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Component-Level Weight Analysis for RBCC Engines

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ABSTRACT

Rocket-based combined-cycle (RBCC) engines have recently received increased attention for use on advanced, reusable space launch vehicles. By combining conventional rocket and airbreathing operating modes into an integrated unit, they have given designers a middle ground between the high-thrust, low-I_{sp} characteristics of a pure rocket and the low-thrust, high-I_{sp} of pure airbreathers. Engine weight (or thrust-to-weight ratio) is a highly sensitive parameter in the design of advanced reusable launch vehicles. While substantial experience exists with ground-test engines from the 1960's, little parametric data exists to help conceptual designers predict weight for today's advanced technology, flight-weight RBCC engines.

This paper reports a new set of component-level parametric weight estimating equations for advanced RBCC engines. These equations are derived from top-down regression analysis of historical data and include variables to account for advanced technologies and materials. Component weight equations are given as functions of engine geometry, internal pressure, flight modes, etc. Taken together, the equations are used to build up an overall RBCC weight estimation model — WATES. This spreadsheet-based model is not intended to replace a more detailed weight analysis, but rather to assist conceptual vehicle designers in assessing the relative advantages of various engine concepts. Sample RBCC engine weight predictions are given.

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NOMENCLATURE

A_c	inlet or cowl frontal area (sq. inches)
C_f	complexity factor for variable geometry
ERJ	ejector ramjet
ESJ	ejector scramjet
I_{sp}	specific impulse (sec.)
L/D	length-to-diameter ratio
LH2	liquid hydrogen
LOX	liquid oxygen
M_{trans}	transition Mach number to rocket mode
MDC	Mixer-Diffuser-Combustor
P_{int}	internal static design pressure (psia)
PR	fan (total) pressure ratio
RBCC	Rocket-Based Combined-Cycle
SERJ	supercharged ejector ramjet
SESJ	supercharged ejector scramjet
SLS	sea-level static (takeoff condition)
T/W	thrust-to-weight ratio
TAD	Technology Availability Date
TRF	Technology Reduction Factor
V	internal volume of MDC (cubic inches)
WATES	Weight Assessment Tool for Engine Scaling
WBS	Weight Breakdown Structure
WER	Weight Estimating Rlationship
$\dot{W}_p$	rocket primary weight flow rate (lb/s)
$\dot{W}_s$	secondary or inlet weight flow rate (lb/s)
$\dot{W}_{total}$	total or nozzle weight flow rate (lb/s)

INTRODUCTION

RBCC Background

Rocket-based combined-cycle (RBCC) engines represent a synergistic combination of traditional rocket and airbreathing propulsive elements within a single piece of integrated engine hardware. Similar to ramjet and scramjet airbreathing engines, RBCC consists of an inlet, diffuser, combustor, and nozzle to

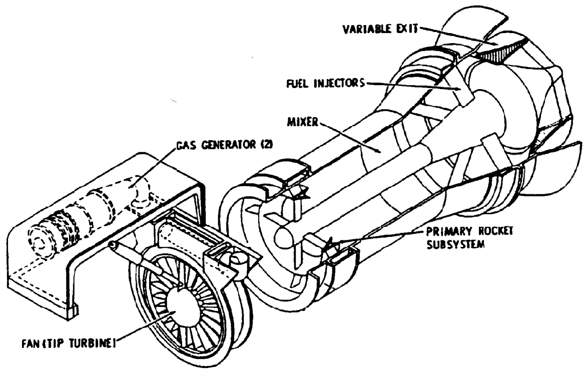

Figure 1 - SERJ RBCC Engine Schematic

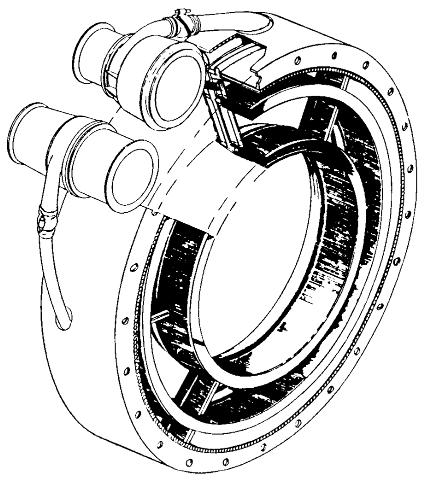

Figure 2 - RBCC Engine Primary Rocket

process incoming air, add fuel, and expand the products of combustion to generate thrust (figure 1). To induce an inlet air flow and provide compression at low speeds, a small rocket (the primary rocket, figure 2) is embedded in the engine flow path near the diffuser. While not as effective at providing flow compression as a compressor-turbine combination, the rocket is lighter weight and can provide thrust in a vacuum.

Early research in RBCC propulsion was conducted in the mid-1960's and early 1970's. In a landmark study available in open literature [1], the Marquardt Company, Lockheed-California, and Rocketdyne investigated a number of RBCC (then 'composite') engine variants for NASA and the U.S. Air Force. This work was later extended to include ground-based experimental testing [2, 3]. Unfortunately, no flight testing was conducted nor was any flight weight hardware built in this study or its follow ons. An excellent retrospective on this early work can be found in reference 4.

The decision to develop the rocket-powered Space Shuttle significantly curtailed research in hypersonics and hypersonic propulsion. However, the concept of RBCC propulsion for reusable space transportation vehicles continued to be advocated throughout the mid-1970's and 1980's by a number of researchers [5], but principally by W. Escher through a number of technical papers and articles available in a compiled form in reference 6.

25 years after the original work in the field, a resurging national interest in low cost access to space prompted vehicle designers to reconsider rocket-based combined-cycle propulsion for reusable launch vehicles. RBCC proponents point toward increased mission flexibility, relatively low gross weights, powered landing and self ferry options, offset launch capability, and synergy with military applications. Currently, active research programs sponsored and conducted by NASA - Marshall Space Flight Center [7] (with Aerojet, Kaiser-Marquardt, Pratt & Whitney, and Boeing - Rocketdyne) and NASA - Lewis Research Center are investigating RBCC engines in subscale and full-scale ground test, computer simulation, and possibly even flight test. Internationally, RBCC research is also being conducted at TNO Prins Maurtis Laboratory in The Netherlands [8].

In concert with current ground test programs, advanced vehicle designers are evaluating RBCC engine variants for a wide variety of X-vehicle and second-generation launch vehicle designs [9-14]. It is hoped that the engine test program and conceptual vehicle design efforts will synergistically lead to an increased understanding of the advantages of RBCC propulsion for low cost space launch.

RBCC Operating Modes

Throughout a typically launch and recovery mission, an RBCC engine will operate in a number of different propulsive modes depending on flight velocity and thrust requirements (figure 3). An RBCC-powered launch vehicle begins its ascent in ejector mode. This mode mainly utilizes the rocket primaries to provide

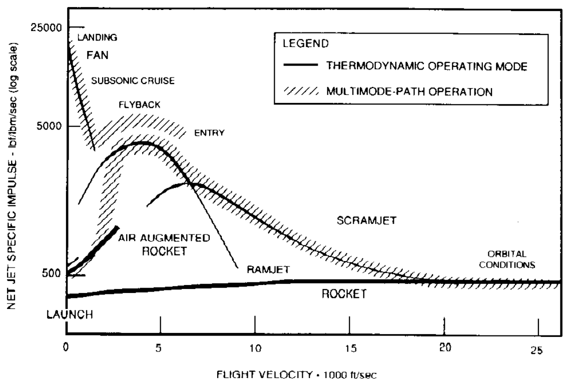

Figure 3 - Typical RBCC Engine Performance (ref. 6)

thrust and to entrain additional airflow from the atmosphere. A low-pressure ratio fan can also be added to this operating mode in order to improve performance. The next phase begins at about Mach 2 to 3 when sufficient ram pressure is generated to shut off the rocket primaries and operate the engine in ramjet mode. The fan can function up to Mach 3 constituting fan-ramjet mode. At around Mach 3, the fan is removed from the flow or windmilled and the engine begins operating in pure ramjet mode up to around Mach 6. At this time, depending on the type of engine, the system either transitions to rocket mode or proceeds through scramjet mode up the vehicle's transition Mach number. Once in rocket mode, the engine inlet is closed and the rocket primaries provide thrust for the vehicle until it reaches its target orbit. In some RBCC variants, it is even practical to provide a powered landing capability.

Available RBCC Weight Database

As previously mentioned, the most thorough study of rocket-based combined-cycle engines to date in open literature was conducted in the mid-60's by the Marquardt Company, Lockheed - California, and Rocketdyne under NASA and Air Force sponsorship [1]. This study provided reasonably detailed weight predictions for a number of RBCC engine configurations using then state-of-the-art materials and construction technologies. However, 30 years of engine technology advancements have left today's designers with only this rough order of magnitude starting point for RBCC engine weights. Recent vehicle studies employing RBCC engines have applied technology reduction factors to the original point design data to approximate weight reductions derived from advanced materials, subsystems, and design innovation. While acceptable for very early conceptual design, more sophisticated conceptual design will require a more accurate and *parametric* weight estimation capability. The research reported in this paper is a first attempt to fill that need.

COMPONENT WEIGHT EQUATIONS

Unlike detailed weight estimation in which the engine geometry and operating conditions are known and fixed (leading to a detailed 'point' analysis), engine weight estimation for conceptual design requires a parametric model of weight as it changes with various engine design characteristics. For example, a vehicle designer might what to know the impact of increasing the transition Mach number from airbreathing to rocket RBCC mode for a given concept. While the trajectory and engine performance model will predict a gross weight decrease for this trade, the engine weight model should predict an engine weight increase as the engine inlet is required to increase. The net result of the trade is not intuitive and will depend on the individual parametric models involved.

Overall Methodology

Parametric weight models are typically a set of algebraic or exponential regression analysis curves in which the dependent variable (weight) is given as a function of one or more relevant independent variables that are likely to be available to conceptual designers (e.g. engine pressure, surface areas, inlet area, maximum Mach number, weight flow rate). These regression analysis curves are called weight estimating relationships, WER's. In building the WER's, one of two approaches can be taken. A 'bottom-up' approach might investigate each engine hardware component in engineering detail to determine how it would be designed, how thick the walls might have to be, what materials would be used, what non-structural weights would be included, etc. These engineering models for each component would then be rolled up to an overall engine weight estimate.

The second approach to building WER's is a 'top-down' analysis. Starting with a database of historical

RBCC engine designs, a set of parametric weight equations could be fit for each component a as function of an appropriate set of design characteristics. This approach is naturally limited by the data diversity available in the database. For example, if the majority of the database uses structural materials available in the 1960's, then the regression equations cannot predict the weight advantages available from more modern aerospace materials. To attempt to capture the weight advantages of modern and future technologies, a technology reduction factor (TRF) is typically applied to top-down WER's. A factor of (1 - TRF) is used to linearly scale a WER down to account for new materials, new design innovations, or new manufacturing techniques. A TRF of zero represents baseline technology from the source database.

The authors' current research effort in RBCC engine weight estimation will eventually lead to the creation of both a bottom-up and a top-down set of engine component WER's. The initial work reported in this paper is a top-down model based on regression analysis of historical, analytical RBCC engine designs. The primary database used to fit the WER's are the class 1 and class 3 engine weight statements available in reference 1 (hereafter referred to as NAS7-377). These weight statements are 'paper point design' predictions of what a flight-weight engine of each type might weigh as determined by Marquardt given the technology of the day. Independent variables in each resulting WER were selected by the authors based on the accuracy of the curve fit, engineering insight into primary weight drivers, and variables likely to be available to conceptual launch vehicle designers.

While the source database in NAS7-377 is rather extensive (36 class 1 engine statements and 2 class 3 engine statements), it is limited in diversity of certain variables that are likely to be important to conceptual vehicle designers. For example, all of the database engines are of axisymmetric configuration. All use LOX/LH2 propellants. Most fall only in the 200 klb - 250 klb thrust class. Peak internal static pressures are typically limited to 100 psi - 150 psi. Maximum airbreathing Mach numbers are either 6 or 12 depending on whether the engine is a ramjet or ramjet/scramjet. TRF's are required to account for modern materials and design innovations. Users of the parametric WER's reported in this paper are cautioned against using the model outside of these variable ranges. It is the authors' hope that engine weight predictions derived from current RBCC research efforts at Aerojet, Kaiser-Marquardt, Pratt & Whitney, and Boeing - Rocketdyne will be published in the open literature so that they might be used to improve the diversity and utility of present model.

Curve Fit Technique

For the WER regression curve fits in the model, a least squares method assuming a function of the general form,

$$Weight = C * x_1^{b1} * x_2^{b2} \qquad (1)$$

was used. This equation was then linearized to form,

$$\ln(Weight) = \ln(C) + b1 * \ln(x_1) + b2 * \ln(x_2) \qquad (2)$$

A standard least squares regression analysis approach is used to determine the unknown constants of each function. Once the constants are determined, the equation is rewritten in the form of equation (1).

Weight Breakdown Structure

A component weight breakdown structure (WBS) was used for this study patterned after the data available in NAS7-377. WER's were created for six subsystems — the optional supercharging fan subsystem (further broken down into fan and gas generator), the primary rocket, the mixer-diffuser-combustor subsystem, the exit nozzle subsystem, controls and lines, and the inlet. The first five components comprise the 'uninstalled' engine weight. These major components and key model variables are illustrated in figure 4. In

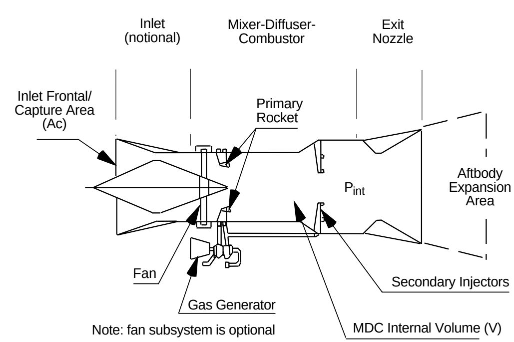

Figure 4 - RBCC Weight Model Variables

addition, a provision is included to attach a contingency weight to the engine weight prediction (a growth margin). However, the weights reported later in this study assume that a growth margin will be added to all weights at the vehicle level, so here the engine weight contingency is zero. The decision to add contingency at the engine level, the vehicle level, or both is ultimately a designer decision. A brief discussion of each component and independent variables used to determine its WER follows.

Fan Subsystem

The fan subsystem was treated as two parts, the fan and the gas generator. This provides a better curve fit than combining the two and gives a clearer picture of the effects of the two variables. Trial and error determined for the fan that secondary air weight flow at sea-level (the air weight flow rate through the inlet, $\dot{W}_s$) provides the best fit. This variable gives a good measure of the size of the component and is readily available in a conceptual design environment.

The other fan subcomponent, the gas generator, drives the fan and must change with a variable that is a good measure of the power output of the subsystem. NAS7-377 reveals a strong correlation between the weight of the gas generator and total pressure ratio (the increase in stagnation pressure across the fan, *PR*). These factors indicate that pressure ratio should provide good fit, and it does. One would also expect the gas generator weight to be a function of the secondary mass flow rate. However, the NAS7-377 data showed little effect of this variable over its limited range of data. Users of this weight model are therefore cautioned to be wary of the gas generator weight when varying the secondary mass flow to extreme values.

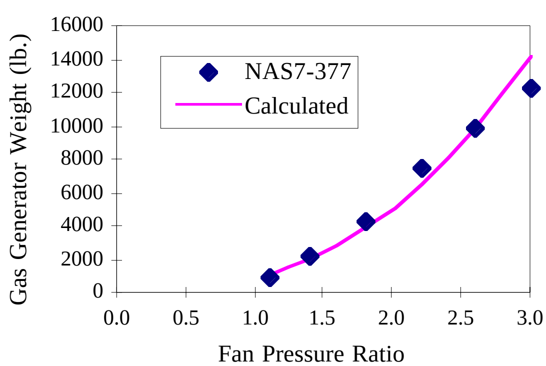

Figure 5 - Curve Fit of Fan Gas Generator

Primary Rocket Subsystem

For the primary rocket system, exit area ratio and primary weight flow were initially considered as variables for regression analysis. Most of the rocket primaries in the NAS7-377 database, however, have a Mach 3 exit velocity. As a result for isentropic flow, the exit area ratio is fixed. Primary weight flow and temperature determine the throat area which then fixes the geometry of the primary. All of the primaries analyzed were stoichiometric LOX/LH2 so their combustion temperatures were similar. For this reason, the rocket primary subsystem scales only with primary weight flow rate. The curve fit for this analysis is in Figure 6.

Mixer-Diffuser-Combustor Subsystem

Initially, a curve fit for internal component volume (V) and maximum internal static pressure (P_{int}) was proposed to predict the weight of the Mixer-

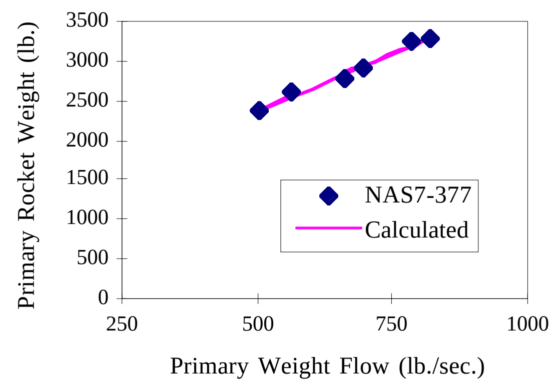

Figure 6 - Curve Fit of Primary Rocket Subsystem

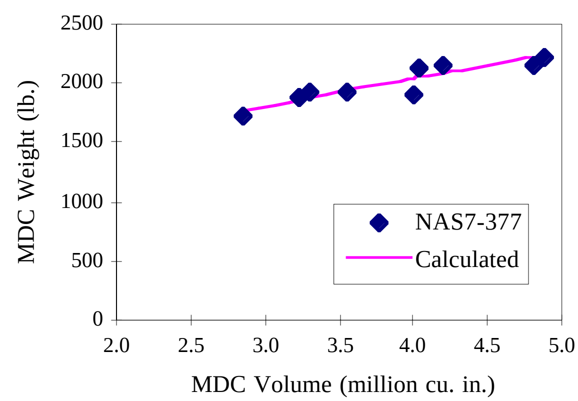

Figure 7 - Curve Fit of Mixer-Diffuser-Combustor

Diffuser-Combustor (MDC) subsystem. Since the MDC shell is similar to a pressure vessel, the weight of the MDC was somewhat arbitrarily assumed to scale *linearly* with maximum internal pressure. MDC weight variation with internal volume (average cross-sectional area times MDC length) was assumed to be exponential as determined by a regression fit. The input dataset for the MDC weight versus internal volume is shown in figure 7. The fuel injection system was assumed to be a fixed percentage of MDC weight and has been included in the overall weight estimate.

Exit Nozzle Subsystem

The curve fit for the weight of the variable geometry exit nozzle was found to correspond well to the transition Mach number (M_{trans}) and total engine weight flow rate ($\dot{W}_{total}$). M_{trans} is the maximum airbreathing mode Mach number at which the engine will operate — that is, the Mach number at which the engine transitions to rocket mode. M_{trans} gives an estimate of the size of the nozzle expansion area required. $\dot{W}_{total}$ is the maximum total weight flow rate exiting the nozzle (primary rocket + secondary inlet + fuel injected directly into the combustor). A complexity factor, C_f, was included to scale the WER up or down depending on configuration differences between the baseline nozzle and a comparative system. $C_f = 1$ implies a variable geometry exit nozzle similar to those in NAS7-377. However, other types of variable exits as well as fixed nozzles can be analyzed using an appropriate complexity factor. For example, a fixed geometry exit with a thermal choke might have a C_f of 0.85 - 0.90. Selection of an appropriate C_f is the responsibility of the designer.

Controls and Lines

Controls and lines weight is modeled as a percentage of other relevant component weights in the engine. In this simple WER, as engine weight and size grow, the controls and lines weight will follow linearly. Note that this subsystem is therefore indirectly affected by weight reducing technologies in other parts of the engine.

Inlet

The baseline for the inlet model is a 2-D, variable geometry ramp inlet similar to that proposed in NAS7-377. A number of independent variables were considered for an inlet WER. The primary scaling effects are an increasing inlet length-to-diameter ratio (L/D) with maximum Mach number, and increasing inlet weight with increasing surface area. A reasonable curve fit to the NAS7-377 data was found using M_{trans} and inlet capture area (A_c) as independent variables raised to exponential powers. Here A_c is the physical frontal area of the inlet or cowl — not a theoretical capture area extending to infinity. A_c therefore remains constant with flight condition. Note that since inlet surface area is a function of diameter * length and L/D is a function of M_{trans}, $A_c * M_{trans}$ is a suitable surrogate for diameter * diameter * (L/D) or inlet surface area.

A complexity factor is included in the inlet WER to account for different variable geometry configurations as well as for components that are not needed when there is a fixed geometry inlet. $C_f = 1$ represents a 2-D variable geometry inlet with mechanical ramps. A simpler, fixed geometry inlet might have a C_f of 0.70 - 0.75. The selection of an appropriate complexity factor is left to the designer.

Improving the accuracy of the inlet subsystem weight prediction is a high priority, as it often comprises fifty percent or more of the installed weight. The inlet regression analysis was significantly limited by a sparse historical database.

RESULTS

Top-Down WER's

A summary of the WER's for the top-down RBCC WBS is given in table 1. For each equation, the result is a weight in pounds. Required units for each of the independent variables are given in the notes section. Again, users of these WER's are cautioned against using them to predict engine weights for inputs significantly dissimilar to those in the reference database (the datapoints in figures 5 - 7).

Table 1 - RBCC Weight Estimating Relationships

Engine WBS	Weight Estimating Relationship (results in lbs.)	Eqn. #	Notes
1.0 Fan Subsystem (optional)			
- supercharging fan	$Weight = 67.5 * \dot{W}_s^{0.4518} * (1 - TRF)$	*W1*	$\dot{W}_s$ is secondary flow rate through inlet in lb/s
- gas generator	$Weight = 807.2 * PR^{2.515} * (1 - TRF)$	*W2*	PR is fan pressure ratio (total pressure increase)
2.0 Primary Rocket	$Weight = 39.45 * \dot{W}_p^{0.6601} * (1 - TRF)$	*W3*	$\dot{W}_p$ is primary rocket flow rate in lb/s
3.0 Mixer-Diffuser-Combustor	$Weight = 3.324 * V^{0.4229} * (P_{\text{int}} / 150\,psi) * (1 - TRF)$	*W4*	V is MDC internal volume in cubic in., P_{int} is maximum internal MDC static pressure in psia
4.0 Exit Nozzle	$Weight = C_f * 3298.2 * M_{trans}^{-0.3364} * \dot{W}_{total}^{0.1173} * (1 - TRF)$	*W5*	$\dot{W}_{total}$ is total mass flow through nozzle in lb/s, M_{trans} is max. airbreathing Mach number, C_f is complexity factor
5.0 Controls & Lines	$Weight = 0.15 * \sum(eqn.W2 + eqn.W3 + eqn.W4)$	*W6*	note, TRF's from other components will affect controls
6.0 Contingency	$Weight = margin\_percentage * \sum(eqns.W1 - W6)$	*W7*	alternately, contingency can be added at the vehicle level
Uninstalled Engine Weight	$Weight = \sum(eqns.W1 - W7)$		
7.0 Inlet	$Weight = C_f * 154.21 * M_{trans}^{0.4894} * A_c^{0.75} * (1 - TRF)$	*W8*	A_c is cowl or inlet frontal area in sq. in., M_{trans} is max. airbreathing Mach number, C_f is complexity factor
Installed Engine Weight	$Weight = \sum(eqns.W1 - W8)$		

Technology reduction factors (TRF's) for the five major WBS subsystems are listed in table 2 versus technology availability date (TAD). The TRF's increase with future TAD's, thereby accounting for weight saving advanced materials, design innovation, and improved manufacturing techniques. These TRF's were derived from similar data available in the reference 5 (hereafter, referred to as the Astronautics report) and, in some cases, from the authors' engineering judgment. TRF's for the fan subsystem (used for both the fan and the gas generator) were derived from goals established by the Air Force/NASA integrated high-performance turbine engine technology (IHPTET) program phase 2 and 3 goals [15].

Table 2 - Technology Reduction Factors (TRF's)

	Technology Availability Date (TAD)			
	1965	1995	2005	2015
fan (1985=0)	N/A	0.38	0.50	0.60
primary	0	0.19	0.31	0.42
MDC	0	0.13	0.39	0.57
nozzle	0	0.44	0.58	0.68
inlet	0	0.44	0.55	0.64

WATES (Weight Assessment Tool for Engine Scaling)

The WER's in table 1 and the TRF's in table 2 were combined to form a Microsoft Excel spreadsheet-based model for RBCC engines. The model is called WATES — Weight Assessment Tool for Engine Scaling. WATES consists of a data input sheet were a user can enter required variables such as engine dimensions, PR, M_{trans}, P_{int}, technology availability date, etc. WATES then creates a properly formatted weight statement (WBS) for the engine and calculates engine T/W. The weight statement in WATES further subdivides the major subsystem weights to a second level based on historical sub-component contributions derived for NAS7-377. For example, the WER-predicted weight for the MDC subsystem is apportioned into mixer, diffuser, combustor, centerbody, turbopump, and fuel injectors based on historical contributions to MDC. A sample of the WATES WBS is shown in figure 8. WATES is a public model available on request from the authors.

RBCC Engine Weight Statement
SERJ, Ejector: Stoich, Combustor: Full Scale Ramjet
2005 TAD

1.0	Fan Subsystem		1840 lbm.
	Fan Assembly	303 lbm.	
	Gas Generators	1120 lbm.	
	Frame and Trunnion Unit	79 lbm.	
	Compartment Structure	157 lbm.	
	Cover	39 lbm.	
	Actuator	28 lbm.	
	Transition Section	81 lbm.	
	Miscellaneous	34 lbm.	
2.0	Primary Rocket Subsystem		1638 lbm.
	Rocket Chamber Assembly	402 lbm.	
	Support Structure	576 lbm.	
	Turbopumps	286 lbm.	
	Gas Generator	115 lbm.	
	Ducting and Valves	72 lbm.	
	Starting System and Misc.	187 lbm.	
3.0	Mixer/ Diffuser /Combustor Subsystem		850 lbm.
	Mixer	184 lbm.	
	Diffuser	166 lbm.	
	Fuel Injection Unit	136 lbm.	
	Combustor	150 lbm.	
	Forward Centerbody	169 lbm.	
	Turbopump and Miscellaneous	45 lbm.	
4.0	Exit Nozzle Subsystem		1782 lbm.
	Exit Bell	457 lbm.	
	Translating Ring Assembly	500 lbm.	
	Fixed Plug	393 lbm.	
	Actuator unit	347 lbm.	
	Miscellaneous	85 lbm.	
5.0	Controls, Lines		219 lbm.
	Control Assemblies	17 lbm.	
	Valves and Lines	202 lbm.	
	Total Weight, Dry		**6329 lbm.**
	Inlet, typical		6718 lbm.
	Total Weight Installed		**13047 lbm.**
	Thrust at liftoff		269000 lb.

Figure 8 - Sample Weight Statement from WATES

Comparison with Historical Weight Estimates

Since comparison with flight weight engines was not possible, WATES is compared point design engine data in NAS7-377 [1] and the Astronautics report [5], the same database used to construct much of the information in the model. Recall that WATES is a *parametric* model capable of analyzing a variety of engine concepts. This comparison will show how closely WATES predicts engines in its own database, which is the most accuracy that can be expected.

Table 3 and figure 9 compare WATES installed weight estimates with four RBCC engines in NAS7-377. As identified, there are four different RBCC configurations — ejector ramjet (ERJ), supercharged ejector ramjet (with fan, SERJ), ejector scramjet (ESJ), and supercharged ejector scramjet (SESJ). The

Table 3 - WATES vs. NAS7-377 Results

Type	Thrust	NAS7-377	WATES
ERJ (class 1)	250,000 lb.	16,969 lb.	17,422 lb.
SERJ (class 3)	203,000 lb.	23,655 lb.	23,249 lb.
ESJ (class 1)	250,000 lb.	18,612 lb.	20,787 lb.
SESJ (class 1)	250,000 lb.	21,421 lb.	24,894 lb.

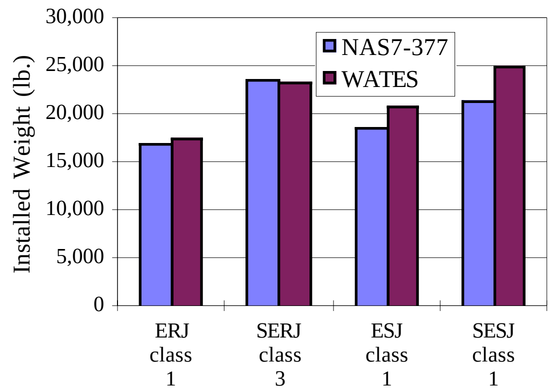

Figure 9 - Comparison of NAS7-377 and WATES

weight estimate for SERJ engine is from the more detailed class 3 stage of the original study. All engines are based on a 1965 TAD. As the table shows, the comparison is quite good for the class 3 engine. The low exit nozzle weights of the class 1 NAS7-377 cause the slight discrepancy in the other comparisons. However, in all cases the weight trends among the different engines are captured. Supercharged and scramjet-capable variants are heavier as expected.

Table 4 and figure 10 are comparisons of WATES installed weights with engine weights from the Astronautics report. Two RBCC configurations are compared, ESJ and SESJ, but this time the technology availability date is varied from 1965 to 1995. WATES estimates the installed weight slightly higher than the Astronautics report (as much a 6.5%) in each case, but the trends are accurately captured. That is, the advancement of technology lowers installed weight and supercharged engines are expected to weight more.

Table 4 - WATES vs. Astronautics Results

Type	Thrust	Astronautics	WATES
ESJ (1985)	250,000 lb.	18,378 lb.	19,479 lb.
SESJ (1985)	250,000 lb.	22,586 lb.	24,055 lb.
ESJ (1995)	250,000 lb.	14,546 lb.	15,338 lb.
SESJ (1995)	250,000 lb.	17,292 lb.	18,174 lb.

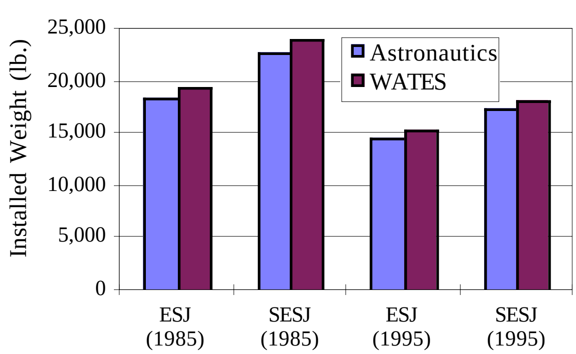

Figure 10 - Comparison of Astronautics and WATES

While more accuracy is certainly desired between WATES and the comparison engine weights from the historical database, it is important to remember that WATES is not intended to replace detailed weight models. Rather, it is intended as a fast, flexible tool for estimating engine weight in the conceptual design or trade study environment. In such an environment, it is often the *relative* comparison (i.e. the trends) between engine concepts that matters most. For its intended application, WATES is more than adequate. The following section illustrates typical engine-level trade study results that can be produced with WATES. A future goal is to demonstrate similar trade results in an integrated vehicle-level synthesis environment.

Typical Trade Studies using WATES

To facilitate trade studies of the WATES model, 2005 TAD reference versions of two of the most commonly considered engines, the ejector scramjet and the supercharged ejector ramjet, were created (table 5). The results of the following trade studies are compared based on installed engine thrust-to-weight ratio (T/W).

Table 5 - Reference Trade Engines Baseline Data

Parameter	SERJ	ESJ
Thrust (SLS)	269 klb.	226 klb.
A_c	144 ft.^{2}	80 ft.^{2}
M_{trans}	6	12
Mixer L/D	1	3
MDC Volume	896 ft.^{3}	1781 ft.^{3}
$\dot{W}_p$	597 lb/s	597 lb/s
$\dot{W}_s$	1791 lb/s	1015 lb/s
$\dot{W}_{total}$	2440 lb/s	1638 lb/s
fan *PR*	1.5	no fan
P_{int}	150 psia.	100 psia.

Note, thrust in this ratio is measured at sea-level static (SLS) or takeoff flight conditions. Engine installed T/W is a very important parameter in advanced launch vehicle design. It can be affected by either thrust or engine weight. In an attempt to isolate the role of WATES (i.e. weight), the trade variables illustrated in the following comparisons are chosen to have a primary manifestation in weight. SLS thrust is kept constant. Certainly other trades studies of interest would affect both SLS thrust and weight (e.g. fan PR, A_c, W_p, P_{int}). The overall impact of *these* trades would require the re-evaluation of engine weight as well as performance (thrust). A number of engine performance codes exist that are capable of evaluating changing engine thrust (e.g. SCCREAM [16]).

The technology reduction factors (TRF's) applied to the various components of the engine have a significant effect on its installed T/W. These factors not only show the T/W increases predicted for RBCC propulsion, but also the promise held if those technologies can be achieved. Figure 11 shows predicted technology growth in RBCC engine installed T/W ratio for the reference SERJ and ESJ engines as technology availability date advances. The baseline engines assume a TAD of 2005.

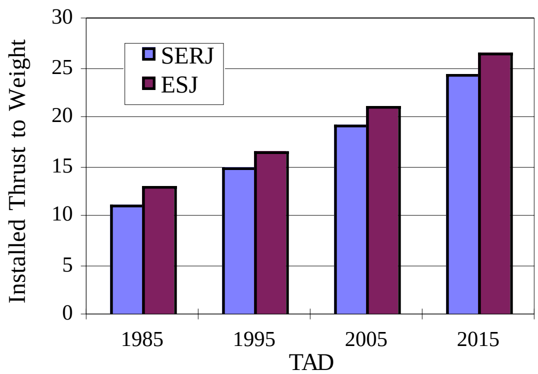

Figure 11 - SERJ and ESJ Thrust to Weight vs. TAD

The length-to-diameter (L/D) ratio of the mixer duct is a factor modeled in WATES. L/D is important in comparing the relative advantages of ramjets and scramjets and also for determining an optimum transition Mach number for a scramjet. Figures 12 and 13 show the change in engine T/W versus mixer L/D for the two reference engine concepts.

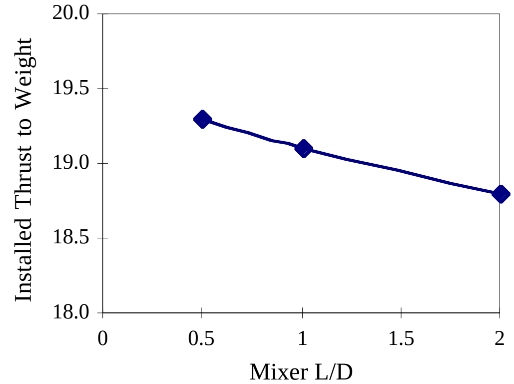

Figure 12 - SERJ T/W vs. Mixer L/D

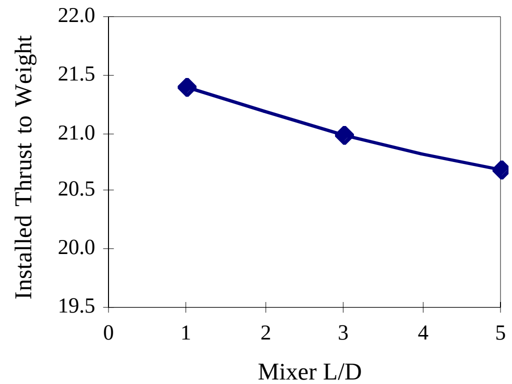

Figure 13 - ESJ T/W vs. Mixer L/D

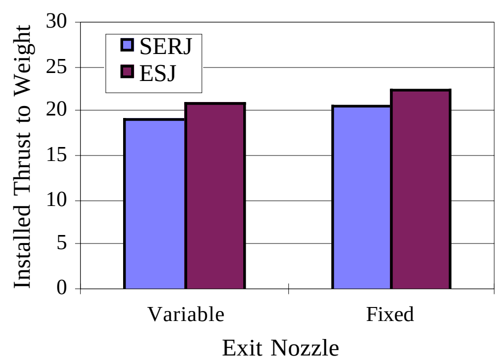

Figure 14 - T/W vs. Exit Nozzle Complexity

Much of the complexity, and therefore weight, of the engine depends on whether or not the inlet and exit nozzles are fixed or variable geometry. The increased performance advantages of variable geometry over a wide flight range come at the expense of engine weight. The WATES results in figure 14 show the increase in the T/W's of the reference engines should fixed exit nozzles be selected rather than the baselined variable geometry configurations.

As a final example of typical trade studies that can be performed with WATES, the effect of transition Mach number (M_{trans}) was examined for the two reference engine configurations. M_{trans} directly affects the weight of the inlet and the exit nozzle in WATES. Since the inlet is the largest single component of an RBCC engine, this variable has a very strong effect on installed T/W as can be seen in figures 15 and 16. As in previous results, the vehicle-level impact of this trade is uncertain. Increasing M_{trans} will increase engine weight, but will simultaneously reduce the fuel weight required to reach orbit (i.e. increase average I_{sp}).

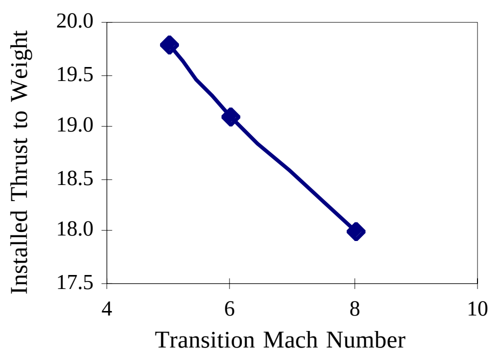

Figure 15 - SERJ T/W vs. Transition Mach Number

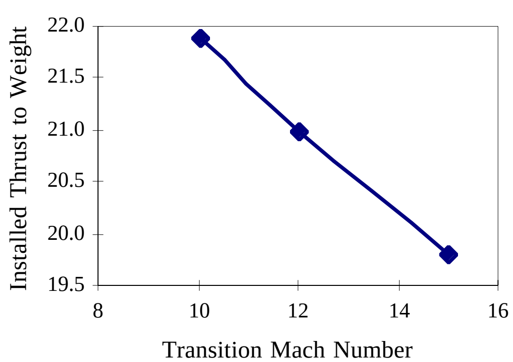

Figure 16 - ESJ T/W vs. Transition Mach Number

CONCLUSIONS

This paper presented a new set of weight estimating relationships for RBCC engines that have been created using a top-down regression analysis of historical engine designs. Independent variables in the WER's were chosen based on engineering insight, accuracy of the resultant curve fit, and availability to conceptual vehicle designers. The WER's were assembled into a parametric spreadsheet-based weight estimation tool, WATES. For a given RBCC engine configuration and set of input data, WATES generates a formatted engine weight statement and an estimate of installed engine thrust-to-weight ratio. WATES was compared to specific engines from it's own database and a representative set of trade studies was presented. Among the specific conclusions drawn from this work are the following.

1. Given two approaches to developing parametric weight estimating relationships for RBCC engine components, WATES uses a 'top-down' approach of fitting regression curves to historical data and adjusting the curves to account for advanced technology and design innovation.

2. The historical database of RBCC engine designs is limited to two primary studies in the open literature — one by the Marquardt Corporation in 1966 and one the Astronautics Corporation in 1987. While a number of engine 'paper point designs' are available in those studies, diversity of information with respect to several key variables is limited (e.g. thrust level, weight flow rates). As a result, the regression curves available in WATES should be used with caution when analyzing parameters outside of the database range.

3. Comparisons to engine point designs from it's own database showed WATES results to be reasonably accurate (within 6% - 7%). Perhaps more significant for conceptual design, WATES was shown to capture the relative weight trends evident between various engine concepts (e.g. fan vs. non-fan, increased technology availability date, etc.).

4. The WATES model is not intended to replace detailed weight analysis of RBCC engines. It is, however, intended as a fast and reasonably accurate tool for use in a multi-disciplinary conceptual vehicle environment. WATES is a public tool and is available on request from the authors.

FUTURE WORK

The work reported in this paper is part of an on-going research effort in parametric weight modeling for RBCC engines. The WATES model will continue to be expanded and enhanced over the next few years. In particular, the following items are priorities for future work.

1. Expand the database used in the top-down component weight model to include results of current NASA-sponsored RBCC research. These new designs should add critical diversity in engine size, thrust level, and configuration. However, raw data must first be available in the open literature.

2. Transition WATES to a bottom-up engineering model. The more physics-based bottom-up approach will increase model fidelity and accuracy and reduce dependence on technology reduction factors. Creation of an engineering model for the mixer-diffuser-combustor shell weight has already been initiated. This new model includes the effects of material strength properties, engine geometry, internal static pressure, and thermal and cooling requirements.

3. Integrate WATES into a automated computing framework for conceptual design. The ultimate goal of this research is to develop a design environment for overall RBCC vehicle synthesis. Just as WATES depends on inputs from the vehicle design (e.g. transition Mach number) and engine performance code (internal static pressure), the vehicle design depends on the engine weight from WATES. This non-hierarchic coupling between analysis tools lends itself well to a collaborative design framework where data is automatically exchanged between disciplinary analysis tools to converge or to even optimize an RBCC vehicle design.

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REFERENCES

1. Escher, William J. D., and Flornes B. J., “A Study of Composite Propulsion Systems for Advanced Launch Vehicle Applications.” Final report for NASA contract NAS7-377, The Marquardt Corporation, Van Nuys, CA, April 1967, Vol. 1 - 9.

2. Congelliere, J., Prevatte, N., and Lime, J., “Advanced Ramjet Concepts, Vol. II Ejector Scramjet Technology.” Final report for USAF contract AFAPL-TR-67-118, The Marquardt Corporation, May 1968.

3. Odegaard, E. A., and Stroup K. E., “1966 Advanced Ramjet Concepts, Vol. VIII Ejector Ramjet Engine Tests, Phase I.” Final report for USAF contract AFAPL-TR-68-118, The Marquardt Corporation, January 1968.

4. Escher, W. J. D., “Synerjet for Earth/Orbit Propulsion: Revisiting the 1996 NASA/Marquardt Composite (Airbreathing/Rocket) Propulsion System Study (NAS7-377).” AIAA paper 96-3040, July 1996.

5. Foster, Richard W., Escher, W. J. D., and Robinson, J. W., “Air Augmented Rocket Propulsion Concepts.” Final report for USAF Astronautics Laboratory contract AFAL-TR-88-004, Astronautics Corporation, April 1988.

6. Escher, William J. D., ed., *The Synerjet Engine: Airbreathing/Rocket Combined-Cycle Propulsion for Tomorrow’s Space Transports*, SAE PT-54, Society of Automotive Engineers, Warrendale, PA, 1997.

7. Turner, James E., and Hueter, U., “Status of the Advanced Reusable Transportation Technologies Project.” AIAA paper 97-2856, July 1997.

8. Dijkstra, F., Maree, A. G. M., Caporicci, M., and Immich H., “Experimental Investigation of the Thrust Enhancement Potential of Ejector Rockets.” AIAA paper 97-2756, July 1997.

9. Foster, Richard W., Escher, W. J. D., and Robinson. J. W., “Studies of an Extensively Axisymmetric Rocket Based Combined Cycle (RBCC) Engine Powered SSTO Vehicle.” AIAA paper 89-2294, July 1989.

10. Billig, Frederick S., “Design and Development of Single-Stage-to-Orbit Vehicles.” Johns Hopkins APL Technical Digest, Volume 11, Numbers 3 and 4, 1990.

11. Olds, John R., and Walberg, Gerald W., “Multidisciplinary Design of a Rocket-Based Combined-Cycle SSTO Launch Vehicle Using Taguchi Methods.” AIAA paper 93-1096, February 1993.

12. Olds, John R., “Results of a Rocket-Based Combined-Cycle SSTO Design Using Parametric MDO Methods.” SAE paper 941165, April 1994.

13. Bulman, Mel, and Seibenhaar, Adam., “The Strutjet Engine: Exploding the Myths Surrounding High Speed Airbreathing Propulsion.” AIAA paper 95-2475, July 1995.

14. Olds, John R., “Options for Flight Testing Rocket-Based Combined-Cycle (RBCC) Engines.” AIAA paper 96-2688, July 1996.

15. Hill, Richard J., “The Challenge of IHPTET.” *Proceedings of the 11th International Symposium on Airbreathing Engines (ISABE)*, AIAA, Tokyo, Japan, September 1993.

16. Olds, John R., and Bradford, John., “SCCREAM (Simulated Combined-Cycle Rocket Engine Analysis Module): A Conceptual RBCC Engine Design Tool.” AIAA paper 97-2760, July 1997.