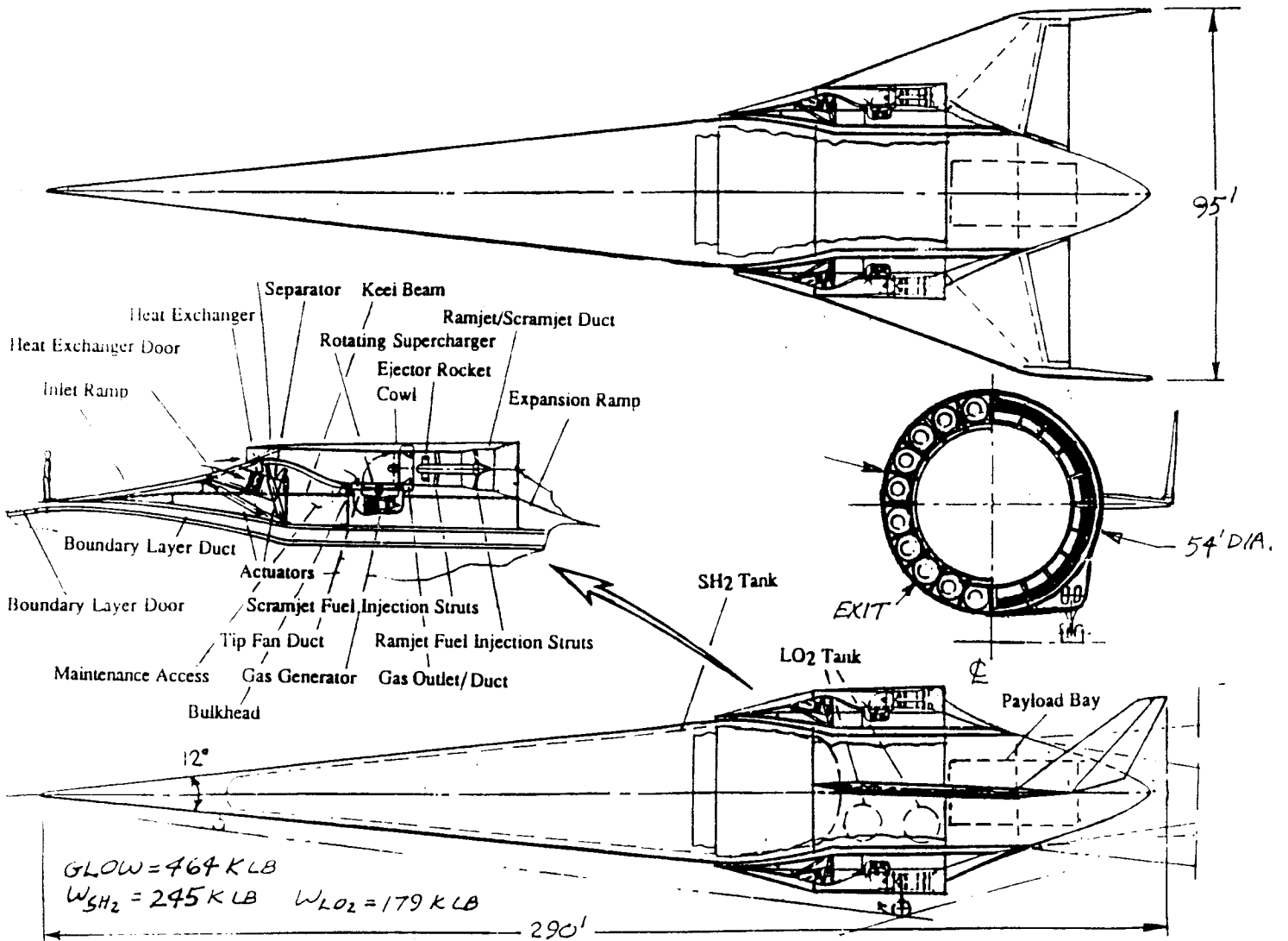
Figure 6: Representative Design

Separator   Keel Beam
Heat Exchanger
Heat Exchanger Door
Inlet Ramp
Rotating Supercharger
Ramjet/Scramjet Duct
Ejector Rocket
Cowl
Expansion Ramp
Boundary Layer Duct
Actuators
Boundary Layer Door
Scramjet Fuel Injection Struts
Tip Fan Duct
Ramjet Fuel Injection Struts
Maintenance Access   Gas Generator   Gas Outlet/Duct
Bulkhead

SH2 Tank
LO2 Tank
Payload Bay

54' DIA.
EXIT

95'

12°

$GLOW = 464 K LB$
$W_{SH_2} = 245 K LB$ $W_{LO_2} = 179 K LB$
290'

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6.4   Summary of Key Findings from Group 1

Combined cycle engines can be effectively applied to the booster element of a near term HTHL staged launch vehicle. These combined cycle concepts show a slightly higher overall ranking than TSTO all-rocket vehicles. Two versions of combined cycle engines were considered:

- The rocket-based version appears to be more complex than could be compatible with near-term utilization (involves fan and air-liquefaction subsystems).

- Due to it's higher level of performance and lower level of complexity, the airbreathing-based version (turbojet/ramjet first stage with all-rocket second-stage) is the preferred TSTO near-term concept.

Additionally, Group 1 recommends enhancing the current "Himate" joint NASA/AF study of this type of engine for such a TSTO application. This enhancement, including the addition of applications assessments, could be an affordable way to broaden NASA's Earth-to-Orbit propulsion technology program beyond the realm of pure rocket systems.

In the mid-term, SSTO rocket systems are preferred over airbreathing TSTO or SSTO systems when applied to Earth-to-Orbit transportation. This conclusion was due in part to the lack of technology maturity and relatively high complexity of the airbreathing concepts. Group 1 recognizes the operational benefits of SSTOs, the need to focus on operational efficiency (such as the Delta Clipper SSRT program), and the value of increasing the thrust-to-weight of both rocket and air-breathing propulsion systems.

In the far term, RBCC propulsion systems exhibit potential benefits for SSTO vehicles including: ascent cross range, powered go-around, self-ferry capability, enhanced entry cross range, and hypersonic cruise spin-off.

Finally, extensive RBCC propulsion system studies, conducted in a NASP information-rich environment, are needed to validate RBCC propulsion systems effectiveness when used in conjunction with a SSTO or TSTO vehicle concept. Such studies must be accomplished as soon as possible and their results compared with those for other options (i.e., all-rocket or separate rocket/airbreather, etc.) before starting any major expenditures on RBCC propulsion system technology development.

7.0 Report of Topical Breakout Group 2
Vehicle Integrated RBCC Propulsion System

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7.1   Introduction

Breakout Group 2 was convened to define propulsion technology requirements for RBCC powered launch vehicles. The group defined criteria for the time frame of application to guide in defining technologies to be developed. Component development areas addressed were the inlet, combustor, nozzle, materials, propellant feed systems, cooling/thermal protection, fuels, structures, and sealing/actuation. A study to define concepts using common groundrules and assumptions so that the technologies can be realistically assessed was recommended as an initial step.

7.2   Propulsion System Definition Criteria

Candidate propulsion approaches were measured against the following criteria set to guide selection of the best choices for development:

- Propulsion systems should have an initial operating capability around the year 2015.

- A system should be considered more favorably if it can be applied to a wide variety of generic vehicles and has easily and economically obtained growth potential.

- A propulsion system index of "goodness" should consider superior propulsion system performance, its overall effect on vehicle empty weight (a measure of vehicle cost), and the ease of vehicle/propulsion system integration.

- The overall economics of the vehicle with a particular propulsion system should be considered as well as the development and manufactured cost of a system.

- The relative propulsion system mechanical complexity and its effect on overall vehicle complexity should be considered.

- The proposed propulsion system should have high potential for an "airline" level of reliability, maintainability and operational safety.

- The propulsion system must have the capabilities to provide the vehicle with survivability during an orbit situation.

The applicability of RBCC propulsion systems to TSTO vehicle concepts allows for the evolution of the propulsion system to SSTO capabilities. The

development of inlets, nozzles, etc., for a two-stage system can provide a valuable database for future SSTO vehicles.

7.3 Concept Definition/Assessment

The Vehicle Integrated RBCC Propulsion System team recognized a need to update and extend past studies involving RBCC propulsion and other viable cycles in light of current requirements (missions, cost effectiveness, operability). Many of the past studies date back to the 1960's and thus did not benefit from the more recent emerging technologies such as those resulting from the NASP and other relevant programs. These studies need to be updated using a common set of groundrules and assumptions to properly focus on enabling technology programs in support of advanced launch vehicles.

This recommended study should include the following design options: liquid air systems, slush hydrogen, single stage vs. two stage, horizontal vs. vertical takeoff, turbomachinery systems to enhance low speed performance, cooling concepts/thermal protection systems, and axisymmetric vs. 2D inlet/nozzle configurations. This study is essential to establish the technical and economic feasibility of RBCC propulsion and prioritize the identified technologies.

7.4 Technologies

7.4.1   Inlet

The inlet performance and configuration is totally dependent on the vehicle configuration and flight profile. Initial compression is provided by the vehicle forebody and the angle of attack along the flight path. Converting the forebody flow properties to acceptable conditions for the combustor components provides the criteria for specifying the configuration and configuration variations required to maximize propulsion performance over the operating speed range.

The inlet must capture nearly all of the air processed by the forebody bow shock. Compressed air that is not captured by the inlet shows itself as additive (or spillage) drag. SSTO inlets must undergo geometric changes to capture the processed air from ejector mode through ramjet and scramjet combustor modes. The correct selection of the shock-on-lip Mach number (the flight speed when the forebody bow shock falls directly on the cowl lip) is critical for providing high performance while minimizing the degree of variable geometry required. TSTO applications enable the environment to be divided between two stages of operation. The range of flight

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conditions for each stage inlet is limited to low or high speed conditions only and thus reduces the requirement for inlet variable geometry.

Based on realistic estimates of engine performance over its intended operating range, an inlet capture area characteristic needs to be established. Corresponding throat area requirements can then be identified to provide initial insight into the degree of variable geometry required. These estimates, coupled with the requirement to fully close the inlet for terminal ascent rocket operation and during re-entry provide a basis for inlet design. Inlet performance estimates can then be made for selected configuration concepts, compared to those levels used in the initial engine performance estimates and the process iterated as required. When the aerothermal performance loop has been successfully resolved, the configuration must be weighed, the weights compared to those used in the initial vehicle performance estimates and the process again iterated as required. The technology should be set at the same level for the same payload to the same orbit for pure rocket propulsion to set performance criteria for measuring the advantages for the RBCC propulsion systems over all rocket propulsion..

7.4.2   Combustors

The combustor section of a RBCC propulsion system must be designed to provide high combustion efficiency and maximum energy release. While combustion technology is relatively mature for rocket and ramjet applications, scramjet combustion technology and multimode propulsion operations do not have the same level of maturity. Combustor technology issues and challenges include: fuel injection, mixing and combustion, propulsion mode transitions, and cooling issues.

Due to the multiple operating modes of RBCC propulsion systems, there are concerns about achieving adequate mixture ratios and the ability to deep throttle the injector over the broad operating range. Fuel injection schemes become an issue at speeds greater than Mach 10 because the momentum of the fuel begins to have a strong impact on the achievable thrust. This suggests the use of axial fuel injection.

Maintaining combustion stability through the various modes and mode transitions needs investigation. The effects of staged vs. simultaneous mixing must be addressed. The final issue discussed by the working group was cooling during the combustion process. A particular concern was cooling of the integral rocket ejector.

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Group 2 strongly recommends experimental efforts be made in combustor technology. This experimentation should demonstrate propulsion concepts, and various mixing and injection schemes. It would be desirable to also tie CFD efforts to the experimental effort.

7.4.3   Nozzles

The nozzle development state of the art is mostly limited to research at various NASA and DOD laboratories and the NASP program. A detailed review of these data, including classified data, must be conducted to ascertain the current technology level. Data are particularly limited at Mach numbers above 8, since propulsion wind tunnels are not available, and most data were obtained from shock tunnel experiments. A coefficient of thrust of 0.98 is probably required to achieve the ducted rocket/dual mode ramjet performance goals.   In addition, the high Mach numbers/exoatmospheric rocket expansion process is unique to the RBCC propulsion system concept, and therefore no data is available from the large ramjet/scramjet technology database.

A study needs to be conducted to determine the criticality of the integration of the rocket nozzle with the ramjet/scramjet nozzle. System performance and/or thermal/structural integrity, are issues for this unique integration of two nozzles. Accurate projections of nozzle performance must be available before an accurate assessment of the RBCC propulsion system can be conducted and trade-off analyses with other candidate propulsion systems for LEO vehicles be determined.

7.4.4   Propellant Feed Systems

The prime propellants to be fed are liquid hydrogen, liquid hydrocarbons, and liquid oxygen. The concerns about pumping include definition of pump inlet conditions such as propellant density, flow rates, vapor pressure, inlet pressure, discharge pressure, and the means for supplying the drive gases to the turbine drivers.

Rocket engine feed system databases and background experience are directly applicable. Boost pumps may be desirable to minimize propellant tank pressures thereby minimizing tank and residual tank pressurization gas weight.

A major problem area is meeting the reliability goals. This may lead to parallel operation (which needs to be demonstrated) of multi-turbopumps with "turbopump-out" capability, while keeping the flow rates, pressures

and other specific feed system requirements within the current state of the art.

7.4.5 Cooling/Thermal Protection

Hydrogen has been considered virtually as the only available fuel which may be used as a coolant. However, hydrogen expended by cooling methods such as transpiration and film cooling reduces engine performance, i.e. I_{sp}. Regenerative cooling concepts offer the most promise.

Water has been suggested as a possible coolant. It is a quite suitable transpirant, film coolant, and effective convective coolant in very high heat flux regions. The principles of its application are well understood; specific applications are configuration dependent.

7.4.6 Fuels

System studies demonstrate that the low density of hydrogen, even slush hydrogen, leads to excessively heavy tankage plus insulation. Dual fuels, a storable hydrocarbon or other semi-cryogenic used in conjunction with hydrogen, can improve tankage efficiency. The addition of denser fuels (such as methane) or of metals shirred into hydrogen in modest percentages can increase storage efficiency without excessive loss of gravimetric heating value. The handling, pumping, injection, and cooling effect of slurried fuels requires technology development. In addition, the realization of the gravimetric heating value of slurries or separate non-hydrogen fuels requires technology demonstration.

7.4.7 Structures, Sealing and Actuation

Group 2 evaluated the RBCC propulsion system considering problem areas associated with advanced structures, sealing concepts and actuation requirements. Experience in this area is derived from the NASP propulsion system which is leading the field in the definition of variable geometry for airbreathing SSTO vehicle concepts. The RBCC propulsion system will require variable geometry, advancements in propulsion system static and variable (moveable) structures, hot seals, and actuation systems.

The NASP technology program has made significant progress in this area but is generally tailored to design specific conditions peculiar to NASP. These initial applications are not optimum, nor in a generic design form. There is a need for development of technology and design for RBCC propulsion system applications. The RBCC propulsion system is likely to have more need for complex internal geometry and a need for variable

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geometries. Cooling techniques and active cooling must be defined and incorporated wherever heat loads demand. The seal loads and temperatures, and the need for reliable moveable seals is very important to the efficiency of the RBCC propulsion systems. Actuation and actuator concepts are required for RBCC propulsion system applications.

General structural design methods for both static cooled and uncooled structures, and variable geometry panels must be developed and demonstrated. These methods should build upon and expand demonstrated NASP capabilities.

Seal technology will limit performance, life and operation of RBCC propulsion systems. Group 2 recommends that research continue to refine and develop advanced sealing materials and concepts building upon the capabilities of NASP movable sealing techniques and concepts. Actuation concepts and systems for NASP are limited; therefore, the desire is to keep the system as close to fixed geometry as possible.

7.4.8 Materials For RBCC Propulsion Systems

Group 2 evaluated the materials requirements for the variety of engine cycles under consideration for RBCC propulsion system applications. The working group recognized that the NASP program has initiated and is conducting work in advanced materials for airframe, engine, cryogenic tanks and insulation. Much of the work appears to be concentrated on light weight, high temperature skin materials and cryotankage.

Materials for RBCC propulsion system applications are derived from both cryogenic rocket engine/systems materials of construction, and materials incorporated into or developed by NASP for engine specific applications. RBCC propulsion system requirements are also generally those peculiar to NASP propulsion. As materials are improved and/or developed they will be included in NASP/X-30 applications. Following formation of the NASP Industrial Consortium, National Security Classification was removed from NASP materials development and these data are available for design and application. .

The working group expressed a concern for materials availability in two areas peculiar to RBCC propulsion system applications. The first addressed the broader range of chemical constituents envisioned as products of combustion, differences in the operating cycles of typical RBCC propulsion systems, the increased presence of water vapor within the engine, and the potential for use of by-product water/steam for improved cooling effectiveness. These constituents challenge materials for those more

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complex environments and considerations for multiple reuse require that the aging/fatigue/cyclic characteristics be well defined.

The second area of concern is associated with the use of alternate fuels in RBCC propulsion systems. Higher density hydrocarbon (HC) fuels have been proposed for some applications, and more exotic metallized fuels are also being discussed. The combustion characteristics of hydrocarbon fuels include high radiation heat flux and higher flame temperatures than hydrogen/air. Materials must be defined and fully characterized for these applications.

Generic hypersonics materials technology programs are continuing the development and characterization of materials for broad vehicle and engine applications. Areas of research activities include materials development for cryogenic tankage, Rare-Earth high-temperature materials based on Yttrium and Zirconium alloys, high specific strength materials emphasizing advanced metal matrix composites (AMMC), and structural design methodology with consideration of the thermal interface.

Group 2 recommends the activities be expanded to include additional work in all aspects of high temperature, high strength materials for RBCC combustor and engine system applications. Characterization activities should emphasize compatibility with hydrogen (embrittlement problems), oxidizing effects, and compatibility with water and/or steam. High pressure operation with hydrocarbon (high) luminosity, high flame temperature combustion and various products of combustion should be emphasized.

7.5 Summary of Key Findings from Group 2

1) A systems level study needs to be done to define specific propulsion development plans.

2) Ejector/combustor performance and operability limits are critical. A great deal of experimental work can be done on basic flow processes without (and prior to) a system level study.

3) Rocket-only operation at very high expansion ratios needs extensive performance development because of the non-optimum integration of the rocket into the scramjet duct and the resulting expansion which starts on the combustor walls, passes through the nozzle, and continues on the vehicle aftbody.

4)   The rocket engine will have to operate over a wide range of mixture
     ratios ranging from very fuel rich to very oxidizer rich and over a
     wide range of fuel and oxidizer flow rates. Such flexibility of
     operation has never been developed.

5)   Inlet performance is critically important. Minimizing variable
     geometry and spillage drag (i.e. the selection of shock-on-lip- Mach
     number) are critical. High performance up to at least Mach 15
     appears to be required from a near-constant geometry inlet which
     can be closed at highest speed to allow rocket operation.

8.0 Report of Topical Breakout Group 3
RBCC-Vehicle Design, Development and Testing Definition

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	Mr. John Erdos	GASL
	Mr. Jim French	Pratt & Whitney
	Mr. Scott Halloran	Rocketdyne
	Mr. Paul McConnaughey	NASA/MSFC
	Mr. Ed Tate	NASA/Stennis
	Mr. Steve Wander	NASA/Headquarters
	Mr. John Weidner	NASA/LaRC

8.1 Introduction

Breakout Group 3 identified required critical technology areas for development, assessed needs in the design methods and tools, and addressed ground and flight test facility requirements relative to operations and design certification. The overall goal was to identify steps needed to develop and validate low cost, mission-based vehicle systems focused on the RBCC propulsion concept.

8.2 Mission Impact on RBCC Powered Vehicle Development

An enabling first step in the RBCC vehicle development process is an accurate definition of the vehicle mission, both for nominal and off-nominal conditions. This would include, for example, mission definition requirements for a Single-Stage-to-Orbit (SSTO) or Two-Stage-to-Orbit (TSTO) primary mission and any secondary missions such as ferry, loiter, etc. Mission definition in turn leads to design requirements critical to the vehicle design, development, and testing phase.

Mission definition and the requisite design requirements are manifested through careful initial planning documentation. These descriptions and requirements are documented primarily in a systems requirements definition plan and a program development plan. The program development plan takes the design guidelines called out in the systems requirements document and lays out the system development sequencing required to phase critical technologies and program schedules. Technology availability and/or maturation issues are prioritized in terms of program and schedule requirements.

Planning should include approaches to design validation and system development certification prior to beginning the vehicle design process. This helps in turn to clarify ground and flight testing requirements prior to vehicle IOC. The documentation serves as a precursor to follow-on detailed test and flight operations plans such as ground test, flight envelope expansion, ground and flight operations plans, safety plans, etc.

In an effort to assure maximum costing efficiency, programmatic procurement costing methods should be defined for all phases of vehicle design, development, and test. The overall concept is to exercise and maintain cost control throughout the vehicle development period, seeking out and implementing the most cost effective way to achieve program goals. This would aid in addressing cost reduction measures for technology

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development, engine cycle integration approaches, vehicle operability (elimination of the launch "standing army"), support concepts.

8.3 Design

8.3.1 Conceptual Design

Conceptual Design will be highly dependent on the use of analytical techniques and computers. The computational speeds and costs of today's computer systems should be significantly improved to reduce the time and resources required to perform this segment of the design. Development of more efficient computation techniques is required along with high-speed computer hardware.

8.3.2 Design Methods

Multi-Disciplinary Integration

An RBCC vehicle will be a highly integrated system, requiring the airframe, propulsion system, thermal management system, and vehicle control systems to be designed as a package. This high degree of system integration will in turn require a multi-disciplinary approach to design. A design methodology must be developed which differs from typical aircraft design methods. Traditional engineering design cycle approaches will need to be revised to permit more of a parallel (as opposed to serial) design process. Subsystem interactions must be communicated more effectively and efficiently between the design disciplines to achieve an integrated design. A design methodology which exploits the new integrated design tools (Section 8.3.3) is envisioned. These tools are expected to integrate the design parameters of flight and engine control systems with thermal and structural design parameters. This should lead to design disciplines of a higher integration level. The by-product of this design organization is improved data flow interfaces among engineering organizations. This in turn permits more efficient design processes to be employed which are built around different, and probably fewer, data interfaces.

Design To Fly

Another design methodology which is necessary for RBCC vehicles is one which produces a "Design to Fly" result. Launch vehicles are often criticized as "Design to be Supported" systems. This is viewed as a major source of high launch operation costs. The Design to Fly methodology is envisioned as an approach which results in minimized ground testing and ground processes with a high vehicle utilization rate. This approach would produce

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a system which resembles the so-called "airline-type operations". In practice, this Design to Fly approach translates into a "design-to-cost" approach with the cost parameters restricted to operations (recurring) costs. This restriction is necessary because higher up-front DDT&E costs will be required to produce the results needed for reduced operating costs. A Design to Fly methodology is therefore just a modified version of more common design to cost methods. An examination of successful design to cost methods and identification of recommended modifications is required to develop a new Design to Fly methodology.

8.3.3   Design Tools

Multi-Discipline Design Code

The highly-integrated design of propulsion systems, thermal control systems, and flight control systems which is required of RBCC powered vehicles is a significant engineering challenge. No design tools have been developed which integrate the design parameters of these systems and the relationships among them. A design code which can capture all of these systems parameters for analysis of the integrated design is required to optimize the design at this integrated level.

CFD Code Development and Validation

The design of RBCC powered vehicles is highly dependent on the use of computational fluid dynamics (CFD) codes. CFD codes have experienced tremendous development over the last few years, but continued development is still required for this critical design tool. The calibration of CFD codes is especially important since these analyses will have to provide high speed data not available from traditional wind tunnel testing. The CFD codes must be improved in the areas of: three-dimensional, nose-to-tail geometry modeling; turbulence modeling; boundary layer transition and prediction; and combustion chemistry and kinetics modeling.

Composite Materials Structural Analysis

Structural designers of RBCC powered vehicles will be challenged to provide exceptionally light-weight structures which operate over a severe range of environmental conditions. Vehicle structures will be stressed by combined loads of high dynamic pressures, high temperatures, and high acoustic pressures. Structural analysis tools which can efficiently analyze the combined loads under dynamic flight conditions need to be developed. This is particularly important for composite materials which are new and not fully understood under these combined load conditions. Conditions where

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dissimilar materials are joined is also of particular concern. The design complexities introduced by non-isentropic and non-linear properties of composite materials provides additional requirements on the structural analysis tools.

Flutter Analysis of Hot Structures

Analysis of the combined thermal and aerodynamic flutter loads on vehicle control surfaces is an engineering challenge which requires new analytical tools. The coupling of these loads on an aerosurface can cause design limits to be exceeded during normal flight maneuvers. These loads are determined from the responses of the vehicle's flight control system to the actual flight environment. To properly analyze the control surface loads, a design tool is required which links the dynamics of the flight control system, the dynamics of the vehicle structure (aeroelastic response), and the aeroheating environment. Without such a tool, the vehicle control surfaces will be overdesigned to loads which could have been reduced.

Integrated Controls Performance

Vehicle control systems for RBCC powered vehicles will be required to integrate highly interdependent propulsion systems, thermal control systems, and flight control systems. A design tool which can analyze the dynamics of all these systems and optimize their performance is required. The tool will be required to produce both local, or instantaneous, performance optimizations and global performance optimizations which will be constantly changing as dictated by the vehicle guidance system.

Life Cycle Cost

Aerospace system designs have historically been driven by high performance requirements, usually sacrificing cost goals to achieve the demanded performance. Designers have little data and no tools which permit them to minimize life cycle costs (LCC) during the design process. A design tool which captures the LCC parameters (and data) and integrates these parameters into design trades is needed. This design tool would also provide the key link between design requirements and system cost. This link must be made early in the design process and maintained through design development.

8.3.4 Design Data/Database

A database must be provided to support the system design. Specific information which is required includes atmospheric models which accurately characterize properties at altitudes above approximately 65K ft. Density variations at higher altitudes can have dramatic effects upon RBCC propulsion system performance. Standardized design specifications (such as MIL or NASA) must be revised to cover the operational range to be experienced by the proposed vehicle. As noted in Section 8.3.2, a wide range of materials including composites will be utilized in an RBCC powered vehicle. The mechanical and chemical properties of these materials must be defined for use by the designer. Material compatibility and joining techniques must be specified. In order to integrate system design, a database for the characteristics of the system components must be provided. This includes performance characteristics of the propulsion system components including inlets, injectors, combustors, and nozzles. Additionally, information on fatigue cycles, thermal cycles, and aging for materials and system components must be acquired and made available to the designer for system life cycle analysis.

8.4 Key Technology Issues

8.4.1 Materials and Structures

The key materials/structures issues for RBCC propulsion systems are the usual ones associated with hypersonic flight with the overriding issue being the requirements for light-weight, high strength, high temperature materials with low catalysis for heat transfer reduction and minimal (or protection from) hydrogen embrittlement. Also required are adequate cooling techniques and technology (materials/fabrication technology, structural concepts). Such cooling techniques could include one or more of the following: backside regenerative, refurbishable ablators, film and transpiration injection. The latter has been determined, from recent tests, to be especially efficacious in shock-boundary layer interaction regions. Additional issues include loads definition (acoustics, thermal, shock, etc.), coatings, fatigue, seals and maintainability.

8.4.2 Subsystems and Controls

As in the materials/structures, the subsystem and avionics issue for RBCC propulsion systems are similar to those usually associated with hypersonic flight utilizing cryogenic fluids. The subsystems issues include: cryogenic turbopumps, with zero-net-positive-suction-head pumping and deep throttling; hydrogen (or slush hydrogen) propellant management; and high

temperatures actuators/valves. Controls issues include vehicle health management, GNC, and communication including blackout.

8.4.3   RBCC Propulsion Systems

There are an almost bewildering array of possible combinations of airbreathing and rocket propulsion systems. The particular system(s) which have the best mix of capability, operability and cost have yet to be determined. Such determinations, if they are to be meaningful, require the resolution of a myriad of technology issues in the areas of propulsion, materials and structures, subsystems and integrated controls/avionics, many of which are common to most if not all of the possible combinations.

Among the most critical questions for an RBCC powered SSTO is the performance of the scramjet airbreathing component at high speeds (9 < M < 16). Scramjet performance has been measured up to Mach 8 but for many reasons, mentioned subsequently herein, scramjet performance is expected to degrade with increasing Mach number at a rate greater than has been conventionally assumed for previous (existing) system studies of RBCC propulsion concepts. A major workshop was held at NASA-Langley in July of 1991 which was specifically aimed at, and resulted in, numerous performance enhancement approaches for high Mach number air breathing propulsion. It is essential that a realistic high Mach number scramjet performance be determined and utilized in further SSTO RBCC powered systems studies and technology be developed to enhance this performance.

Aside from the high Mach number scramjet performance issue the other critical RBCC propulsion system performance and operability issues include feasibility of an oblique detonation wave scramjet for the high Mach number (especially for TSTO), possible problems with (combined) rocket combustion chamber instability and control thereof, enhancement of ejector and combustor mixing rates, air liquefaction subsystem performance and optimization, ramjet thermal choke stability, cycle integration and mode transition, and the feasibility of the "disappearing fan" turbocharger.

8.4.4   Rocket Mode Operation

Issues related to rocket mode operation of the RBCC propulsion systems center on transition from scramjet operation to the rocket mode of operation. Closing the scramjet inlet for transition to the rocket mode will result in a rocket combustion chamber geometry and injector design that will be outside the current rocket database. Issues associated with this include combustion stability, injector plume interaction, acoustic environments in the inlet and diffuser region after inlet closure, the control of O/F ratios

during inlet closure while maintaining vehicle thrust, and most importantly, combustion chamber pressures, temperatures, and heat fluxes as a result of the rocket mode relative to the scramjet mode.

The latter issue is that in the scramjet mode, low chamber pressures (10s of psi vs. 100s) and lower temperature (low O/F ratios) results in lower heat fluxes and chamber/nozzle cooling requirements relative to rocket engine operation. This high-risk transition is affected by downstream pressures as a result of injector plume interaction and high O/F ratios, and may require active cooling techniques more efficient than regenerative film cooling techniques. Also, as likely scramjet combustion chamber designs are nearly rectilinear, combustion stability modes for the rocket mode may exist that would not exist in the scramjet mode. Conventional methods for stability control (baffles and Helmholtz cavities) would be difficult to implement as mode dependent retrofits. With closure of the inlet, another cavity upstream of the injectors, not normally present in rocket engines, is available for acoustic activity. Control of O/F ratios during inlet closure will be critical as thrust level and benign chamber and nozzle environments must be maintained during mode transition.

Methodology to assess these risks include component testing and extensive flow and thermal analysis. A key design challenge is the optimization of the combustion chamber for both scramjet and rocket mode operations. In this analysis, it is assumed that the ejector/injector system will be used to deliver LOX in the rocket mode.

8.4.5 High Mach Number Scramjet Performance

The performance level of the scramjet at high Mach numbers is the most critical aspect of airbreathing performance in terms of enhancing overall RBCC system performance, given that 2/3 of the total energy to orbit is input to the vehicle above Mach 12. Unfortunately component losses at these speeds are on the rise, while overall scramjet I_{sp} is becoming more sensitive to flow path losses. This higher sensitivity to losses results from the fact that the energy within the airstream becomes much larger than the energy added by the fuel, so that net thrust becomes a small percentage of gross thrust. Most losses act on the flow path airstream so that net thrust and specific impulse can be lost very quickly. The result is a critical need to identify high Mach number performance levels, and to find ways to optimize that performance.

To address high Mach number scramjet performance, the total flowpath must be considered, from the forebody leading edge to the aftbody trailing

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edge. Losses start on the vehicle forebody in terms of skin friction and boundary layer growth. The forebody must be shaped to delay transition from laminar to turbulent flow in order to minimize friction drag and boundary layer thickness, while providing a uniform flow at the propulsion modules. Wave drag and skin friction continues through the internal inlet, with the added complexity of strong shock/boundary layer interactions and boundary layer separation control. The combustor adds additional opportunities for losses and approaches for performance enhancement. Skin friction and heat transfer must be treated, and could benefit from techniques such as mass addition, ablative surfaces, and transverse cavities. The integral rocket is an added feature of the RBCC application, and must work with fuel injection schemes to enhance mixing and overall combustor nozzle integrated performance. Issues associated with nozzle performance include: dissociation losses, thrust direction and balance of the vehicle, and flow uniformity associated with the combustor and inlet flow process. Performance enhancement techniques which should be pursued include favorable wave interaction, jet vortex generators for separation control, mixing enhancement, fuel heating and parallel injection, and catalytic nozzle recombination.

8.4.6 Cycle Integration/Mode Transition

A cycle integration involves operating more than one engine cycle within a single flowpath, or dual flowpaths using common components such as the inlet and nozzle. Specific problem areas will be a function of the particular cycles under study, and could be as simple as an air-augmented rocket, or as complicated as a Recycled Supercharged ScramLace. Challenges include designing around transients/instabilities that could occur, as well as performance optimization in the presence of a multi-cycle engine shape. Rocket to ramjet and ramjet to scramjet mode transitions have been experimentally demonstrated.

8.4.7 Manufacturing

Robust, reliable, cost effective hardware requires capable manufacturing technologies. The three elements of this area are: fabrication processes, quality control methodology, and production cost estimation. Development of fabrication technology should focus on key elements of the engine and airframe including: engine coolant panels and leading edges, seals, and advanced fiber-reinforced materials. The coolant panels and leading edges comprise the majority of the engine and airframe structure exposed to high heat flux environments. These surfaces are critical to both system performance and safety. Techniques for channel forming, face sheet attachment, and coating application must be developed that are optimized

for maximum quality and minimum cost. Seals are also critical for engine and airframe integrity. Designs developed from seal technology programs will require fabrication in various shapes and sizes. Manufacturing processes that can replicate these parts in the required forms will be important to the operational success of the seal systems.

Many advanced, high temperature materials under consideration are based on fiber reinforced composites. While insertion and alignment of the fibers are essential to the demonstration of the materials at laboratory scale, similar processes must be developed for production scale to ensure the viability of these materials for vehicle applications.

Quality control methodologies can be grouped into two classes: off-line and on-line methods. Off-line methods seek to design quality into the manufactured parts through the application of modern quality practices such as Taguchi Methods and continuous process improvement. On-line methods focus on inspection of the manufactured part. While modern quality approaches tend to de-emphasize the use of on-line methods, key assemblies such as coolant panels and liquid air system heat exchangers contain many thousands of material bonds, and demand extreme reliability. Non-destructive examination (NDE) methods customized to these assemblies will be a vital ingredient to their operational success.

Production cost estimation methodologies will ensure that individual parts and systems are designed for minimum life cycle cost. Formulation of these methodologies must commence at the earliest phases of structural design, and evolve through the preliminary and detail design stages. In this way, these methods can help guide the selection of materials, structural concepts, and manufacturing.

8.5   Development Facilities

8.5.1   Ground Test Facilities

Testing of RBCC propulsion systems is fundamentally different than testing of pure rocket systems in that use of wind tunnel facilities is imperative. Furthermore, the size of RBCC systems and the test requirements stretch the capabilities of current and contemplated (or contemplatable) wind tunnels and static test facilities.

Wind Tunnels

The required wind tunnel facilities can be divided into two categories:

(a) subscale and/or short duration (pulse type) facilities for research and component technology development.

(b) fullscale, long duration (1 second to 1 minute) facilities for flight-type engine modules.

A number of existing facilities cover the Mach 0-8 adequately for subscale engines and direct connect combustor tests. These typically provide run time in the 10's of seconds to minutes range. No new facility requirement has been identified for research and component technology development for the Mach 0-8 range.

A high priority requirement exists for near term research and component technology development test facilities in the Mach 8 to 18 (minimum) range. These short test duration pulse facilities need real gas capability, (i.e., true total enthalpy and true total pressure capability with chemically correct (or acceptable) test gas composition) capability to provide true temperature hydrogen fuel and LOX augumentation capability. Existing facilities (in the U.S.) include: the Calspan shock tunnels; the free piston driver shock tunnel, T5, at California Institute of Tech; NASA'S Hypulse (expansion tube) facility at GASL; and NASA's combustion driven shock tunnel at the Ames Research Center. The Calspan shock tunnel currently provides Mach 10 capability and on-going upgrades should yield Mach 12-14. The Ames shock tunnel provides comparable capability. T5 offers Mach 12 to 18 capability, but with significant test gas dissociation, as well as operating and optical instrumentation limitations due to melting/oxidation of the tube and nozzle walls. The Hypulse facility offers Mach 13-20 capability with clean air and low dissociation, but with marginally low pressures for combustion research and limited model scale.

Potential upgrades to provide the required near term test capabilities include addition of a free piston driver to the Hypulse facility to provide necessary pressure capability and acceptable model scale. The estimated cost for this upgrade is $4 M. Completion of the RHYFL shock tunnel (large scale version of T5) is also desirable. Its estimated cost is $20M.

Another high priority requirement exists for near term upgrades to existing large scale, long duration, clean air facilities for engine development tests in the Mach 0-8 range. These include the on-going modifications to the 8 foot

HTT tunnel at NASA Langley and proposed upgrades to the ASTF and APTU tunnels at Arnold Engineering Development Center.

Finally, a requirement exists for large scale, long duration, real gas facilities for engine development tests in the Mach 8 to 18 range. The only known facility with suitable capabilities in the Mach 10-12 range is the Piston Gasdynamic Unit (PGU) tunnel at TSNIIMASH in Russia. Options here include adapting the PGU technology to a new facility (using the RHYFL hardware, for example) and extending the technology to higher enthalpy and pressure requirements. However, this will entail development of thermal and oxidation protection methods for the nozzle throat and acceptance of gas dissociation in the Mach 14-18 range. The cost of such a facility is about $50 M, if the RHYFL hardware is used. The other option is development of a new class of facilities (started in the 1970's) involving two-stage energizing of the test gas. The first stage uses conventional technology, e.g., an arc-heated wind tunnel, to accelerate the flow to supersonic speeds without incurring the extreme throat heating or dissociation/recombination chemistry problems associated with the high hypersonic conditions. A second stage acts on the supersonic flow using MHD technology, e.g., to further accelerate the flow to the required hypersonic conditions. The cost of this type facility is probably on the order of $250 M. The third option is a very large free-piston driver expansion tube, but this will involve a cost-test time trade that may put the test time requirement at unaffordable levels.

Static Test

Large static test stands of the type required for RBCC do not currently exist. These are:

(a) a large scale system component stand, for fuel tanks with heat loads simulating the flight environment, for example.

(b) a long duration, full operating range, cryogenic turbopump test stand

Instrumentation

The need for the further development of ground test instrumentation is recognized. Prominent among these is the requirement to measure thrust (directly) in pulse-type facilities. Recently developed optical instrumentation, e.g. PLIF, have succeeded in pulse facilities (Hypulse, e.g.) due to the ease of optical access. However, while feasible in long duration facilities, the windows have proven intrusive due to film cooling

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requirements. More work is clearly needed in this and other ground test facility instrumentation areas.

8.5.2   Flight Tests/Evaluation/Certification

The propulsion system technical development issues can be addressed in specialized flight testing utilizing existing and near-term test beds. These test bed vehicles would be powered by their existing propulsion systems with test engine subsystems and test rigs mounted on board. This approach is similar to that planned for NASA's hypersonic research engine (HRE) with the X-15. These vehicles cover the flight regimes from subsonic for the B-747 Shuttle Carrier Aircraft (SCA) and the NB-52 to supersonic for the SR-71 to hypersonic with the ICBM boosters, the space shuttle and X-30 NASP.

The SCA and NB-52 have carrier strongback capability now. The SR-71 has been used as a supersonic carrier previously, and a top-mounted carrier system is currently in development to address external burning. The space shuttle is the only existing hypersonic, recoverable vehicle available today. ICBM boosters are a potential resource that may be very economical as systems are decommissioned. However, carrier systems and recovery techniques must be developed.

The trade with ground test facilities must be made for low speed systems. Flight testing can in most cases provided a realistic environment in terms of ambient turbulence, humidity, cross winds, etc. that may provide a superior testing approach even at higher per test costs.

The SR-71 is perhaps the most useful test vehicle, but ground test facilities exist in that supersonic speed range. The SR-71 is an aging aircraft system; therefore, it is important to perform a near-term evaluation of its usefulness before the existing small fleet is totally decommissioned.

The Pegasus/Swerve vehicle has not been flown and is still in the development phase, but is planned as a hypersonic flight test system. It may be relatively straight forward to adapt specific RBCC technical issue experiments to this system in the planning stages. However, this is a relatively small system which would limit its use.

Vehicle drop tests can be used to develop glide-back and landing data using subscale models. These models can be initially unpowered or powered with gas turbine engines for safety and flexibility. This would be an adaptation of the approach used for the space shuttle drop tests which were full-scale, unpowered tests. The Soviet Buran drop testing was conducted with a

powered orbiter (gas turbines) to improve safety and flexibility. Drop testing of a SSTO system would most logically be subscale for the vehicles being considered, but full scale drop testing could likely be performed on both stages of TSTO vehicles.

8.6   Validation

8.6.1   Ground Tests

The following ground testing requirements have been identified for a generic RBCC type vehicle:

a)   Subsystem Performance Validation

b)   Vehicle Structural Validation

c)   Launch Site Validation

Details of these requirements are presented in the following sections.

Subsystems

Launch site ground testing for subsystem performance validation will be required on all new flight vehicles. The purpose of this testing is to uncover and correct any and all defects in the vehicle prior to its acceptance into the flight program. Testing should be conducted on component, subsystem, and vehicle levels. The final phase of the subsystem ground testing program will be the Flight Readiness Firing of the RBCC propulsion system.

Launch site and/or component test stand ground testing will be required for all software, hardware and/or propulsion system LRU changes made to any flight vehicle. The purpose of this "green run" testing is to verify that the new component is defect free and meets all specified requirements.

After installation into the flight vehicle all effected components, subsystems, and systems shall be tested to verify that the replacement component has not impacted the performance of these associated systems.

The crew escape module, if included in the final RBCC powered vehicle design, will require extensive ground testing. This testing will be conducted at low speed (below Mach 1). Static testing may not be required if other means of escape is provided for the crew prior to launch. Flight

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testing will be required to verify escape module performance up to the maximum subsystem design Mach number.

Structure

Large scale ground testing will be required to validate the structural adequacy of the RBCC vehicle system. These tests will include ground vibration testing, static load testing, and combined systems testing. The structural validation vibration tests must be performed in a vacuum at very high temperature with the propellant tanks filled with cryogenic liquids in order to correctly simulate the vehicle operating environment. It is not known if any current test facility can provide these test conditions.

Launch Site

Dry-runs of all pre and post-flight ground operations and maintenance procedures will be required at the launch site prior to loading cryogenic propellants into the vehicle. The purpose of conducting the dry-runs is to provide training to the operations personnel and to verify that the operations tasks are being performed in a safe and efficient manner. Required procedure changes will be identified, incorporated and re-verified prior to completing the dry-run check out phase.

Special attention will be required with regards to the problems associated with the use of cryogenic propellants in a RBCC powered vehicle. This is particularly true with regards to the use of liquid (or slush) hydrogen. The three basic concerns associated with the LH_2 are fire, explosion and the formation of LAIR. Hydrogen fires give off very little visible light and therefore are very dangerous to personnel working around the vehicle. Hydrogen and air form an explosive mixture over a very wide range of mixture ratios. Detection of small amounts of gaseous hydrogen requires the use of special instruments. The third problem associated with the use of LH_2 is the formation of liquid air (LAIR). The concerns associated with LAIR are essentially the same as those with liquid oxygen.

After completion of the dry-run checkout phase of launch site ground testing, the vehicle can be loaded with propellant in preparation for the powered phase of the ground testing program. This will include static thrust tests of the vehicle propulsion system followed by low speed and high speed taxing tests.

8.6.2   Flight Tests

Prior to the start of vehicle testing, certain test approaches will need to be analyzed to determine whether ground testing or flight testing is the most cost effective method for certification. A complete set of criteria will need to be defined as a basis for evaluating and certifying the vehicle. The range requirements for the vehicle will be determined which will allow tracking, telemetry, and data relay to base sites and facilities to be determined and established. Sites and facilities for recovery and locations for aborted mission landings will also be established. Real time man-in-loop simulation will be conducted before and during the flight testing period to provide familiarity with the system. Software tools for real-time analysis of flight tests will need to be developed and implemented before tests are conducted. Instrumentation of the vehicle will need to be accomplished using sensors, devices, methods, and attachment schemes compatible with the extreme conditions encountered in flight. These might include non-intrusive methods such as electron beam and other optical techniques as well as high temperature strain gauges and other intrusive probes. Low speed flight testing will begin with an air launched approach and landing for a horizontal landing vehicle, or a low altitude hover and land for a VTOVL.

After these initial stages of testing the vehicle will continue to expand the flight envelope until it achieves its nominal operating specifications at which time it will be considered at its initial operating conditions.

Two major issues during flight testing will be instrument system calibration and hot gas containment. Previous hypersonic vehicles such as the shuttle and the X-15 have had problems in this area. The seals on this vehicle will need to be thoroughly tested during the flight tests to ensure the sealing issues have been properly dealt with. From the initiation of flight testing through IOC, ongoing work will be conducted in correlating the flight test data with the ground test data.

8.7   Advanced Technology Issues

8.7.1   Feasibility of the Oblique Detonation Wave Engine (ODWE)

Studies at NASA/Ames and GASL have indicated that an oblique detonation wave/shock assisted combustion scramjet engine may have significantly higher performance than a "conventional" diffusive burning scramjet for Mach numbers greater 13. The reasons for the increased performance include lower inlet and combustor losses (heat transfer, shear, weight,

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cooling requirement, etc.) obtained via fuel injection into and mixing within the vehicle forebody.

Preliminary numerical studies indicate that the oblique shock provides stable combustion. The issues associated with this propulsion device include stabilization of the oblique (combustion-assisting) wave, fuel injection and premixing (without excessive preignition) in the forebody shock layer, the apparent lack of an applicable experimental data base in the M > 13 speed range, and preliminary systems studies of TSTO devices utilizing this as a second stage propulsive device. Previous propulsion devices of this type were studied at lower speeds only (generally M < 8).

An analysis of the ODWE was accomplished by Dr. Charles Lindley in review of a claim that the thermodynamic performance of an ODWE exceeded that of a conventional scramjet. His verbatim comments follow:

> "The two supporting papers avoided the complexities of real gas analysis by assuming an ideal gas with a gamma of 1.4, a reasonable simplification for ballpark work. But this was compared with real gas performance for a diffusive burning ramjet and exceeded it at higher Mach numbers. If I recalculate the performance of the diffusive burning ramjet with ideal gas assumptions, this engine was better than the OWDE.
>
> Another flaw in the real gas analysis of the references was that the effect of injected hydrogen fuel on Mach number was ignored. To react on passage through the detonation wave, the hydrogen must already be premixed there, and probably even before one earlier compression shock. Stoichiometric hydrogen/air increases the sonic velocity by 15 to 20 per cent: Thus reducing the Mach number entering the last shock and the detonation wave is reduced thereby greatly reducing the available pressure ratio.
>
> Another problem with some of these analysis is that the exact spatial relation assumed between detonation wave pressure rise and combustion heat addition is not spelled out by the analyst. He probably assumes, by default, that the pressure rise is completed first. If the heat addition occurs after the pressure rise we get a relatively good performance level. If it occurs before the pressure rise, the performance level is terrible. If the two occur simultaneously, there must be a performance penalty. Since pressure rise, temperature rise, entropy rise and reaction kinetics all involve energetic collisions that occur in a few mean free paths

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of the molecule, it seems to me that the reaction must start within the shock thickness. What do the analyses assume?

Before we invest heavily in experimental work on the ODWE, it seems that we should be clear on the performance that is possible. This can be done by analysis with carefully defined conditions and a consistent set of groundrules. One experiment that might be justified is a detonation tube test to determine the relationship of pressure rise and heat addition at appropriate conditions.

Even if there is no hope of a performance gain from ODWE, there may still be other reasons for attempting an ODWE design, such as reduced cowling length, weight and cooling loads. But if we begin the effort looking for non existing performance gains, we will waste our time and money chasing the wrong goals."

Dr. Lindley recommended dropping this concept from the findings until careful fundamental analyses and perhaps shock tube tests to determine what can be expected from this advanced technology are performed.

8.7.2 Scramjet Thermal Choke Control

Mission performance necessitates an engine configuration biased toward the high Mach number scramjet shape. Therefore, the ramjet mode must operate within that shape.

When operating the engines in the mid-speed ramjet mode a thermal choke is required, which forces an upstream terminal shock system that drives the flow subsonic. Thus fuel addition and a resulting thermal choke must be contained within the high speed diverging nozzle section. Issues would be heat addition and thermal choke control in a diverging area, and the resulting downstream nozzle expansion process. Upstream, the terminal shock system must be driven close to the inlet throat within the high-speed constant area combustor section, allowing a high back pressure to be established by the downstream combustion process without unstarting the inlet. In addition, conditions at the inlet throat in terms of Mach number and distortion will influence the pressure rise across the terminal shock, and thus effect overall pressure rise and resulting ramjet performance.

8.7.3 Ejector Mixing Enhancement

The ejector operates on the principle of mixing between two streams of gas and the associated length to mix constitutes a performance loss in terms of drag, weight, etc. This loss can be minimized and performance improved

via efficient mixing enhancement techniques. A plethora of mixing enhancement approaches are available including: wave interactions, set-up and excitation of discrete instabilities associated with turbulent shear flows, and longitudinal vortices including bursting and increased turbulence of the fuel exit flow. These approaches need to be understood, evaluated, optimized, and perhaps combined for the ejector case.

8.7.4 Liquid Air System Development

The liquid air system consists of the following components: heat exchangers, inlet, dehumidification system, control system, leak detection system, and possibly a LAIR separator. Heat exchanger configuration and frontal area are critical design parameters since the volume of this system has a significant impact on vehicle structure and closure weight. The dehumidification system is essential to the practical application of the liquid air system. This system requires both moisture detection and removal.

The critical issue in the area of structures and materials is the development of lightweight, leak-free, cost effective tubing designs and joining techniques. Shortfalls in this area will negate system feasibility.

Testing and validation requirements include structural proof articles, static and wind tunnel testing of both sub and full scale systems, as well as flight testing on carrier aircraft. These tests require liquid hydrogen supplied at 500 psia to avoid two-phase flow effects. Flight testing will validate the operation of the entire system under atmospheric operating conditions. Inlet and liquid air system response to density perturbations, acceleration, vibration, and attitude change can be uniquely simulated with flight testing. Recommended are long duration subsonic testing on the NB-52 aircraft, and short duration supersonic testing on the SR-71 aircraft. The latter test will validate system operation in the presence of inlet unstart.

8.8 Summary of Key Findings from Group 3

Key findings in the technology deficiencies centered on the scramjet engine cycle and scramjet-rocket integration. The primary scramjet concern is on performance at high Mach numbers in the Mach 8 to 16 regime. Inadequate ground test facilities above Mach 8 for correct simulation of proper engine size and flow/operating conditions and a lack of flight tests has resulted in scramjet development lag. This includes validating component performance and evaluating performance loss mechanisms such as skin friction, flow field distortion, chemical kinetics effects, and heat transfer.

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Additionally, the optimum scramjet cycle has to be determined between the diffusive burning and the oblique detonation wave-type concepts. Forebody boundary layer, shock and flow control must be understood and refined. Thermal choke control for the integrated ramjet-scramjet cycle needs to be better understood. Fuel injection and combustion mixing enhancements, component interaction and mode transition, and cooling techniques must be investigated and optimized. The performance potential of the liquid air subsystem to generate oxidant "on the fly" must be further explored. This includes issues in systems, and structures and materials such as the development of lightweight, leak free tubing; dehumidifiers and heat exchangers; inlets; control systems; etc.

Propulsion system integration of the airbreathing scramjet with the rocket needs major development emphasis. This includes such things as the configuration dissimilarity between airbreather and rocket, large differences in operating conditions and the transition/stability between those states, and the optimization techniques for such a combined system.

Advanced lightweight, high strength, high temperature materials are needed for both the engine and the airframe. Adequate cooling techniques are required to insure material survivability and material integrity. This includes materials, structural, and fabrication issues to resolve. Other materials issues needing attention include surface catalysis and oxidation, coatings and thermal protection materials, and cryogenic hydrogen embrittlement and other material effects.

Design methodology database development and tool validation is already underway, but needs a lot more development. New multi-disciplinary design methods and tools are needed to tackle the highly integrated nature of these vehicles and their systems, and the interactive effects influencing flight operation. These design "tools" include such things as computational fluid dynamics analysis codes, composite materials structural analysis techniques, hot structures flutter analysis, integrated controls performance, and life cycle codes. These tools must be validated through a combination of ground and flight tests. Design databases and specifications must be built up to aid in the design development and certification process. As an integral part of the total design process, manufacturing and fabrication methodologies must be developed. This includes the fabrication process, quality control methodology, and production cost estimation techniques.

Ground test facilities that provide large scale, long duration testing for engines in the Mach 8 to 18 regime do not currently exist and require extensive development. This includes the ability to properly simulate real gas conditions with the correct air chemistry, true enthalpy, accurate fuel

temperatures, LOX augmentation capability, and the proper pressure levels. Existing lower speed facilities need to be upgraded to handle large scale, combined cycle engines. Large static test stands do not currently exist for the engines nor the subsystems and components such as propellant tanks, turbopumps, etc. Static engine test stands and test techniques for the integrated engine system must be developed. Further development of advanced instrumentation and diagnostic equipment is needed, especially non-intrusive techniques and direct thrust measurement systems for pulse facilities.

The entire flight test infrastructure must be developed to test and certify the full, integrated vehicle system. This includes launch site ground and systems test facilities, maintenance and servicing facilities, and mission control and range tracking facilities. Sites and facilities for vehicle recovery and mission aborts must be established. A large lag exists in the vehicle flight instrumentation system technology area. Efficient, compact, lightweight systems must be developed that can operate in the hostile flight environment of the vehicle mission envelope. Non-intrusive techniques; hot environment capabilities; non-aircraft system redundant, distributed system concepts, etc. must be developed.

9.0 Report of Topical Breakout Group #4
Spaceflight Fleet Applications and Operations

Group Leaders:	Mr. David Froning	Consultant
	Dr. Charles Lindley	Aerospace Corp.
Working Group:	Mr. Wendell Childs	Teledyne Brown
	Mr. Bob Cooper	Rocketdyne
	Mr. Charles Eldred	NASA/LaRC
	Mr. Sol Gorland	NASA/LeRC
	Mr. Russell Rhodes	NASA/KSC
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9.1 Introduction

Breakout Group 4 traced the life-cycle of an RBCC powered vehicle from its testing phase through certification and to its operation phase. The group formulated test approaches, designed a certification process, developed an operations scenario, and discussed life cycle costs (LCC).

9.2 Role of Ground and Flight Testing

9.2.1 Ground Testing

Sustained hypersonic operating conditions above a Mach number of 8 cannot be produced in ground test facilities. The upper end of the test envelope, LEO velocities and altitudes, must be explored with large scale flight test vehicles. Therefore, the advanced research phase will merge with the DDT&E phase to a greater extent than has been experienced in any aircraft or rocket vehicle system to date.

Experience has established the experimental value of "streamtube" engine test rigs. This approach uses modular building block engine elements to provide valid comparative performance data quite economically. Streamtube engines can be constructed in boilerplate configurations to explore various duct geometries, subsystem and component design alternatives, combustion dynamic phenomena, etc., under varying operating conditions.

These tests can be conducted in established test facilities using both direct-connect and free-jet test configurations. The direct-connect alternative allows the engine operation to be investigated separately from inlet conditions. Inlet systems can be separately tested and the engine and inlet system integrated into a free-jet test facility. Existing test facilities can be used to evaluate streamtube configuration engines up to Mach numbers of 8. Facilities currently under construction will be able to evaluate configurations up to a Mach number of 12 (See Section 8.5).

9.2.2 Flight Testing

The use of the modular streamtube engine approach for exploratory investigations of engines of this type is usually cost beneficial primarily due to boilerplate construction. As information is gained by the streamtube program, and questions are resolved, the test rig is modified. In the situation where the propulsion system can be completely tested in ground facilities, the DDT&E program can be carried out with heavy reliance on ground testing. This is not the case with RBCC propulsion systems designed

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to propel vehicles to LEO since the higher velocities and altitudes can not be duplicated in ground facilities.

This leads to two basically different alternatives for the RBCC propulsion system program. The first alternative is to implement a flight test program with test vehicles developed specifically for the purpose of obtaining information in the higher speed flight regimes for the RBCC subscale engine program. This approach has the weakness that it cannot provide the flight environment near LEO.

The second alternative is to consider the research findings of the NASP/X-30 program. This vehicle may provide a testbed, if it has orbital or near-orbital capability, that could explore the entire operating envelope of RBCC propulsion systems. This approach is similar to that proposed by NASA/Langley Research Center in the HRE program, where investigators sought to use the X-15 vehicle as a testbed. However, the termination of the X-15 program prevented such a flight test program from being carried out. This same approach might be implemented using the Shuttle (STS) Orbiter.

If the X-30 or STS Orbiter options cannot be implemented, a subscale flight test program involving two types of vehicles is recommended. The first vehicle type would consist of expendable, or partially recoverable, vehicles to investigate scramjet operation up to a Mach number of 15 and the initial portion of all-rocket mode. This vehicle would be boosted by an expendable rocket to hypersonic flight conditions. The propulsion subsystem could be recoverable. This vehicle is referred to as the Hypersonic Propulsion Test Vehicle (HPTV).

The second flight test vehicle would increase the number of subsystems provided in the test article to more closely emulate the full RBCC powered SSTO vehicle. This would include lifting surfaces and aerodynamic controls. This vehicle, substantially larger than the HPTV, would initially use self-powered takeoff and landing for lower flight speed regimes followed by expendable rocket boost to achieve higher airbreathing flight termination velocity. This vehicle is referred to as the Self Powered Unmanned Vehicle (SPUV).

The HPTV and SPUV flight test vehicle investigations would be integrated with ground test operations. All three of these efforts may be integrated into the initial portions of the DDT&E program leading to the full-scale RBCC powered SSTO vehicle system.

The initial focus of the flight test program would be on the rocket-boosted HPTV. This concept has precedents such as the rocket-boosted ramjet X-7 vehicle. Similar tests were planned but not implemented by Marquardt and General Electric for other scramjets. The primary objective of the HPTV is to conduct testing in those regimes which cannot be explored in ground test facilities. Ramjet and scramjet performance will be derived both from internal on board recorded instrumentation and from external vehicle tracking station measurements. Recovery, and possible reuse, of the HPTV may be quite important since telemetry transmission of data may not be practical due to plasma-sheath radio blackout effects.

Following the HPTV program, the SPUV program would be closely coordinated with the ground test program as well as with the initial portion of the DDT&E program leading to the full scale vehicle. There would be a progressive increase in the final end-of-powered-flight velocity until near LEO conditions are approached. At the same time, SPUV could provide a testbed for DDT&E subsystem hardware designs.

9.3   Technology and Hardware Development

A subscale RBCC propulsion development ground and flight test program must be carried out to provide the basis for beginning the DDT&E phase of an RBCC powered vehicle program. The following sections contains a plan for propulsion system development originally taken out of Air Augmented Rocket Propulsion Concepts.

9.3.1   Directed Component Technology

Schedule: Years 1 to 3 (3 years)

Scope: Individual subsystems and component research and technology efforts are undertaken as required to achieve performance and weight goals for the full-scale engine (at IOC). Engine design and analysis work is pursued in parallel and provides overall engine system performance characterization.

Facilities: This work will be performed using existing ground test facilities available to the engine contractor and subcontractors in most cases. If new facilities are necessary, they must be expedited at program startup.

Principal Output: Achieves and demonstrates subsystem/component technology readiness to enable full-scale development to proceed on all subsystems.

Breakdown of Subsystems/Components:

- Engine controls, instrumentation and integration

- Ejector Primary Rocket Subsystem
  Combustor/nozzle assemblies (2)
  Turbopumps and drive gas generators
  Valves, piping and structure
  Ramjet fuel injection provisions
  Scramjet fuel injection provisions
  Subsystems controls, instrumentation and integration

- Mixer/Diffuser/Combustor/Nozzle
  Regeneratively-cooled duct, centerbody and web structure
  Fuel injectors and retraction provision
  Pumps and drives
  Controls, instrumentation and integration

- Vehicle interface
  Structures
  Electrical and instrumentation connections
  Fluid connections

9.3.2   Subscale Engine Demonstration

Schedule: Years 1-1/2 to 3 1/2 (2 years)

Scope: At a selected scaled down size (to be heavily influenced by test facility capabilities), several versions of both boiler-plate and semi-flightweight subscale engines are fabricated and tested. Both ground-and-flight-test facilities support this effort. Each mode is explored over its applicable flight-speed range. At least one subscale engine will be capable of all modes and will be so tested.

Facilities: Subsonic, supersonic, and hypersonic ground-test facilities, both Government and contractor operated, will be utilized as required. In recognition of the present upper flight-speed simulation limitations (of about Mach 7-8) a hypersonic flight-test vehicle is to be developed and utilized. This could range from a simple solid-rocket boosted vehicle to the new X-30 research aircraft. Utilization of the Space Shuttle system is another possibility.

Principal Output: Demonstrates and validates overall engine design capabilities and achievable levels of performance at the selected scale.

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Provides a direct development tool for the full-scale engine effort which overlaps the subscale program. Directly supports flight-test phase.

Preliminary Set of Hardware Builds:

- Ramjet/Scramjet test unit

- Rocket test unit

- All-mode test unit (ground test)

- All-mode test unit (flight test)

9.3.3   Component and Subsystems Demonstration (Full Scale)

Schedule: Years 3 to 4 1/2 (1-1/2 years)

Scope: All engine subsystems and components are developed as engineering prototypes, and subsequently as production-type items, and tested over the applicable operating range as subsystems. Interfaces are simulated by facility operations as necessary (flight testing, generally speaking is not applicable at this stage).

Facilities: To extent ground-test facilities are available, emphasis will be on full subsystem evaluations. Otherwise, critical components will be separately evaluated. If necessary, individual full-scale elements will be tested (e.g., individual combustor fuel injection struts).

Principal Output: Enables the full-scale Ground Demonstration Engine program element to be implemented in a short time and at an acceptable level of technical risk. Similarly, this activity supports the Pre-Flight-Readiness-Test, First Flight, and Qualification Engine efforts by making available continuously improving hardware.

9.3.4   Subscale Flight Testing

Schedule: Years 4 to 6 (3 years)

Scope: An appropriate set of subscale engine flight test vehicles (e.g., HPTV and SPUV) will be developed and operated to explore and document propulsion system operation outside the flight regime provided by ground test facilities, with overlap for correlation purposes. Flight type engine test

hardware is derived from the earlier "Subscale Engine Demonstration" (Section 9.3.2).

Facilities: In addition to the test vehicles to be used in the conduct of this activity, an appropriate flight test operations facility is needed (e.g., EAFB, NASA-KSC).

Principal Output: Experimental assessment and verification of propulsion system performance and operations in flight regimes which cannot be effectively simulated in ground-test facilities. Other engineering aspects of the overall advanced vehicle system under development may be explored and validated by use of the same or similar flight-test vehicle. The data obtained in the context of a flight-test vehicle can be on an installed basis. Thus, vital engine/vehicle integration aspects can be quantified (e.g., further exhaust expansion on the vehicle aft-end).

Suggested Flight-test Regimes of Interest:

- Hypersonic flight - Mach 6 to 15, 60 to 150 Kft. altitude

- Hypersonic flight - Mach 12 to 15 to near-orbital speed, 110 to 180 Kft altitude
- Space environment - above 200 Kft altitude

9.3.5 Full Scale Ground Demonstration Engine

Schedule: Years 4-1/2 to 6 (1-1/2 years)

Scope: Several builds of the prototype full-scale engine are ground tested at sea-level static and (to the extent supportable by available facilities) over the operating envelope. Both direct connect and, as appropriate to inlet selection and development status, free-jet tested. These highly instrumented systems will be made up of the components and subsystems deriving from the previous 1-1/2 years effort. Although the engine may not be entirely flightweight, it will closely approach the production engine configuration and overall functions.

Note: In view of ground test facility limitations, and the engine size, the entire operating envelope can only be explored and demonstrated in the later developmental flight testing activity.

Facilities: This program element will make maximal use of available ground test facilities as noted. New and otherwise modified facilities will be needed in all probability. These will continue to serve during the subsequent PFRT and Qualification program elements.

Principal Output: Experimentally determined design improvements and production prototype detailed configuration definition, plus the completion and proofing of ground test facilities for the remainder of the development program.

Anticipated Testing Regimes:

- Sea-level static (initially emphasized)

- Subsonic flight speeds (sea-level and altitude)

- Transonic flight speeds (altitude)

- Supersonic flight speeds (altitude)

- Hypersonic flight speeds (altitude)

- Space environment

9.3.6   Prototype Subsystems Development

Schedule: Years 6 to 7-1/2 (1-1/2 years)

Scope: Production prototypes of all subsystems and critical components are designed, fabricated and tested in preparation for overall production prototype engine development to follow. This effort proceeds directly from the component and subsystem full-scale demonstration effort, and runs parallel with the ground demonstration program element, from which direct design-impacting feedback is received. This effort will encompass complete specification/configuration management documentation and control, and the establishment of production tooling requirements.

Facilities: Ground-test facilities capable of documenting and validating the resulting production prototype subsystems will be required, as well as basic production facilities for the developmental hardware involved. Contractor, subcontractor and vendor administrative arrangements will be formulated to establish the overall span of facility resources for the remainder of the development and acquisition program.

Principal Output: Production prototypes, followed by production items for all engine subsystems. This program element is the key lead-in activity in support of the subsequent production engine development phase.

9.3.7   Production Engine Development and Prototype Fabrication

Schedule: Year 7 to 8-1/2 (2-1/2 years)

Scope: Initially yielding production prototype engines for test and evaluation operations (leading to PFRT and Qualification systems), this program element sees the completion of overall engine development activities. It is directly followed by engine production commencing the acquisition/procurement phase of system life cycle operations. It is directly supported by the preceding prototype subsystem development phase.

Facilities: Engine assembly and subsystem fabrication facilities are required to support this program element as well as the full-production phase to follow. Developmental facilities involved are largely those to support the PFRT and Qualification programs.

Principal Output: Productions prototype engine systems, including hardware to be evaluated in meeting PFRT and Qualification goals, as well as first-flight engines for delivery to the associated vehicle contractor's facilities.

Estimated Number of Engines through Qualification

•	Pre-PFRT test evaluation	2
•	PFRT	5
•	Pre-Qualification	3
•	Qualification	<u>8</u>
	Total	18

9.3.8   Preliminary Flight Rating Test (PFRT) and Qualification Program

Schedule: PFRT: Year 7-1/2+ (5 months)
.Qualification: Year 8 (8 months)

Scope: PFRT processing of several production prototype engines assure a competent, low risk first flight capability by suitable "spot-checking" of performance and operations across the operating envelope within the capabilities of round-test facilities. Upon successful completion of PFRT, the engine type is released for final vehicle/engine integration and initial flight testing.

The Qualification process is substantially more detailed and involves several times the test of PFRT. Here the engine is checked through testing for total specification adherence, again within the capabilities of available ground test facilities. The Qualification process is to be completed in the developmental flight test sequence following PFRT completion (to make the engines available for this.

Facilities: Qualification follows PFRT in the same set of facilities, spanning the ground-testable envelope of the engine.

Principal Output:
PFRT: flightworthy engines for the development flight test phase (not the IOC systems).

Qualification: complete specification adherence demonstration which permits engine production to be initiated with a "finalized" product.

9.3.9 Vehicle/Engine Integration and Development Flight Testing

Schedule: Years 7-1/2 to 10-1/2 (3 years)

Scope: In this phase, the vehicle/engine engineering liaison process moves to the hardware stage as the prototype vehicles are physically mated with the propulsion systems evolving from the production engine development activity. With the completion of PFRT, first flight vehicle engines are delivered for installation and overall vehicle system ground testing proceeds toward the first-flight milestone. Developmental flight testing completes the qualification process by exercising the engines over their overall operating envelope (not feasible through ground-testing alone).

Facilities: Facilities capable of supporting the vehicle development and production activity being presumed, the facility requirement associated with this phase of the program is that of experimental flight test support in the field (likely equates to the equivalent of EAFB, NASA-KSC, et al).

Principal Output: As noted, completion of development flight testing completes the engine qualification process (and other subsystems as well, e.g., avionics, flight control). Its completion marks the milestone, "Development Complete".

<u>Estimated Number of Engines Required to Support Flight Testing:</u>

First flight vehicle	10
Spares	<u>4</u>
Total	14

<u>Engine Production and Initial Operating Capability (IOC)</u>

One and one half years into this activity, engine production begins. This activity must support achieving IOC 2.5 years later. Vehicle production begins 6 months prior to engine production.

9.4   Life Cycle Costs (LCC) Analysis

The LCC of a RBCC propulsion system integrated into an axisymmetric baseline vehicle configuration (similar to the vehicle discussed in Chapter 6) has been developed to provide a baseline to assess the cost merits of using RBCC propulsion technology. The axisymmetric, vertical takeoff vehicle configuration is rocket-like in appearance and propellants, but must be judged from the standpoint of aircraft-like launch operations and support requirements.

This cost exercise uses Cost Estimating Relationships (CERs) to calculate LCC. Cost elements include development, production and operations costs. Reduced operations costs are directly related to the reduction of the launch manpower (standing army) and turnaround time.

9.4.1   RBCC Strawman Vehicle Description

Group 4 investigated conical shaped hydrogen fueled vehicles with wraparound engine modules and inlet strakes and highly swept wings. The combined cycle engines are capable of operation in ejector, ramjet, scramjet and rocket mode with fan subsystem and liquid air subsystem capabilities.

A flight test plan was identified with a number of flights and appropriate schedule. LCC were estimated for the DDT&E, production and operational phases.

The RBCC Strawman vehicle is characterized by a 5° cone half angle and a continuation of the conical shape to the engine area, where the vehicle body is tapered inward toward the aft nozzle. The engines are wrapped around the maximum diameter section of the vehicle and placed between tapered strakes which channel air flow into the engines. The aft body of the vehicle

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serves as a half nozzle for the engines. The strakes change height but not thickness as they traverse the vehicle length.

The RBCC Strawman vehicle was established as a conceptual design concept and provided reference for vehicle shape, dimensions and weight estimations. The cone angle, strake configuration and fuel volume continually changed during the study iteration process. Therefore, the final conceptual design will draw from the sensitivity studies along with technology assessments

9.4.2　　　Applications

The primary function of a cost model is to estimate the LCC for a given vehicle and mission model. The total costs broken down into subsystem costs for analysis require further valid detail costs, which are difficult to obtain. Sensitivities as a function of cost are reliability, vehicle weight, vehicle life, vehicle size, flight rate, facilities, manpower, IOC date, complexity factors, stand down time, etc.

9.4.3　　　Cost Model Inputs

The following four types of inputs are usually required for a LCC model:

- Complexity factors

- Vehicle design characteristics

- Annual flight rate (mission model)

- Commonalty factors

The outputs from a cost model are only as good as the inputs and it is well to remember that cost models provide an estimate and must be given a "sanity" check by senior subsystem and system personnel.

9.4.4　　　Major Cost Categories

LCC are broken down into the cost categories of DDT&E costs, facilities costs, production costs and operations costs. It should be noted that there are cost models which will breakdown the costs to the subsystem and even the component level. However, these models are expensive to operate and to keep up to date (maintain viable data base) in both manpower and time.

9.4.5 Ground Rules and Assumptions

The following ground rules and assumptions were uses for the RBCC Strawman vehicle:

- FY87 dollars ($1.05^5 = 1.27628$ escalation factor for FY92 dollars),i.e., FY87 dollars X 1.27628 = FY92 dollars.

- Point design vehicle weight

- Structure and engine life (100 flights)

- Engine type (ejector scramjet)

- Stage up reliability with abort (.996)

- Stage down reliability with abort (.996)

- Mission success (.992)

- IOC date (2005)

- DDT&E time period (1997 - 2002)

- Number of test vehicles in DDT&E phase (5)

- Number of production vehicles (7)

- Number of operating bases (2 - ETR and WTR)

9.5 Costs

The similarity between the RBCC subscale engine development program and the NASA/Langley HRE program carried out between 1966 and 1975 provides a basis for cost estimation. The final revised cost estimate for the HRE program.which included flight testing provides the benchmark. The funds expended for engine development were $50 million FY75 dollars ($115 million FY92 dollars). The projected "run out" cost of the completed program with 25 X-15 flights was and additional $125 million FY75 dollars ($287 million FY92 dollars).

In the proposed subscale engine test program, a two to three year program will be required to carry out the ground testing with an additional four

years flight test program. The proposed flight test phase will overlap the initial DDT&E phase for full scale vehicle development.

It is estimated that $215 million FY87 dollars ($274 million FY92 dollars) will be required for the ground test operations. An additional $285 million FY87 dollars ($364 million FY92 dollars) will be required for the flight test program for a total of $500 million FY87 dollars ($638 million FY92 dollars) for this proposed subscale engine program.

9.5.1　　DDT&E Costs

The DDT&E costs are the largest component of the Life Cycle Cost (LCC). This is consistent with the first attempt to put a SSTO manned vehicle into LEO with airbreathing engines. The engineering design and development of the vehicle system will be more than half of the entire DDT&E effort. The simplified ground systems require minimal effort. The flight test hardware is the next largest contributor to DDT&E costs (three flight test vehicles and two structural test vehicles). Ground processing facilities are assumed to be built at WTR and ETR. Production facilities are included in the DDT&E costs. The ground processing facilities account for 84 per cent of the total facility construction costs. The subscale engine testing discussed in section 10.2.1 is necessary prior to entering the vehicle directed DDT&E efforts.

9.5.2　　Production Costs

The propulsion system production costs are about half of the systems production costs. The majority of this can be attributed to the engines with an estimated First Unit Cost (FUC) of $81 million FY92 dollars. This mission model requires seven vehicles which is a low number when compared with aircraft production. Therefore, no learning curve was used to reduce the unit costs.

9.5.3　　Operations Costs

Unlike the operation costs for the STS, this is the smallest element of the LCC. Launch operations represent the manpower for a five day turnaround working one shift per day. Processing in the vehicle system facility consists of several parallel tasks. The payload is integrated in this facility, but prepared off-line. The cost of slush hydrogen is twice the cost of NBP liquid hydrogen used in existing vehicles. Propellant is not a cost driver, i.e. 15 per cent of overall operations costs. Payload loss cost are computed in the cost model as a function of reliability and a cost of $10,000 per pound.

9.5.4 Life Cycle Costs (LCC)

The LCC for the RBCC powered SSTO vehicle are summarized in Figure 7. Note that the DDT&E costs are slightly greater than the production costs for this proposed program due to small production run (seven vehicles).
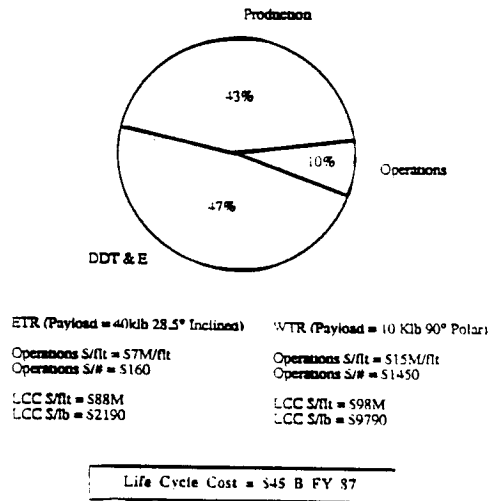
Production

43%

10% Operations

47%

DDT & E

ETR (Payload = 40klb 28.5° Inclined)	VTR (Payload = 10 Klb 90° Polar)
Operations S/flt = S7M/flt	Operations S/flt = S15M/flt
Operations S/# = S160	Operations S/# = S1450
LCC S/flt = S88M	LCC S/flt = S98M
LCC S/lb = S2190	LCC S/lb = S9790

Life Cycle Cost = S45 B FY 87

Figure 7: Vehicle and Engines Life Cycle Cost

9.6 Operational Considerations

Traditionally the high payload costs to LEO are dominated by operational costs. For any new vehicle whose major objective is to reduce payload cost to LEO, it is imperative to involve operations and user representatives in the conceptual design phase, if one expects to reduce the launch staff (standing army) and expensive facilities.

Any new LEO vehicle should contain self-diagnosing and self calibration sensors as well as an autonomous health management system free from ground control.

The vehicle should be designed to minimize propellant preconditioning and propellant detanking constraints. Payload insertion capability should be provided just before launch. If there is more than one vehicle stage, each stage should use independent propellant tanking and detanking lines to eliminate umbilical between stages.

Vehicle flight should not be pilot dependent. If a manned flight is required, an independent crew module should be used for life support and crew safety (abort).

To enhance system reliability and dependability, all dynamic subsystems should be operated below rated capability. This may provide a measure of

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system robustness and may reduce operations costs and may increase flight reliability.

Business considerations must be used to determine necessity for capitol investments at multiple launch or landing sites. To stimulate commercial interest, large fixed costs, large launch staffs (standing army) and expensive facilities must be avoided.

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[5] Eldred, C.H., "Advanced Manned Launch System Studies," RBCC Propulsion Technology Workshop, Huntsville, AL, March 1992.

[6] Billig, F.S., "Research on Supersonic Combustion," AIAA-92-0001, 30th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 1992.

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