# A CONCEPTUAL DESIGN TOOL FOR RBCC ENGINE PERFORMANCE ANALYSIS

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# A CONCEPTUAL DESIGN TOOL FOR RBCC ENGINE PERFORMANCE ANALYSIS

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## Abstract

Future reusable launch vehicles will depend on new propulsion technologies to lower system operational costs while maintaining adequate performance. Recently, a number of vehicle systems utilizing rocket-based combined-cycle (RBCC) propulsion have been proposed as possible low-cost space launch solutions. Vehicles using RBCC propulsion have the potential to combine the best aspects of airbreathing propulsion (high average Isp) with the best aspects of rocket propulsion (high propellant bulk density and engine T/W). Proper conceptual assessment of each proposed vehicle will require computer-based tools that allow for quick and cheap, yet sufficiently accurate disciplinary analyses. At Georgia Tech, a spreadsheet-based tool has been developed that uses quasi-1D flow analysis with component efficiencies to parametrically model RBCC engine performance in ejector, fan-ramjet, ramjet and pure rocket modes. The technique is similar to an earlier RBCC modeling technique developed by the Marquardt Corporation in the mid-1960's. For a given sea-level static thrust requirement, the current tool generates engine weight and size data, as well as Isp and thrust data vs. altitude and Mach number. The latter is output in tabular form for use in a trajectory optimization program. This paper reviews the current state of the RBCC analysis tool and the effort to upgrade it from a Microsoft Excel spreadsheet to a design-oriented UNIX program in C suitable for integration into a multidisciplinary design optimization (MDO) framework.

## INTRODUCTION

Even before the first successful lunar landing, U.S. engineers were working on advanced propulsion concepts for reusable earth-to-orbit launch vehicles predicated on the use of atmospheric oxygen. One of these concepts, rocket-based combined-cycle propulsion, is currently being revisited by today's vehicle designers. RBCC engines (Figures 1 and 2) combine elements of rocket and airbreathing propulsion into a single, integrated engine capable of multi-mode operation. A landmark study of RBCC propulsion (then called 'composite' propulsion) was conducted in the mid-1960's by the Marquardt Corporation assisted by Lockheed and Rocketdyne and under contract to NASA (Escher 1967). Marquardt's study considered many different RBCC variants for use on a two-stage-to-orbit horizontal liftoff launch vehicle. These variants included supercharged and non-supercharged versions, engines capable of scramjet or only ramjet operation, and liquid air cycle engines. Based on preliminary vehicle performance analysis, the ejector scramjet RBCC engine was shown to be one of the more attractive alternatives. Later work showed the advantages of incorporating a supercharging fan into the engine for operational flexibility and safety (forming a 'supercharged' ejector scramjet, SESJ) (Escher 1995).

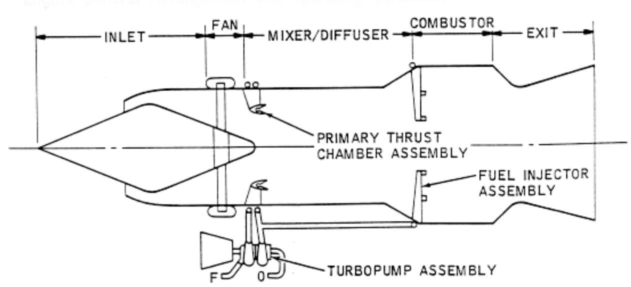


FIGURE 1. Supercharged Ejector Ramjet (SERJ).

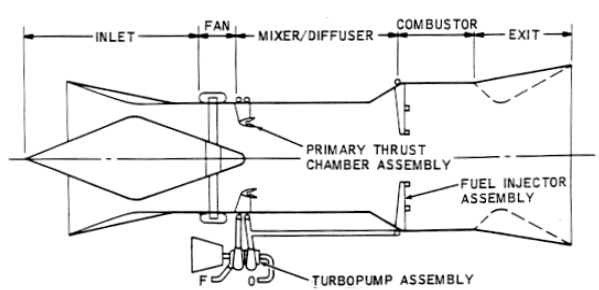


FIGURE 2. Supercharged Ejector Scramjet (SESJ).

Launch vehicles utilizing RBCC engines operate in a number of different propulsive modes. From liftoff to about Mach 2 or 3, the engine operates with rocket primaries ‘on’ in the ejector mode. This is a high thrust, air-augmented rocket mode where 80% - 90% of the thrust is provided by the rocket primaries and the remainder is provided by combusting secondary, entrained air. When the vehicle reaches sufficient velocity, the primaries are shut off and the engine behaves like a ramjet while the vehicle flies along a high dynamic pressure trajectory. On some versions of the engine, the ramjet is actually a dual-mode ramjet/scramjet and the engine transitions to supersonic combustion around Mach 5 or 6. For final acceleration to low earth orbit, the scramjet fuel injectors are shut off and the rocket primaries are restarted, providing 100% of the thrust. This ‘pure-rocket’ mode resembles a very high expansion ratio rocket engine.

Non-supercharged vehicles return to earth on unpowered, gliding reentry trajectories. Supercharged variants have the additional flexibility of powered ‘fan-ramjet’ and ‘fan-only’ modes during flyback and landing operations. Supercharged vehicles can also utilize fan-ramjet mode during ascent between ejector and ramjet modes. However, the fan must be physically removed from the flowpath if the vehicle is to operate in airbreathing modes above Mach 6.

## INITIAL TOOL DEVELOPMENT

To maximize utility, the current RBCC analysis tool is capable of analyzing engines with or without supercharging fans and with or without scramjet modes. The data reported in this paper is for a liquid oxygen-liquid hydrogen supercharged ejector ramjet (SERJ) RBCC engine that was used as a baseline during the tool development. Published data from Marquardt for a $1.11 \times 10^6$ N (250,000 lb) version of the SERJ engine (Escher 1967) was used to provide validation of the current tool during development.

### RBCC Analysis Methodology

Based heavily on the conceptual RBCC analysis technique originated by Marquardt, the current tool uses basic thermodynamic and quasi-1D compressible flow equations (conservation of mass, momentum, and energy) and component efficiencies to determine engine thrust and Isp at various flight conditions. An engine is schematically represented by a series of components (inlet, rocket primary, mixer, etc.) (Figure 3). Numbered ‘stations’ indicate locations where the local flow conditions are calculated. The compressible flow equations are iterated locally at each station to determine pressure, temperature, density, Mach number, velocity, mass flow rate, etc. In some cases, iteration is required between stations, but more typically the solution proceeds sequentially from inlet to nozzle. Initial efficiencies used for each component were based on values derived from Marquardt’s earlier work. These values are user definable.

The station breakdown can be visualized as a series of internal flow problems. The freestream flow (or ‘secondary’ flow) passes through a forebody shock and enters the inlet at station 0. For the current work, the forebody shock was assumed to be generated by a 2-D wedge with a user-definable half angle. Appropriate external compression effects were included at supersonic flight speeds. Internal inlet compression occurs between stations 0 and 2. For this implementation, a simple inlet total pressure recovery schedule vs. Mach number was used in lieu of modeling the actual inlet flow. Internal engine cross sectional areas are user-defined. The primary rockets are located at station 2, just after the optional tip-driven, supercharging fan. To prevent premature combustion of the oxygen in the entrained

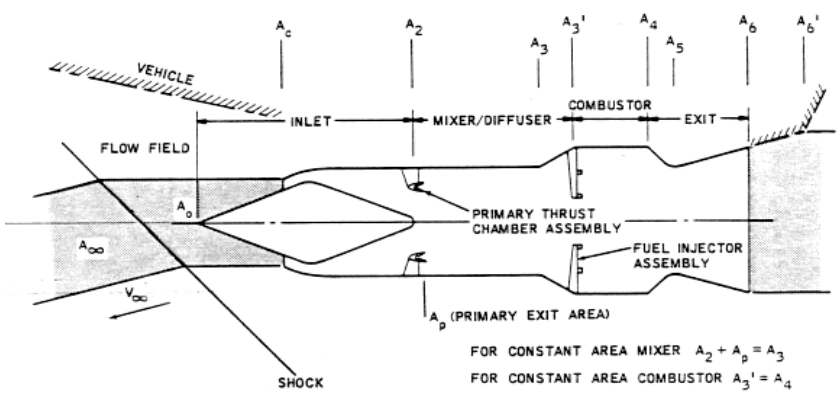


FIGURE 3. Typical RBCC Station Schematic (Escher 1967).

secondary air flow, the rocket primary is typically operated stoichiometrically in ejector mode. From station 2 to 3, the secondary and primary flows are mixed and then diffused as the area expands from station 3 to 3'.

The combined flow enters the combustor at 3' and leaves at 4. Fuel is added in this section as a user-defined fraction of the atmospheric oxygen from the secondary flow — typically stoichiometric. Note that as a consequence, the rate of tanked oxidizer consumption (used only in the rocket primary) in ejector mode is proportional only to the throttle setting, while the rate of fuel consumption also varies with the flight conditions. Energy is released according to the fuel flow rate, the total enthalpy of the fuel, and the efficiency of the combustion process. In the current implementation, both the mixer and the combustor are constant cross sectional area. The flow is physically or thermally choked at station 5 and exits the nozzle as supersonic exhaust. Additional expansion benefits along the aft body are neglected in ejector and ramjet modes, but are included in rocket mode. Engine thrust and Isp are calculated from control volume analysis for the entire inlet-to-nozzle engine (Hill 1965). Engine weight and length parametric sizing equations have been derived from previous Marquardt work (updated to reflect current technology levels).

In the current implementation, the tool does *not* have the ability to calculate scramjet performance. In fact, it can be argued that this simplified analysis methodology cannot accurately treat the complexities of scramjet operation. As a placeholder, scramjet Isp's and thrust coefficients for a wing-cone configuration previously published by researchers at NASA - Langley have been included in the tool (Shaughnessy 1990). This data is currently 'hardwired' into the tool and scaled to provide a smooth transition from ramjet to scramjet operation, but future plans are to develop a scramjet analysis capability suitable for conceptual design.

It is acknowledged that the analysis methodology described here is rather simplified compared to state-of-the-art analysis capabilities. Detailed design will still obviously require complete computational fluid dynamics and complete real gas combustion analyses. However, the intent of this research is to develop a tool appropriate for quick and cheap conceptual-level vehicle evaluation. For that stated purpose, the methodology described has been adequate.

## Spreadsheet Implementation

Initially, the RBCC analysis methodology described above was implemented as a Microsoft Excel spreadsheet running on a Macintosh or PC-class desktop computer. For a given user-defined internal engine geometry and rocket primary mass flow rate, engine performance is determined for a range of flight conditions (altitudes and flight Mach numbers) and operating modes (ejector, ramjet, etc.). A separate sheet is assigned to each operating mode, and each sheet contains 50 - 150 different rows for a thorough mapping of the design space. Each row of each sheet represents a complete, iterated inlet-to-nozzle thrust and Isp solution for one operating mode at a single altitude and Mach number. The altitude and Mach number ranges for each operating mode were determined based on engineering experience and the desire to have some overlap between modes (Table 1). The final engine data is summarized in formatted tabular form for easy transfer to a trajectory optimization program.

TABLE 1. Engine Mode Mach Number and Altitude Ranges.

| ***Engine Mode*** | ***Mach # Range*** | ***Altitude*** |
|---|---|---|
| Ejector | 0.0 - 3.0 | 0 - 25 km (0-80 kft) |
| Fan Ramjet | 2.0 - 4.0 | 9-45 km (30-150 kft) |
| Ramjet | 2.0 - 6.0 | 9-45 km (30-150 kft) |
| Scramjet | 6.0 + | 9-45 km (30-150 kft) |

Although each sheet is an individual mode with different Mach number and altitude ranges, they are all linked by the engine geometry and primary flow rate (except ramjet mode, which has no primary flow rate). All the analysis is therefore dependent on a single set of user inputs, and any changes automatically update the performance of all modes. Typically, a user starts with an engine geometry that fits a desired vehicle and then iteratively determines the rocket primary mass flow rate that results in a required engine thrust at sea-level static conditions. To simplify user input requirements, much of the engine geometry is determined based on a set of internal area ratios (e.g. mixer area/inlet area) derived from Marquardt's earlier work. The user inputs the available engine frontal geometry, or "engine box", dimensions limited by vehicle width and shock-on-lip conditions. The sheet then automatically calculates engine diameter to maximize the number of circular cross-section engines across the vehicle. This fixes the cowl (inlet) areas from which the rest of the engine cross sectional areas are determined using the above area ratios.

## Sample Analysis: TSTO Conceptual Design

To demonstrate and evaluate the new tool, it was used on a two-stage-to-orbit (TSTO) vehicle design project in the graduate Spacecraft and Launch Vehicle Design course at Georgia Tech. The project goal was to develop a TSTO launch vehicle system using a SERJ RBCC-powered booster stage. A reusable upper stage was designed for low-earth-orbit and Space Station missions. An expendable upper stage was also included for geosynchronous transfer orbit missions.

The design environment was truly multi-disciplinary and multi-analysis code. In addition to the RBCC engine tool, contributing analyses included trajectory, aeroheating, aerodynamics, booster and upper stage weights and sizing, and life cycle economic analyses. The RBCC engine tool received target engine thrust and engine box geometry from the booster sizing code. Installed engine thrust-to-weight (T/W) and thrust and Isp tabular data were produced as outputs. The process required repeated, manual execution of the spreadsheet over many vehicle-level iterations. Sample spreadsheet results for the final vehicle design are given in Table 2, Figure 4, and Figure 5. The data is for a final engine in the 2.67 x $10^5$ N (60,000 lb) class at sea level static (SLS) conditions. Five such engines were used on the booster.

TABLE 2. Sample TSTO Booster RBCC Spreadsheet Output.

***Engine Sizing Variables (each engine)***

| | |
|---|---|
| **mp (iterate)** | **58.24 kg/s** |
| A inlet max (Ac) | 1.456 m2 |
| A exit max (Ae) | 2.202 m2 |
| A*inlet/Ac | 0.25 |
| Max. A/B Mach number | 6.0 |
| A* inlet | 0.364 m2 |
| A4 (combustor) | 1.214 m2 |
| A4/A3 | 2.0 |
| A3 (mixer) | 0.607 m2 |
| Combustor fuel enthalpy | 116.3 MJ/kg |
| Fan Po ratio (1 if none) | 1.3 |

***Overall Engine Box Dimensions***

| | |
|---|---|
| max height | 1.372 m |
| max width | 6.809 m |
| forebody angle | 10° |
| best inlet dia | 1.362 m |
| total frontal area | 9.339 m2 |
| frontal area/engine | 1.868 m2 |
| no. of engines | 5 |

***Total Thrust Values (SLS)***

| | |
|---|---|
| Calculated Thrust | 1331.41 kN |
| Thrust Needed (post) | 1331.42 kN |
| Thrust Difference | 0.01 kN |

***Total Engine Weight (all engines) with ramjet only (Engine 11):***

| | |
|---|---|
| Wgt (uninstalled) | 43.06 kN |
| Engine T/W (SLS) | 30.9 |
| Wgt (installed) | 58.50 kN |
| Engine T/W (SLS) | 22.8 |

***with scramjet (Engine 12):***

| | |
|---|---|
| Wgt (uninstalled) | ---------- |
| Engine T/W (SLS) | ---------- |
| Wgt (installed) | --------- |
| Engine T/W (SLS) | --------- |

***Component Efficiencies***

| | |
|---|---|
| eta primary nozzle | 0.980 |
| eta primary combustor | 0.975 |
| eta mixer | 0.900 |
| eta combustor | 0.950 |
| eta nozzle | 0.980 |

***Rocket Primary Values***

| | |
|---|---|
| Primary area ratio | 18 |
| Primary Ae | 0.111 m2 |
| Primary Pc | 13,790 kPa |
| Primary flow enthalpy | 12.9 MJ/kg |
| Primary exit vel. | 4066.03 m/s |

***Engine Lengths (w/o scramjet)***

| | |
|---|---|
| Inlet length | 4.110 m |
| Total engine length | 7.226 m |

***Engine Lengths (w/ scramjet)***

| | |
|---|---|
| Inlet length | ----------- |
| Total engine length | ----------- |

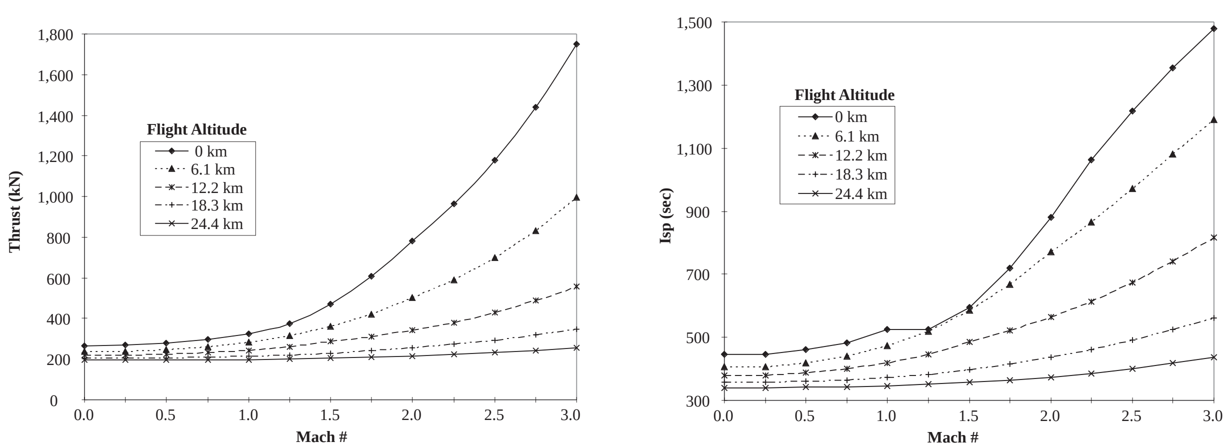


FIGURE 4. Thrust and Isp charts for Ejector Mode Performance.

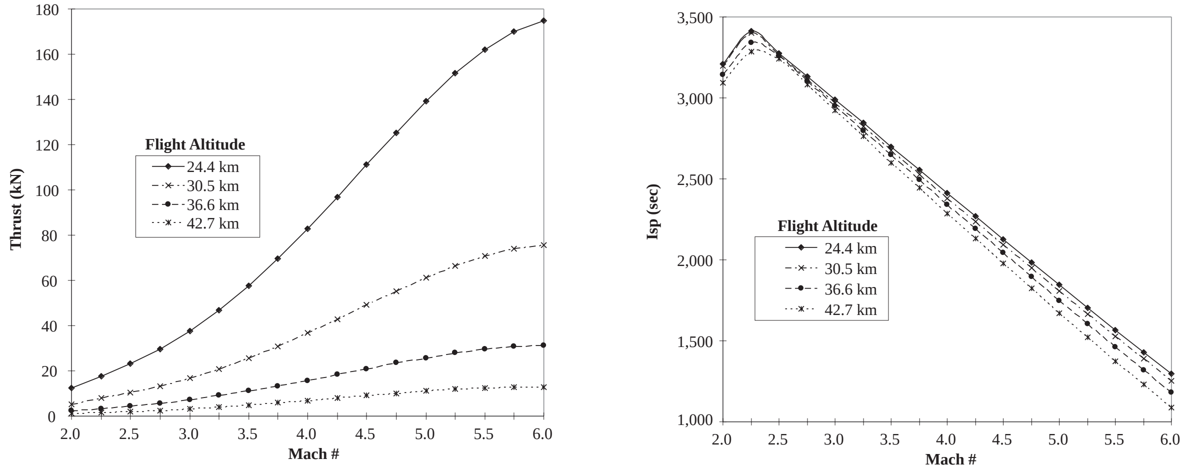


FIGURE 5. Thrust and Isp charts for Ramjet Mode Performance.

## CURRENT PHASE: COMPUTER PROGRAM IN C

Use of the spreadsheet for the TSTO test project was successful. However, after several manual iterations of the design process, the advantages of a more automated, design-oriented approach become obvious. To use the current spreadsheet-based RBCC analysis tool, it was necessary to interactively execute the spreadsheet, save the results as a text file, upload them to a UNIX workstation-class machine for trajectory optimization, and then wait for new target thrust and engine box dimensions to be produced by the booster sizing analysis. The process was repeated several times before the design variables converged. This proved to be quite time consuming during the TSTO study, and demonstrated the need to port the RBCC analysis methodology to an automated, UNIX-based standalone code or subroutine. The next stage, therefore, became the conversion of the Excel tool into such a program.

The conversion of the station equations used in the spreadsheet into C code is currently underway. A subroutine has already been created that determines engine thrust and Isp in ejector, fan-ramjet, or ramjet mode for any user-entered engine geometry, rocket primary mass flow rate, and flight conditions. This subroutine has been linked to an executive program that uses repeated subroutine calls to automatically produce the thrust and Isp tables required for modeling the RBCC *ejector* mode in a trajectory optimization code. Future work will extend the capabilities to automatically generate properly formatted tables for all engine modes. The ultimate goal is to integrate the new tool into a multidisciplinary design optimization (MDO) framework of tightly-integrated disciplinary analysis codes.

## CONCLUSIONS

The RBCC engine is potentially the next important propulsion concept, and the technology is within the grasp of the launch vehicle designers. The spreadsheet version of the RBCC engine performance (and weight prediction) tool created under this research has been successfully applied to the design of a TSTO launch system. Conversion of the tool into a more design-oriented computer program is currently underway and preliminary capabilities have already been demonstrated. This conversion will eliminate the tedious processes of interactive calculations and file uploads and will enable the tool to be integrated into an improved MDO design framework. An improved conceptual-level scramjet analysis component is also planned.

The future of launch vehicle and spacecraft design lies not only the advancement of new technological ideas, but in the concurrent updating of methodologies to reduce cost and design time. If designers are to meet the ambitious cost goals established for new launch vehicles, their design methods must be adjusted accordingly. New methods and tools must allow for a quick, cheap, and efficient exploration of the design options while retaining a sufficient level of analysis accuracy. The authors hope that the RBCC analysis tool will meet those requirements.

## Acknowledgments

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## Nomenclature

### English

A: engine cross sectional area ($m^2$)
A/B: airbreathing
eta: component efficiency
Isp: specific impulse (sec)
mp: rocket primary mass flow rate (kg/sec)
MDO: multidisciplinary design optimization
Pc: rocket primary chamber pressure (kPa)
Po: total (stagnation) pressure (kPa)
RBCC: rocket-based combined-cycle propulsion
SERJ: supercharged ejector ramjet
SESJ: supercharged ejector scramjet
SLS: sea-level static (zero velocity)
T/W: engine thrust-to-weight ratio
TSTO: two-stage-to-orbit
V: velocity (m/s)

### Greek

∞: freestream condition

### Superscripts

*: critical condition (choking)

### Subscripts

Stations:
0: behind forebody shock (engine entrance)
2: mixer at primary (reduced by primary)
3: mixer (constant area)
3': entrance to combustor
4: exit of combustor (constant area)
5: main nozzle throat (choked)
6: main engine nozzle exit (also e)
6': simulated aftbody expansion exit
c: inlet cowl (inlet)
e: exit (also 6 for main nozzle)
p: rocket primary nozzle exit

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