Please see attached

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MEMORANDUM FOR PRR (Contractor/In-House Publication)

FROM: PROI (TI) (STINFO)


Moszee, "Liquid Rocket Propulsion – Evolution and Advancements: Rocket-Based Combined Cycle"
AIAA (Public Release)

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Spreadsheets
☑ DTS
Liquid Rocket Propulsion –
Evolution and Advancements

Rocket-Based Combined Cycle

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Edwards AFB, CA
June 25, 1999

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Outline

- Background
- History of RBCC
- Integrated Performance Analysis
- Current Activities
- Future Prospects
<table>
<thead>
<tr>
<th>Cycle Benefits</th>
<th>Benefits derived from <strong>Airbreathing Propulsion</strong></th>
<th>Benefits derived from <strong>Rocket Propulsion</strong></th>
<th>Optimum performance is achieved by combined cycle approach</th>
<th>Synergistically blends rocket and ram/scramjet propulsion technology</th>
<th>Vehicle designer’s options are broadened considerably</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine performance covers a broad operating range</td>
<td>• High specific impulse</td>
<td>• High thrust (acceleration)</td>
<td>• High energy density</td>
<td>• Design experience</td>
<td>• Low vehicle gross weight</td>
</tr>
</tbody>
</table>
RBCC Engine Operating Modes

- Ducted Rocket
  - Low Speeds
  - Mach 0 to 1.5

- Rocket Ramjet
  - Low Mach Numbers
  - Mach 1.5 to 3

- Ramjet
  - Mach 3 to 5

- Scramjet
  - Mach 5 to 10

- Rocket
  - Mach > 10 and/or
  - High Altitude

• Bridges air and space more than any propulsion concept
• Enables low cost DoD and commercial space launch systems
• Provides trans-atmospheric vehicle capability enabling many new missions
RBCC Engine Description
RBCC History

- RBCC engine is **not** a new propulsion cycle
  - Significant work has been accomplished back in the 60’s

- Engine cycle experienced a rebirth in the 90’s
  - Military applications
  - Commercial applications

- Performance and structural challenges of the past will hopefully be solved by incorporating recent technology advancements
  - Improved specific impulse
  - Higher engine thrust-to-weight
  - Efficient thermal management

- Opportunities exist for joint government / industry investments
Hyperjet

Dual-Mode Rocket/Ramjet Engine (1958)
Reached the Flight Demonstration Stage

Rocket Mode Launch

The First RBCC Engine Tested
Rocket Engine Nozzle Ejector (RENE)

RENE Propulsion System (1960)

SIMPLE AIR-AUGMENTED ROCKET
(e.g., RENE-ROCKET ENGINE NOZZLE EJECTOR)

Air-Augmented Rocket Powered Multistage Vehicle

- MIXING/EXPANSION CHAMBER
- ROCKET THRUST CHAMBER CLUSTER (FUEL - RICH)
- NOZZLE
- AIR INLET
Rocket Engine Nozzle Ejector (RENE)

Detailed Hardware View of the LO₂ / RP-1 Water-Cooled Thrust Chamber Assembly Used in the Air-Augmented Cluster

12 Thrust Chamber Cluster at NASA MSFC Test Laboratory
Rocket Engine Nozzle Ejector (RENE)

12 Thrust Chamber Cluster at NASA MSFC Test Laboratory

MSFC Rocket Cluster Firing LO₂ / RP-1, 12x500 lbₜ-thrust, 1000 psi
Inlet Flow Entrainment

- Ejector (primary) rocket provides inlet airflow entrainment (Mach 0-3)
  - Operates on the principle of mixing between two streams of gas
  - Mixer length constitutes a performance loss in terms of drag, weight, etc.
  - Various mixing enhancement techniques have been explored.
  - Additional research in this area is needed to better understand and optimize the cycle.
- Inlet (secondary) airflow provides substantial rocket performance augmentation
  - Induced air mixes and burns with fuel-rich gases from the primary rocket exhaust
  - Improvements occur in both engine thrust and Isp
The Ejector Ramjet Engine

- Extensive RBCC ejector ramjet testing conducted from 1964-68
  - Air Force Aero Propulsion Laboratory (Sponsor)
  - The Marquardt Corporation
  - Explored both ejector and ramjet modes (Mach 0-6 range)

- Subscale “boilerplate” engines built and tested (16-18” dia.)
  - Regeneratively cooled
  - Fixed and variable area throats (translating plug nozzle)
  - Hydrogen / oxygen propellants
  - Hydrogen-peroxide / JP-4 propellants
The Ejector Ramjet Engine

USAF / Marquardt Ejector Ramjet
Subscale Ground-Test Engine (1965)
Hydrogen / Oxygen Propellants
as Initially Configured

USAF / Marquardt Ejector Ramjet
Subscale Ground-Test Engine (1966)
Hydrogen / Oxygen Propellants
The Ejector Ramjet Engine

Ejector Ramjet Engine Under Test in Ejector Mode ($\text{H}_2\text{O}_2$ / JP-4)

Integrating RBCC and LACE

- RBCC was only one of several innovative engine types
  - Interest existed in exploring potential uses of cryogenic hydrogen
  - Various applications were examined in the late 50s, early 60s

- Experimental work included the Liquid Air Cycle Engine (LACE)
  - Practical application of cryogenic hydrogen fuel
  - LAIR served as the rocket oxidizer combusting with hydrogen
  - SLS Engine Isp could Triple that of the ERJ (1300-1400 sec)

- Primary rockets in the RBCC could operate at an O/F = 34:1
  - Offered unprecedented performance for the propulsion community
  - Came with the cost of additional (and often complex) hardware
  - Came with the cost of certain operational complications

- The basic LACE was literally an airbreathing rocket engine
  - Several high performance engine concepts were derived
Liquid Air Cycle Engine

Basic LACE Engineering Test Apparatus

Basic Liquid Air Cycle Engine (LACE)

RBCC LACE Ejector Ramjet (RAMLACE)
Flightweight LACE Concept

- LACE was originated by Marquardt in 1957
  - Charles Lindley and the late Carl Builder were the inventors
  - Requires a series of compact cryohydrogen heat exchangers
  - Operation is constrained by thermal balances and temperature difference
  - Needs far more hydrogen than required for stoichiometric combustion
- LACE remains an attractive option up to speeds in the range of Mach 5-6
  - Performance falls off drastically at higher speeds due to inlet momentum penalties
  - A diverse set of approaches were explored to further enhance performance
The NAS7-377 Study

“A Study of Composite Propulsion Systems for Advanced Launch Vehicle Applications”

- A systematic assessment of the significance and merits of a variety of composite propulsion systems in the post-1975 period
  - Provided a detailed examination of technology ramifications
  - Emphasized critical or pacing technology requirements
  - Successfully “sorted out” and defined the leading contenders

- NASA contract was awarded in 1966 to a Marquardt-led team
  - Rocketdyne’s rocket expertise complemented TMC’s A/B forte
  - Lockheed California provided the hypersonic vehicle design expertise

- Emphasis was on two-stage horizontal takeoff and landing concepts
  - First stage was powered by a range of “composite” A/B - rocket engines
  - Second stage used advanced hydrogen / oxygen rocket propulsion
The NAS7-377 Study

- Study provided for a progressive screening down of engine concepts
  - From original 36 to 12, and finally to 2
  - The analysis and design level of each selection was progressively increased

- The “finalist” engines turned out to be:
  - Supercharged Ejector Ramjet (SERJ) engine (nearer-term technology)
  - ScramLACE (SL) engine (“further out” technology)
NAS7-377 Selected Engines

Supercharged Ejector RamJet

ScramLACE
NAS7-377 Vehicle Concepts

Advanced Rocket System

Cylindrical Body/Wing System

Lifting Body System
Same Methods and Techniques Should be Used to Conduct Integrated Performance Analysis.
• SERJ and SL surpassed the all-rocket and composite cycle comparison cases.
  – Composite cycle propulsion is a strong competitor for advanced launch vehicles.
• NASA elected to support an “extension phase” effort.
  – Marquardt / Rocketdyne / Lockheed team provided further design details.
  – Conducted special studies on points of interest emerging from the basic study
  – All total, a nine volume final report set resulted
Genesis of SERJ
Integrated Performance Analysis

- We can build from what was learned in the past.
  - Methodologies are about the same.
  - Tools have changed since the mid-1960s.
  - Make use of available databases.

- There is a better understanding of the requirements for reusable space transportation.
  - Focus on performance analysis
  - Incorporate broad analytical trade studies

- Design support must be provided by:
  - Propulsion
  - Structures
  - Aerodynamics
  - Aerothermodynamics
  - Mass properties
  - System level optimization
Integrated Performance Analysis

RBCC Propelled SSTO Concept
Airbreathing Engine Performance Profiles

Note: Hydrocarbon fuels offer logistically supportable aircraft-like operations.
Airbreathing Engine Performance Profiles

Note: Hydrocarbon fuels offer logistically supportable aircraft-like operations.
Representative RBCC Flight Profile

SSTO Trajectory Simulation

- Altitude, (ft)
  - 300
  - 250
  - 200
  - 150
  - 100
  - 50
  - 0

- Velocity, (ft/sec)
  - 0
  - 5000
  - 10000
  - 15000
  - 20000
  - 25000
  - 30000

- Key Phases:
  - Ducted Rocket
  - Ram/Scramjet Operation
  - Rocket Augmentation
  - Maximum Dynamic Pressure
  - Controlled Climb
  - Maximum Heat Rate
  - Hohmann Transfer
Payoffs of Combined Cycle Engines

- Lower gross takeoff weight for a given payload

- Improved engine specific impulse
  - Rocket  Isp  455 sec (vacuum)
  - RBCC   Isp  2200 sec (Mach 10)

- Relaxed vehicle mass fraction requirements
  - Rocket  SSTO  0.88 - 0.91
            TSTO  0.85 - 0.86
  - RBCC   SSTO  0.64 - 0.72
            TSTO  0.57 - 0.64

- Increased flight performance and maneuvering capability
  - All inclination flight
  - Longer duration launch window
  - Increased safety (abort options)
Comparison of I* versus Mass Fraction for All-Rocket and RBCC Systems

Graphical portrayal of the modified ideal rocket equation showing characteristic performance and PMF ranges for all-rocket and RBCC propulsion.

Mission: SSTO 100 NMI polar circular

Equivalent effective specific impulse, I*, sec.

NASA RBCC Paper
Two-Stage vs. Single-Stage-To Orbit

- We’re still trading two-stage versus single-stage-to-orbit.

- Conventional wisdom says SSTO least costly.
  - Maintaining one vehicle cheaper than two
  - Vehicle mating operations eliminated
  - Flight operations simplified
  - BUT,
    - Required mass fractions are elusive.
    - Payload bay volume dominated by propellant volume.
    - Weight margins easily exceed payload weight.

- Two stage systems are more forgiving in design.
  - Less dependence on advanced technologies required.
  - Lift-off mass doesn’t go all the way to orbit and back.
  - Less sensitive to weight growth
  - Denser hydrocarbon propellants are attractive.
Each Concept has been Parameterized:

- Propulsion Characteristics
- Vehicle Mass Fractions
- Trajectory
Ascent Trajectory Modeling

\[ \Delta V = \frac{V_f}{V_o} \int \frac{1}{F(V)} \, dV \]

where: 
- \( F(V) \) is the ratio of the actual change in velocity to \( \Delta V \) invested
- \( V_o \) is the initial velocity
- \( V_f \) is the final boost velocity

Total \( \Delta V \) Required to Achieve a Required Boost Velocity

---

Trajectory Models for Various Ascent Profiles

Total Delta Velocity (mps)

- Lifting, Air Breathing to Mach 16
- Lifting, Air Breathing to Mach 12
- Lifting, Air Breathing to Mach 6
- Vertical Takeoff, Ballistic
- Horizontal Takeoff, Ballistic
- Airdrop, or Takeoff, Assisted Launch, Ballistic
Effective Isp and Ascent Profile Modeling

\[ I_{sp} = \frac{\int \frac{1}{F(V)} \, dV}{\int \frac{dV}{F(V)I_{sp}(V)}} \]

where: \( F(V) \) is the ratio of the actual change in velocity to \( \Delta V \) invested
\( V_0 \) is the initial velocity
\( V_f \) is the final boost velocity

- **Airbreathing propulsion assumptions:**
  - All concepts assuming LH\(_2\) fueled Rocket Based Combined Cycle engines of various designs
  - Air Breathing to Mach 16: Assumes an approximate model from NASP
  - Air Breathing to Mach 12: Assumes a model from the Aerojet Strutjet project
  - Air Breathing to Mach 6: Assumes a model from NASP history
  - All concepts assume LH\(_2\) & LOX rocket propulsion at higher Mach numbers

- **Single, or first, stage rocket propulsion assumptions:**
  - Two broad categories assumed:
    - Hydrocarbon & LOX, \( I_{sp} \approx 340 \) sec vac
    - LH\(_2\) & LOX, \( I_{sp} \approx 450 \) sec vac

- **Upper stage propulsion, when applicable**, \( I_{sp} \approx 320 \) sec vac
Vehicle Mass Accounting
Space Lift Concepts

Payload delivered to orbit the key performance “Figure Of Merit” (FOM) for space lift concepts

- Greater than zero means it is feasible
- Relative merit when compared to other concepts
- A key parameter which determines cost

Performance FOM:
Payload Weight to Gross Takeoff Weight Ratio

\[
\frac{M_c}{M_o} = \frac{MR + MF - 1}{MF}
\]

-or-

\[
\frac{M_c}{M_o} = 1 - \left(1 - \frac{1}{MR}\right) - \frac{f}{MP + TW_e}
\]

- Simple mass accounting which captures the key mass contributors
  - Airframe, Engines, Payload & Propellant
- The mass of all concepts are easily parameterized with this accounting

Mass Accounting of the Vehicle Concepts

\[M_o = M_g + M_p + M_e + M_c\]

where:
- \(M_o\) is the mass of the vehicle at takeoff
- \(M_g\) is the dry mass of the vehicle without the engine
- \(M_p\) is the mass of the propellant
- \(M_e\) is the mass of the engines
- \(M_c\) is the mass of the payload

Other Useful Definitions & Relations

\[MR = \frac{M_o - M_p}{M_o} = e^{\frac{\Delta V}{I_{sp90}}}\]

\[MF = \frac{M_p}{M_p + M_e + M_o}\]

\[MP = \frac{M_p}{M_p + M_e}\]

\[MF = \frac{MP(1 - MR)}{(1 - MR) + MP f / TW_e}\]

\[MP = \frac{MF(1 - MR)}{(1 - MR) - MF f / TW_e}\]

where:
- MR is the vehicle mass fraction
- MF is the propellant mass fraction
- MP is the airframe propellant mass fraction
- \(f\) is the vehicle thrust to weight fraction at takeoff
- \(TW_e\) is the engine thrust to weight at takeoff conditions
X-33 Provides a Technology Touch Stone

- For concepts where airframe technology has not been demonstrated, X-33 provides a relative measure of what may be possible.
## Space Lift Concept Comparison
### Payload to Orbit Performance Calculations

| Concept               | \( \Delta V_T \) | \( \Delta V_1 \) | Eff.\( I_{sp} \) | MR\(_T\)/W\(_{Eng} \) | T/W\(_{Veh} \) | MP\(_1 \) | MF\(_1 \) | M\(_1\)/M\(_0 \) | M\(_f\)/M\(_0 \) | \( \Delta V_2 \) | Eff.\( I_{sp} \) | MR\(_2 \) | MF\(_2 \) | M\(_2\)/M\(_1 \) | M\(_c\)/M\(_d\) | M\(_c\)/M\(_0 \) |
|-----------------------|------------------|------------------|-------------------|----------------------|----------------|-------------|-------------|---------------- |----------------|---------------- |---------------- |-------------|-------------|---------------- |-------------|---------------- |-------------|
| RBCC TSTO w/ Store. UStg 11160 | 6340 | 1586 | .666 | 23 | 1 | .75 | .70 | .1302 | .511 | 4820 | 320 | .215 | .85 | .140 | 18.5% | 4.0% |
| RBCC TSTO w/ Cryo UStg 11160 | 6340 | 1586 | .696 | 23 | 1 | .75 | .70 | .1302 | .511 | 4820 | 450 | .335 | .85 | .177 | 55.1% | 10.0% |
| LACE TSTO w/ Store UStg 10116 | 4711 | 983 | .613 | 12 | 1 | .75 | .65 | .2084 | .401 | 5405 | 320 | .178 | .85 | .033 | 5.2% | 1.34% |
| LACE TSTO w/ Cryp Ustg 10116 | 4711 | 983 | .613 | 12 | 1 | .75 | .65 | .2084 | .401 | 5405 | 450 | .294 | .85 | .169 | 26.6% | 6.8% |
| **Launch Assist** | 7250 | 3624 | 320 | .315 | 40 | 1 | .78 | .76 | .2163 | .100 | 3626 | 320 | .315 | .85 | .194 | 8.3% | 1.9% |
| Rocket Recoverable TSTO 9200 | 4600 | 320 | .231 | 70 | 1.2 | .88 | .86 | .1252 | .109 | 4600 | 320 | .231 | .85 | .095 | 7.4% | 1.03% |
| Generic MSP Pop-Up 9200 | 5500 | 426 | .268 | 70 | 1.2 | .83 | .81 | .1717 | .101 | 3700 | 320 | .307 | .85 | .185 | 10.3% | 1.9% |
| Generic Rocket SSTO 9200 | 9200 | 435 | .116 | 70 | 1.15 | .915 | .90* | .0985 | .017 | - | - | - | - | - | 18.3% | 1.7% |
| | | | | | | | | | | | | | | | | (-41.3%)(-8.1%) |
| Generic RBCC SSTO 11160 | 11160 | 730 | .210 | 30* | 1 | .84 | .81* | .1838 | .026 | - | - | - | - | - | 14.2% | 2.6% |
| | | | | | | | | | | | | | | | (-31.6%)(-9.7%) |

* A stated requirement, but not necessarily a demonstrated technology or capability

(##) Estimate from the author's estimate of a achievable technology
- Parametric study of concepts allows “apple-to-apple” comparisons
- Comparison illuminates the potential of each concept
- Emerging propulsion technology offers significant performance improvements
Reusable Military Aerospace Vehicle (RMAV) Study

- Providing an in-depth systems analysis of vehicle concepts designed to accomplish the future requirements for a military spaceplane
  - Focus on TSTO configurations, with various staging Mach numbers
  - Evaluating both all-rocket and combined cycle propulsion options

- Forming multi-disciplinary teams
  - AFRL’s Propulsion (PR), Air Vehicle (VA), Space Vehicle (VS) Directorates
  - Aeronautical Systems Center (ASC)
  - Space and Missile Center (SMC)
  - NASA Research Centers (Langley, Glenn, and MSFC)

- Anchoring vehicle performance levels using nationally accepted codes
  - ENG-92 - APAS - CONSIZ - ROCETS
  - POST - RJPA - RAMSCRAM - Etc.

- Conducting a detailed, iterative synthesis process involving many design parameters and internal variables
  - Including assessment of technology readiness and development schedule
Integrated Performance Analysis

Rocket Engine Performance

Airbreathing Engine Performance

Launch Weight Comparison

Altitude vs Velocity

Creating Analytical Models and Addressing Vehicle Integration Issues For
Trailblazer Project

- Focusing on Technologies to Enable Affordable Access to Space
- Integrating RBCC Propulsion into a Near-Term Demonstrator
  - SSTO VTOHL Configurations
  - Three Different Class Concepts
- Parallel Development of Vehicle and Propulsion Technologies
- Vying to Become an Integral Part of NASA Bantam Program
  - Concept Downselect in 2001
  - Flight Demo in 2007
- Five In-House Test Rigs in Work
  - Subscale Inlet
  - Ejector Rocket
  - Variable Mode Combustor
  - Vehicle Aerodynamics
Airbreathing Launch Vehicle (ABLV) Study

- Study is sponsored by NASA MSFC’s Advanced Reusable Technologies (ART) project
- Cooperative effort by NASA LaRC, Glenn, and MSFC to evaluate a matrix of SSTO concepts for access to space missions
  - 8 HTOHL configurations
  - 4 VTOHL configurations
- Emphasis on RBCC & TBCC propulsion integration and vehicle design resolution
  - Design
  - Performance Analysis / Closure
  - Sensitivities
Advanced Reusable Technologies (ART) Program

- NASA’s Most Aggressive Pursuit of RBCC Engine Technology
- Four Engine Companies Selected (1996)
  - Aerojet
  - Kaiser Marquardt
  - Rocketdyne
  - Pratt & Whitney
- Additional Support Provided By:
  - Pennsylvania State (CFD)
  - Astrox Corp. (Flowpath Analysis)
- Several Subscale Engines Built and Tested at GASL, Focusing On:
  - Performance
  - Mode Transition
- Results Could Lead to Flight Demo.
  - Bantam
  - Future -X

ART is Establishing a Pipeline of Demonstrations that will Facilitate Future RBCC Engine Designs
Future Prospects

- Air Force and NASA recognize RBCC technology may be the key to affordable access to space.

- Today’s engine technology programs are leveraging off of past accomplishments
  - Liquid rocket propulsion is the Foundation to the engine cycle
  - Ejector rocket are very Mature and have a large database
  - Liquid rocket technology advancements are directly applicable to RBCC

- There is a need to better understand overall engine performance
  - Identify performance margins
  - Increase design robustness
  - Build flight-type hardware
  - Characterize engine mode transition

- Many challenges are being addressed in current programs.
Future Prospects

- RBCC technology is rapidly approaching the limit of what can be accomplished through ground testing.

- The next step is the design, fabrication and testing of a lightweight propulsion system
  - Actively cooled composite structures
  - Flight-type propellant delivery system
  - Flight-type engine controls

- For military operations, there is a need for engine analysis and design using hydrocarbon fuels.

- RBCC technology holds the promise of routine access to space
  - Vehicle robustness
  - Increased payload mass fractions