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A COMPARISON OF HORIZONTAL TAKEOFF RLVS FOR NEXT GENERATION SPACE TRANSPORTATION

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Abstract

Andrews Space has developed the “Alchemist” Air Collection and Enrichment System (ACES), which enables a paradigm shift in reusable launch vehicle (RLV) architecture safety and operability while meeting NASA’s Next Generation RLV requirements. Horizontal takeoff horizontal landing (HTHL) architectures have been shown to have substantial operational benefits over traditional vertical takeoff rocket systems. In this paper, we present a status report of an in-house study comparing a two stage to orbit (TSTO) RLV using Alchemist ACES with two 3rd Generation RLV concepts: Turbine Based Combined Cycle (TBCC) TSTO and Rocket Based Combined Cycle (RBCC) TSTO; using common design ground rules and the same Figures of Merit. The final results of our in-house study will be available for the IAF conference in Bremen in late September, but current partially-optimized results show that the three concepts have very similar performance characteristics with equivalent technology assumptions. Hence, the relatively low risk Alchemist can bring 3rd Generation capability at 2nd Generation technical risk.

Acronyms

AAR	Air Augmented Rocket
ACES	Air Collection and Enrichment System
ACS	Attitude Control System
FAR	Federal Aviation Regulations
FRCI	Fibrous Refractor Composite Insulation
GTOW	Gross Takeoff Weight
HTHL	Horizontal Takeoff Horizontal Landing
I_{sp}	Specific Impulse
LEO	Low Earth Orbit
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
OMS	Orbital Maneuvering Engines
RBCC	Rocket Based Combined Cycle
RLV	Reusable Launch Vehicle
SECO	Second-stage Engine Cut Off
SERN	Single Expansion Ramp Nozzle
SLST	Sea Level Static Thrust
SSME	Space Shuttle Main Engine
SSTO	Single Stage To Orbit
TABI	Tailorable Advanced Blanket Insulation
TJ	Turbojet
T/W	Thrust-to-Weight Ratio
TBCC	Turbine Based Combined Cycle
TPS	Thermal Protection System
TSTO	Two Stage To Orbit

Introduction

Andrews Space personnel conducted trade studies looking at three candidate HTHL vehicles. The three concepts are: Turbine Based Combined Cycle (TBCC) TSTO, Rocket Based Combined Cycle (RBCC) TSTO, and Alchemist ACES TSTO. All three systems are designed using the operating ground rules currently used in NASA’s Next Generation Launch Technology Studies with 2008 technology levels, and all three use densified hydrogen (4.5 lbm/ft^3) and LOX (71 lbm/ft^3). The design mission for each is roundtrip to LEO (100 nmi, 28.5 degrees orbit) with a 20,000 lbm payload in a 15 foot diameter by 30 foot length payload bay, plus reserve propellants. First order system sizing was performed using fundamental sizing relationships of the type developed by Professor Paul Czysz of Saint Louis University (References 1, 2, and 3). The fundamental relationships have been modified slightly to match launch vehicle variables and nomenclature, but the overall trends are similar. Configuration aerodynamics and engine characteristics were derived from data published in References 4-8.

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Turbine Based Combined Cycle Concept

We will use the Turbine-Based Combined Cycle (TBCC) as an example of how this "quick-look" sizing technique works. The configuration selected is the ABLV-7C shown below. It is a spatula-nosed, hypersonic lifting-body with an X-33 type lifting-body second stage recessed into the upper surface. A staging Mach number of ten was preselected as being representative for this class of vehicle based on the results of trades in Reference 7. This configuration is described in References 4-8 and shown below in Figure 1. Both turbofans and advanced turbojets were examined in the trades. The turbofans were F-135 derivatives and the turbojets were P&W Augmented Turbojets per 2001 Cycle Revision. The over/under installation assumed is shown in Figure 2.

The fundamental quantity to be determined is the inert weight of the first and second stages. Inert weight is the weight at Main Engine Cutoff (MECO) for the first stage, less the weight of the second stage, and the weight at Second-Stage Cut Off (SECO), less the payload. It includes the dry weight, the propellant reserves and residuals, and various unused fluids. First stage inert weight can be approximated by:

$$W_{inert1} = (1 + WtGr) * (W_{AF1} + W_{TPS1} + W_{LG1} + W_{Systems1} + W_{Propulsion1} + W_{SepSys}) + W_{Fluids1}$$

where:

- $WtGr$ = Weight Growth Margin (assumed to be 15 % at this stage of development based on data in reference 9)
- $W_{AF1} = I_{str1}\ Swet1 + 0.18 * (W_{inert2} + W_{TotProp2} + W_{Payload})$
- $W_{TPS1} = I_{TPS1} * Swet1$
- $W_{LG1} = 0.035 * GTOW$
- $W_{Systems1}$ = 10,000 lbm (4,500 kg)

$$W_{Propulsion1} = 1.3 * SLST1/(T/W_{eng1}) + 1.02 * VacThrust1/(T/W_{rocket1}) + 1.8 * VacThrust1/VacIsp1 + I_{scrj} * A_{inlet}$$

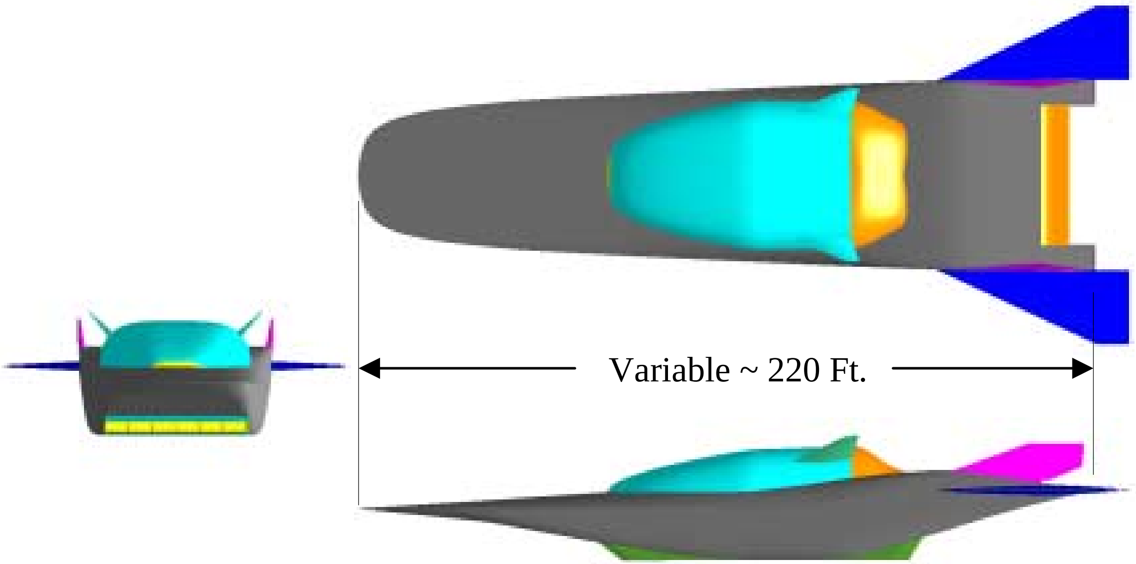
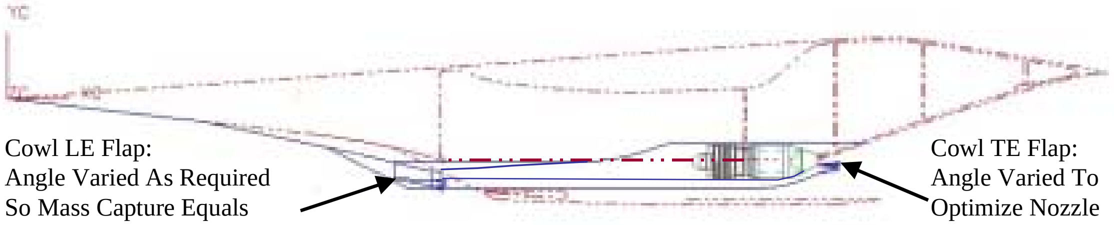


Figure 1. ABLV-7C Shape and Rough Sizing.



Cowl LE Flap:
Angle Varied As Required
So Mass Capture Equals
Engine Airflow Demand as f(M)

Cowl TE Flap:
Angle Varied To
Optimize Nozzle
Perf. vs. Mach

Figure 2. Over/Under Turbine-Based Combined Cycle Flow Path.

- $W_{Fluids1} = W_{residuals1} = 0.005_{\ WtotProp1}$
- $W_{SepSys} = 0.28*S_{plan2} + 4.71*T_{vac2} / (W_{inert2} + W_{totProp2} + W_{payload}) * W_{inert1} / 1000$
- I_{str1} is the Structure index for the 1st stage and is a function of the airframe material and construction type. A value of 3.0 psf (14.4 kg/m^2) was chosen as approximately state-of-the-art for composite structure with internally insulated, integral tankage.
- I_{TPS1} is the TPS index, or specific TPS weight, and is a function of total heat load averaged over the entire wetted area (S_{wet1}). For the 1st stage, the average total heat load on the windward side can be approximated by:

$$Q_{ave} = 0.0193*(2*q_{ave})^{0.5}*M_{stg}^{\ 3.15} / axialG,$$

where,

- Q_{ave} is in Joules/cm^2
- q_{ave} is the dynamic pressure during ram/scramjet operation in psf
- M_{stg} is staging Mach number
- axialG is the average acceleration in gravities during the airbreathing phase.

TPS unit weights as a function of heat load are shown in Figure 3. For staging in the Mach 10 to 15 range with an average axial acceleration of 0.5 g, the average heat load will be between 2000 and 9000 J/cm^2. The calculations shown in this paper assume both the TBCC and RBCC boosters accelerate at a dynamic pressure (q) of 2000 psf and use FRCI 12 on the windward side and TABI on the leeward side (except the nozzle region). The reduction in heating on the leeward side results in a correction factor of 0.48 when calculating TPS Index from TPS unit weights generated using the average total heat load on the windward side. An approximation for the body TPS index is:

$$I_{TPS} = 0.3107*A_{wet}*q_{ave}^{\ 0.05}*M_{stg}^{\ 0.11} / axialG.$$

I_{scrj} is the Scramjet index or scramjet weight per unit frontal area at the cowl lip, and is a function of operating time, the operating dynamic pressure, and staging Mach number. Assuming insulated composite structure with active cooling the Scramjet Index can be approximated by the formula:

$$Iscrj = 7.66((2*q_{ave})^{0.5}M_{stg}^{\ 3.15}/axialG)^{0.3}$$

Second stage inert weight can be approximated by:

$$W_{inert2} = (1+WtGr) * (W_{AF2} + W_{TPS2} + W_{LG2} + W_{Systems2} + W_{Propulsion2}) + W_{Fluids2}$$

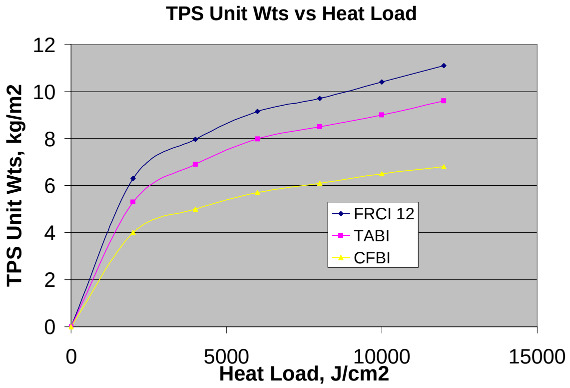


Figure 3. Stg1TPS Unit Weights versus Heat Load

where,

- $W_{AF2} = I_{str2}\ S_{wet2} + 0.6*W_{maxpayload}$
- $W_{TPS2} = I_{TPS2} * S_{wet2}$
- $W_{LG2} = 0.03*W_{SECO}/16.7$
- $W_{Systems2}$ = 5,000 lbm (2,250 kg)
- $W_{Propulsion2} = 1.3*SLST/(T/W_{eng}) + 1.02*T_{Vac2}/(T/W_{rocket2}) + 1.8*T_{Vac2}/Isp2$
- $W_{Fluids2} = W_{residuals2} + W_{OMS} + W_{reserves}$

where:

- $W_{residuals} = 0.005_{\ WtotProp2}$
- $W_{OMS} = W_{SECO}*(EXP(\Delta V_{OMS}/Isp_{OMS}*g)-1)$
- $W_{reserves} = W_{SECO}*(EXP(0.01*\Delta V_{Ideal}/Isp_2*g)-1)$

The first step in calculating W_{inert} is to calculate the volume and wetted areas of each stage. Starting with 2nd stage volume:

$$V_{tot2} = V_{prop2} + V_{rocket2} + V_{PayloadBay} + V_{lg2} + V_{Systems2} + V_{void},$$

where:

$$V_{prop2} = W_{LOX2}/(pf_{LOX}*71) + W_{H22}/(pf_{H2}*4.5)$$

where weights are in lbm and where the packing fraction (pf) is the fraction of propellant relative to the volume of propellant plus the volume lost to such things as insulation, tank domes, and feed and fill lines. Propellant packing fractions are usually in the 0.85 to 0.95 ranges.

$$V_{rocket2} = 1.1*T_{vac2}/(T/W_{rocket2} *\rho_{rocket2})$$

where:

- $\rho_{rocket2}$ is the average density of the rocket powerhead and surrounding machinery in lbm/cuft.
- $V_{PayloadBay} = 1.2 * V_{payload}$
- $V_{lg2} = 0.03 * W_{SECO}/16.7$
- $V_{Systems2} = W_{Systems2} /12$
- $V_{void2} = k_{vv2} * V_{tot2}$

where k_{vv} is the fraction of wasted space and amounts to 0.2 to 0.3 of the total stage volume.

The next step is to calculate the volume and wetted areas of the first stage. The first stage volume:

$$V_{tot1} = V_{prop1} + V_{tj1} + V_{rocket1} + V_{2ndStgRecess} + V_{lg1} + V_{Systems1} + V_{void1},$$

where:

- $V_{prop1} = W_{LOX1}/(pf_{LOX}*71) + W_{H21}/(pf_{H2}*4.5) + W_{HC1}/(pf_{HC}*50)$
- $V_{tj1} = 1.2*SLST1/(\rho_{tj1}*T/W_{tj1})$
- $V_{rocket1} = 1.1*Tvac1/(T/W_{rocket1} * \rho_{rocket1})$

(note that rocket engines have a low effective density because they mount heat shields and must gimbal around inside their compartment)

- $V_{2ndStgRecess} = k_{recess} * V_{tot2}$
- $V_{lg1} = 0.035*GTOW/16.7$
- $V_{Systems1} = W_{Systems1} /12$
- $V_{void1} = k_{vv1} * V_{tot1}$

The relationship between volume and vehicle planform area is expressed with the Küchemann volume parameter, τ, which is the body volume divided by the planform area to the 3/2 power. Fatter bodies have a larger τ. The relatively sleek shapes for hypersonic accelerators have a τ between 0.10 and 0.14, and the much blunter second stages have a τ between 0.18 and 0.20. The second shape parameter is the ratio of wetted area to planform area, K_w, which varies between 2.5 to 3.0 for both first stage accelerators and second stage orbiters.

System sizing processes are as follows. For a given GTOW, the planform area is determined by the 102 lb/ft^2 (500 kg/m^2) planform-loading requirement to limit the liftoff speed to 300 knots for advanced tire speed considerations. The Küchemann τ for the TBCC shape of interest is 0.116, and the Kw is 2.59, so we can quickly calculate the volume and wetted area corresponding to the candidate GTOW. Performance variables for the 1st stage are the amount of jet engine Sea-Level Static Thrust, the amount rocket thrust installed (if any), the size of the Ram/Scramjet installation measured by its inlet area, the size and weight of the second stage, and the propellant weight and volumes.

For the candidate configuration shapes chosen, there is a range of inlet geometries where the capture area is known as a function of Mach number and angle of attack (see Figure 4) without extensive flowpath analyses. We propose to stay within those boundaries and not conduct a flowpath analysis for this first order comparison. The original plan was to calculate mass flow along the trajectory and estimate net thrust using the capture area plots as shown below, but for this initial phase of the study, we opted to use published thrust coefficients[4-8].

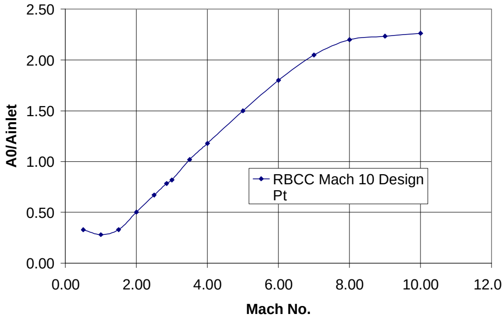


Figure 4. Relative Capture Area versus Mach Number.

The second stage sizing is similar in that the reentry and landing planform loading based on the SECO weight cannot exceed approximately 35 lb/ft^2 (225 kg/m^2) in order to use existing TPS, and for approach and landing considerations. This allows us to calculate planform area and volume corresponding to a candidate SECO weight.

For each initial pick of GTOW, SECO weight, and the performance variables, we can calculate a weight and volume buildup for both stages. The buildups go into a simple trajectory program, which varies thrust levels (via the number of engines or ramjet inlet area), steering, and propellant weights until the SECO conditions are met (note that payload weight and net volume margin might be negative or positive). If the payload and the volumes have large discrepancies, we reiterate with different GTOW and SECO weights to meet payload requirements. If the payload requirements can be met, but the volume will not close, this will result in shape changes to either accommodate additional volume requirements or eliminate wasted volumes.

Table 1. Sizing Variables (TBCC Example).

Stage 1 Design Constants	English	SI	**Stage 2 Design Constants**	English	SI
Küchemann $\boldsymbol{\tau}$ - Volume/(Planform Area)$^{3/2}$	0.116	0.116	Küchemann $\boldsymbol{\tau}$ - Volume/(Planform Area)$^{3/2}$	0.178	
K_{w1} - wetted area/planform area,	2.59	2.59	K_{w2} - wetted area/planform area,	2.57	
I_{str1} – Structural Index, lbm/ft^2	3.0		I_{str2} – Structural Index, lbm/ft^2	3.0	
I_{TPS1} – TPS Index (M_{stg}=10, axialG=0.5), lbm/ft^2	0.56		I_{TPS2} – TPS Index (Entry W/C_lA=60), lbm/ft^2	1.41	
T/W_{eng1} – Uninstalled TJ Engine T/W, Lbf/Lbm	6.65		T/W_{eng2} – Uninstalled Engine T/W, Lbf/Lbm	N/A	
T/$W_{rocket1}$ – Rocket Engine T/W, Lbf/Lbm	N/A		T/$W_{rocket2}$ – Rocket Engine T/W, Lbf/Lbm	50	
Isp1 – Isp of 1st Stg Rocket Engine, seconds	N/A		Isp2 – Isp of 2nd Stg Rocket Engine, seconds	458	
I_{scrj} –Scramjet Index Engine Wt/Inlet Area, lbm/ft^2	200		$W_{maxpayload}$ –Design Max payload wt, lbm	20,000	
ρ_{tj1} – Turbojet Compartment Density, pcf	250		Isp_{OMS} – Isp of 2nd Stg OMS Engines, secs	440	
$\rho_{rocket1}$ – 1st Stg Rocket Bay Density, pcf	50		$\rho_{rocket2}$ – 2nd Stg Rocket Bay Density, pcf	30	
k_{recess} – Fraction of 2nd stg recessed in 1st stg	0.9		$V_{payload}$ – 15 ft dia by 30 ft long, cuft	5,300	
k_{vv1} – 1st Stg Void Fraction	0.25		k_{vv2} – 2nd Stg Void Fraction	0.30	
Stage 1 Design Variables			**Stage 2 Design Variables**		
Takeoff Speed, knots	300		Landing Speed,, knots	187	
Max Takeoff Weight	1,050,000		Max Landing Weight	90,000	
S_{plan1} – Stg1 Planform Area, sqft	10,500		S_{plan2} – Stg2 Planform Area, sqft	2,585	
Stg1 Volume req'd for Takeoff	123,000		Stg2 Volume req'd for Landing	23,394	
Stg1 Volume req'd for Vehicle Elements	113,669		Stg2 Volume req'd for Vehicle Elements	23,354	
$W_{TotProp1}$ – Stg1 Total Fuel, lbm	212,782		$W_{TotProp2}$ – Stg2 Total Propellants, lbm	180,711	
T_{vac1} – Stg1 Total Sea-Level Static Thrust, Lbf	726,165		T_{vac2} – Stg2 Total Vac Rocket Thrust, Lbf	305,675	

Sizing Results - TBCC

The input data for the TBCC TSTO example case is shown in Table 1 for the nominal design conditions (300 knot takeoff and F-135 derivative turbofan engines burning hydrogen). Sensitivity to increased takeoff speeds and more advanced turbojet engines are included in the summary data.

Rocket-Based Combined Cycle (RBCC) Concept

The RBCC concept is based on Boeing Company data published in Reference 8. The ram/scramjet performance data used to size the RBCC concept employed a different reference area from the ram/scramjet data published by ARC and used to size the TBCC, so the inlet area tabulations are misleading. However, the unit weights are almost identical as are the specific impulses, so the differences are in the nomenclature. This will be corrected in later versions of this paper. The RBCC configuration shown in Figure 3 has seven propellant and fuel tanks to insure balance and trim. We did not track balance in this quick look study and take it for granted that the tanks shown will suffice.

The RBCC first stage analyzed here shares the Spatula-nosed, lifting-body shape of the TBCC first stage, and the second stage is identical. The turbine accelerator engines are replaced by rocket nozzles buried in the ramjet/scramjet sidewalls. The RBCC operates as an Air Augmented Rocket (AAR) during takeoff to Mach 3, where the rockets are phased out and secondary injectors allow the system to operate as a subsonic combustion ramjet. Base-burning is used to reduce base drag during transonic and supersonic acceleration. At Mach 5.5, use of additional fuel injectors allow the engines to switch to supersonic combustion up to Mach 10, where a pull-up maneuver is initiated to reduce dynamic pressure for staging to 200 psf. At 200 psf, the scramjet is shutdown and a push-over maneuver is initiated to aid in separation of the second stage. A separation system based on air-bags under the second stage was assumed, and weight penalties were included. After separation, the air-bags fill the void in the top of the first stage. Note that 90% of the second stage volume is recessed into the first stage for both the RBCC and TBCC configurations. This reduced transonic drag and eliminated the need for a tail rocket to augment the low speed propulsion system during acceleration through Mach 1.0.

Sizing Results - RBCC

The thrust loading of the AAR is assumed to be 1500 lbs thrust per square-foot of inlet area and the RBCC engine characteristics are based on data published in Reference 8. The sizing constants and the resulting design variables are shown in Table 2. The data shown is for the nominal 300-knot takeoff speed. Sensitivity to increased takeoff speed was assessed to allow the RBCC to more closely match the planform loading required for takeoff with volume needed to hold the required systems. The optimum takeoff speed appears to be slightly more than 360 knots.

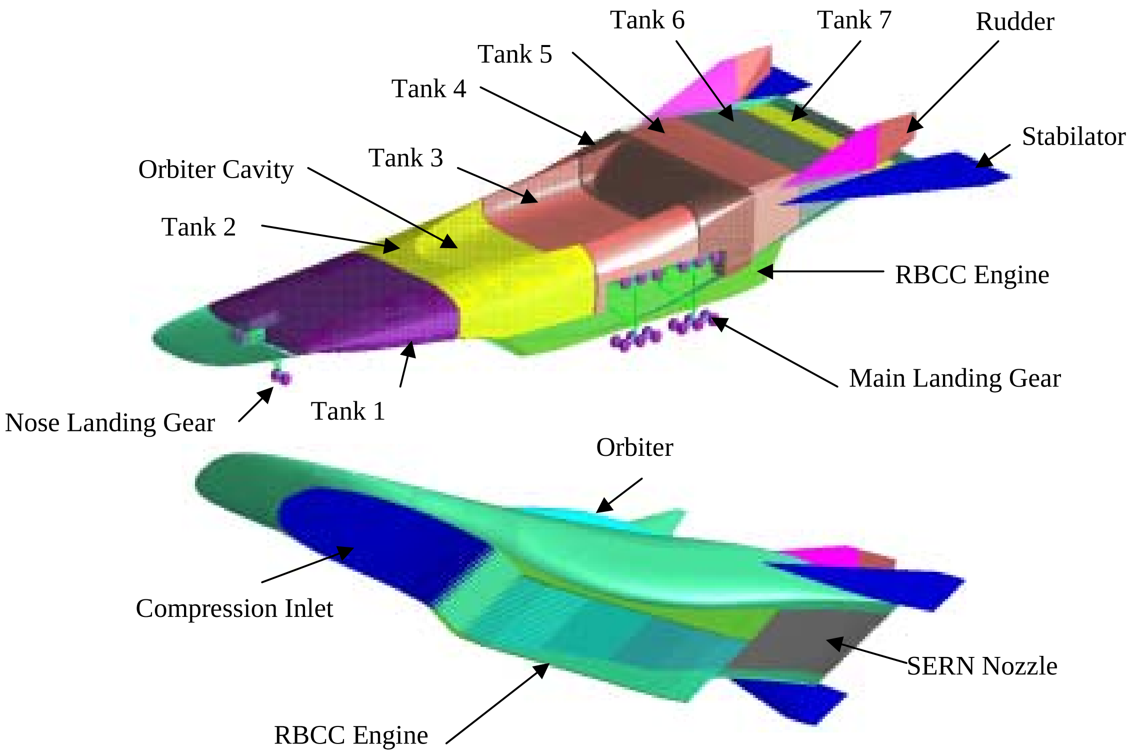


Figure 5. RBCC Configuration Features.

Table 2. Sizing Variables – RBCC Example.

Stage 1 Design Constants	English	SI	**Stage 2 Design Constants**	English	SI
Küchemann τ - Volume/(Planform Area)$^{3/2}$	0.116	0.116	Küchemann τ - Volume/(Planform Area)$^{3/2}$	0.178	
K_{w1} - wetted area/planform area,	2.59	2.59	K_{w2} - wetted area/planform area,	2.57	
I_{str1} – Structural Index, lbm/ft^2	3.0		I_{str2} – Structural Index, lbm/ft^2	3.0	
I_{TPS1} – TPS Index (M_{stg}=10, axialG=0.5), lbm/ft^2	0.56		I_{TPS2} – TPS Index (Entry W/C_lA=60), lbm/ft^2	1.41	
T/W_{eng1} – Uninstalled TJ Engine T/W, Lbf/Lbm	6.65		T/W_{eng2} – Uninstalled Engine T/W, Lbf/Lbm	N/A	
T/$W_{rocket1}$ – Rocket Engine T/W, Lbf/Lbm	N/A		T/$W_{rocket2}$ – Rocket Engine T/W, Lbf/Lbm	50	
Isp1 – Isp of 1st Stg Rocket Engine, seconds	N/A		Isp2 – Isp of 2nd Stg Rocket Engine, seconds	458	
I_{scrj} –Scramjet Index Engine Wt/Inlet Area, lbm/ft^2	85		$W_{maxpayload}$ –Design Max payload wt, lbm	20,000	
ρ_{tj1} – Turbojet Compartment Density, pcf	250		Isp_{OMS} – Isp of 2nd Stg OMS Engines, secs	440	
$\rho_{rocket1}$ – 1st Stg Rocket Bay Density, pcf	50		$\rho_{rocket2}$ – 2nd Stg Rocket BayDensity, pcf	30	
k_{recess} – Fraction of 2nd stg recessed in 1st stg	0.9		$V_{payload}$ – 15 ft dia by 30 ft long, cuft	5,300	
k_{vv1} – 1st Stg Void Fraction	0.25		k_{vv2} – 2nd Stg Void Fraction	0.30	
Stage 1 Design Variables			**Stage 2 Design Variables**		
Takeoff Speed, knots	300		Landing Speed,, knots	160	
S_{plan1} – Stg1 Planform Area, sqft	10,500		S_{plan2} – Stg2 Planform Area, sqft	2,585	
Stg1 Volume req'd for Takeoff	121,945		Stg2 Volume req'd for Landing	23,394	
Stg1 Volume req'd for Vehicle Elements	113,669		Stg2 Volume req'd for Vehicle Elements	23,354	
$W_{TotProp1}$ – Stg1 Total Propellants, lbm	212,782		$W_{TotProp2}$ – Stg2 Total Propellants, lbm	180,711	
T_{vac1} – Stg1 Total Sea-Level Static Thrust, Lbf	726,165		T_{vac2} – Stg2 Total Vac Rocket Thrust, Lbf	305,675	

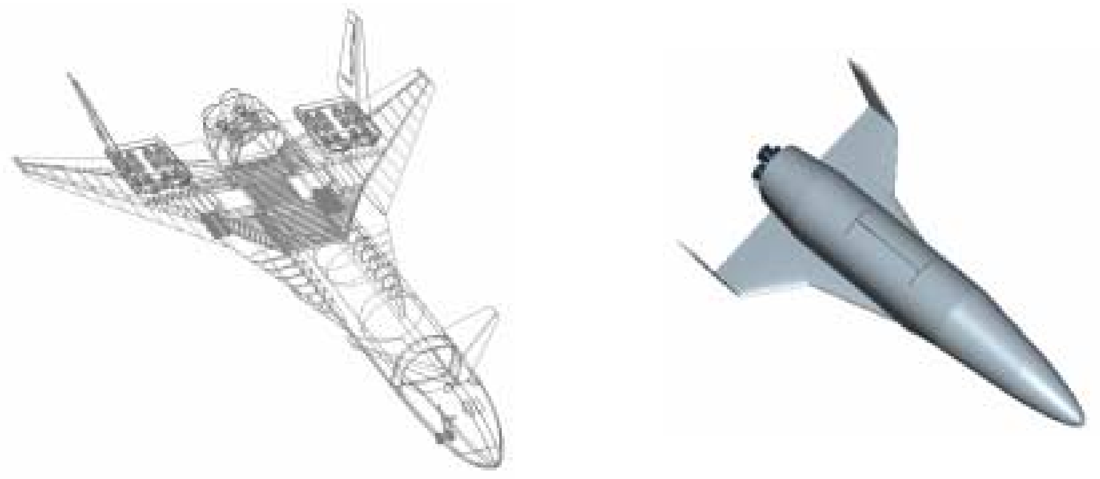


Figure 6. Gryphon First and Second Stage Configurations.

Alchemist ACES Concept

Introduction to Alchemist ACES

Andrews Space has developed an in-flight propellant collection system, the “Alchemist” Air Collection and Enrichment System (ACES), that is significantly different from previous proposed ACES in that it operates subsonically, thereby eliminating many of the issues involved with integrating a large two-stage supersonic/hypersonic aircraft (References 10-12). ACES propulsion technology enables reasonably-sized TSTO RLVs that take off and land horizontally with fault tolerant air breathing and rocket propulsion systems to enable safe trans-atmospheric and space operations. All internal and NASA-funded activities have shown that ACES, previously proposed for hypersonic combined cycle RLVs, is a higher payoff, lower-risk technology if LOX generation is performed while the vehicle cruises subsonically (References 13-16). We have named the subsonic variant of ACES “Alchemist”, since it turns air into rocket propellant. The Alchemist ACES proposed by Andrews Space has only moderate technical risk with its enabling technologies because key elements have been demonstrated during previous programs (Reference 12).

Mission Operation / Profile

During a typical mission for an ACES-driven, HTHL Two-Stage-to-Orbit (TSTO) architecture (shown in Figure 6), both stages use liquid hydrogen and oxygen rocket engines for rocket powered flight. The second stage, which consists of either an Orbiter or an Upper Stage, rides “piggyback” on the Aerospaceplane first stage. The vehicle, fueled with its compliment of hydrogen and jet fuel, takes off and climbs using military turbofan engines, which are used based on the requirements for high thrust at altitude (low bypass ratio) and engine augmentation (afterburners). Once at altitude, the RLV can either cruise for thousands of miles or begin generating LOX. The ACES uses liquid hydrogen at approximately fifteen pounds per second, outputs approximately one hundred twenty pounds of 95+% pure LOX, and supplies the gasified hydrogen at high pressure to the turbofan engines where it is burned to augment the Jet-A normally burned for cruise. Complete LOX collection takes two to three hours, which allows the vehicle to cruise to the desired launch point and address all azimuths from a single operating base.

Once LOX tanking is finished, the RLV assumes the proper heading, a pull-up maneuver is initiated, the first stage rocket engines fire, and the combined stages begin a rapid climb. Shortly thereafter the second stage engines ignite. The turbofan engines are shut down shortly thereafter at about Mach 1.7, and the inlets are covered. At approximately Mach 6, the propellant cross-feeds disconnect, the first stage throttles back to match the acceleration of the second stage, and the stages separate. The first stage then shuts down its engines and, using its ACS, rotates to a high angle of attack (between 30 and 60 degrees) for re-entry. The second stage proceeds to LEO and begins payload operations as required. The first stage re-enters, restarts the turbofan engines, and returns to base. In this architecture, the Alchemist ACES provides all required LOX and all liquid nitrogen required for tank chill-down, so when the vehicle flies off the runway, it has no oxidizers on-board and theoretically meets all FARs for commercial aircraft operations.

Table 3. Sizing Variables (Alchemist ACES).

Stage 1 Design Variables		**Stage 2 Design Variables**		**Comments**
Takeoff Speed, kts	238	Landing Wing Loading, psf	65	Orbiter touchdown speed ~ 187 kts
LOX Generation Rate, pps	120	Payload Bay Diameter, ft	15	
Max Duct Bleed Fraction	0.85	Payload Bay Length, ft	30	
Alchemist Collection Ratio	8.75			
LOX Yield Fraction	0.90			
Alchemist Spec Wt, lbs/ppsLOX	345			
SLS Installed HP/ pps LOX	1500			
Sp_{SHP} (SLS) available, HP/lbm	6.0			

Sizing Results – ACES

The reference ACES has eight F-135 derivative turbofan engines and four SSMEs for propulsion on the first stage. If a rocket motor should fail during the first stage burn, the remaining rocket engines are shut down, LOX is dumped, the combined vehicle stack reenters, the jet engines are restarted, and the carrier with the upper stage and payload flies home. This is main propulsion system fault tolerance. The second stage has three 200,000 pound thrust RS-2100 engines (IPD derived), and if one fails (non-catastrophically), there is an overlap between the opportunities for safe return to launch site and abort to orbit. This is made possible by the ability to fly up-range during LOX-collection and stage almost directly over the recovery base.

Because the ACES concept is a wing body configuration, the inert weights are calculated differently. The wing area on the first stage is selected to meet takeoff speed, the body is sized to hold the required propellants and systems, and the second stage is carried externally since transonic T/W is not a problem. We have generated a weight estimating relationship, which accurately models the inert weight based on the basic design variables:

$W_{inert1} = 18.1342 * S_{ref1} + 0.1445 * W_{TotProp1} + 0.1746 * (W_{inert2} + W_{TotProp2} + W_{Payload}) + 0.0315 * n_{Stg1} * T_{Vac1} + 0.2724 * n_{TF1} * Fn_{SLS1} + S_{Hpinstal} / Sp_{SHP} + 82147.3$

where:

- S_{ref1} is the wing reference area
- $W_{TotProp1}$ is the total rocket propellant in stage one including the propellants cross-fed to stage two during boost
- n_{Stg1} is the number of rocket engines on stage one
- T_{Vac1} is the vacuum thrust of each engine
- n_{TF1} is the number of turbofans
- Fn_{SLS1} is the maximum sea level static thrust for each (wet)
- $S_{HPinstal}$ (SLS) is the total shaft power of the turbo-shaft motors used to drive the air compressors
- Sp_{SHP} (SLS) is the specific power of each turbo-shaft engine in HP/lb_m.

This weight estimating relationship assumes the duct-extraction option of Alchemist ACES is used where auxiliary turboshaft engines drive a second bank of compressors to raise the pressure of the bleed air from 40 psia to 270 psia before it enters the first bank of heat exchangers. The final ACES optimization assumed the core extraction option where air is extracted from the engine core flow at 220 psia, compressed to 270 psia, chilled to its dew point, oxygen component removed using fractional distillation, recompressed, and injected back into the engine core. This requires considerably less power, which reduces the ACES weight penalty.

A similar weight estimating relationship can be written for the inert weight of the second stage:

- $W_{inert2} = 0.5090 * W_{maxpayload} + 0.1046 * W_{TotProp2} + 0.0431 * n_{Stg2} * T_{Vac2} + 43557$

- Where:
- $W_{maxpayload}$ is the maximum design payload capacity of the stage
- Other variables are as in stage one.

Summary of Results

Table 4 below shows the advantages of airbreathing first stages for horizontal takeoff TSTO RLVs. Comprable takeoff weights for all-rocket horizontal TSTO RLVs would be the in 2.5 Mlb range. Notice that there is actually not much difference between the inert weights and performance of the three concepts when equivalent technologies are applied. In effect, the higher specific impulse of the hypersonic air-breathers is canceled out by the additional drag losses relative to the air-launched rocket using ACES.

The lifting body shape of the TBCC and RBCC demands higher takeoff speeds or auxiliary wings to effectively package the required propellants and subsystems. This will require new tire development or use of a ground accelerator facility. The ACES concept would also benefit from higher speed tires, but not as much. Lighter airbreathing engines help all concepts, and the lightest systems use both high takeoff speed and lighter airbreathing engines. In the case of ACES this was use of the core extraction option, which significantly reduced the Alchemist specific weight from 345 lb_m/pps LOX to 217 lb_m/pps LOX.

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The bottom line is which concept provides the lowest cost and development risk? The choice is between Alchemist ACES for which the key components have essentially already been demonstrated in ground test versus a TBCC or RBCC with new hypersonic air-breathing engines, new-active cooled structures, new high-speed wheels and tires, and a new advanced low-speed propulsion system. The choices are not quite that simple, but risk will probably be a key factor in future RLV decisions.

Table 4. Performance Comparison.

	ABLV-7C TBCC			ABLV-7C RBCC			Alchemist ACES		
	300 kts	310 kts	+AdvTJ	300 kts	311 kts	360 kts	240 kts	300 kts	+CETF
Max q	2,000	2,000	2,000	2,000	2,000	2,000	800	800	800
Pullup Mach No.	10.00	10.00	10.04	10.00	9.99	10.01	0.96	0.95	0.93
Pullup Max Normal G	1.92	2.00	1.96	2.00	1.99	2.00	1.71	1.73	1.99
Pullup altitude	95,707	95,891	95,694	96,608	96,598	95,799	20,048	19,504	18,694
Stg Mach No	9.13	9.12	8.94	8.70	8.76	8.74	5.96	6.20	6.20
Stg Altitude	145,196	145,136	144,115	145,260	144,136	142,973	182,037	183,518	177,760
Stg q	200	200	200	181	192	200	21	21	27
1st Stg TF/TJ SLST	913,043	787,180	460,430	N/A	N/A	N/A	345,330	345,330	345,330
1st Stg SCRJ Inlet Area	382.35	340.48	277.09	628.38	594.04	464.42	N/A	N/A	N/A
2nd Stg Rocket VacThrust	291,175	295,160	300,050	306,920	305,000	317,500	588,450	564,600	537,120
Takeoff Weight	1,231,146	1,132,214	978,458	1,466,565	1,251,091	1,023,286	1,100,635	1,048,867	958,572
1st Stg Splan	12,200	10,400	10,400	14,500	11,410	7,080	9,703	6,210	5,675
1st Stg Volume Req	158,461	139,750	123,029	206,020	162,327	120,075	N/A	N/A	N/A
1st Stg Inert	654,148	577,705	457,989	530,605	462,076	348,257	559,873	517,058	428,583
1st Stg Rocket Propellant	N/A	N/A	N/A	403,396	302,028	226,029	774,073*	754202*	681,847*
1st Stg A/B Fuel	313,550	290,113	252,452	255,745	206,604	168,952	252,050	221,600	214,020
2nd Stg Ign altitude	154,843	154,108	153,759	155,637	153,119	149,574	37,293	34,393	36,285
2nd Stg Splan	2,585	2,585	2,585	2,630	2,630	2,630	2,163	2,132	2,104
2nd Stg Volume Req	23,394	23,394	23,394	24,008	24,008	24,008	N/A	N/A	N/A
2nd Stg Inert	67,303	67,418	67,294	68,391	68,355	68,702	118,840	115,995	114,239
2nd Stg Prop	176,146	176,977	180,723	188,429	192,028	191,346	379,925	362,558	357,097
Payload	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
Stg1 DV Ideal	20,666	20,504	21,097	22,127	18,855	17,098	8,390	8,631	8,551
Total DV ideal	36,575	36,449	37,254	38,563	35,517	33,702	27,420	27,383	27,280

* At Ignition

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