AIAA 2004-3728

Aztec: A TSTO Hypersonic Vehicle Concept Utilizing TBCC and HEDM Propulsion Technologies

T. Kokan
J.R. Olds
V. Hutchinson
J.D. Reeves

Space Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA

40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference And Exhibit
11 - 14 July 2004
Fort Lauderdale, Florida

Aztec: A TSTO Hypersonic Vehicle Concept Utilizing TBCC and HEDM Propulsion Technologies

Timothy Kokan*, John R. Olds†, Virgil Hutchinson*, John Daniel Reeves*

Space Systems Design Lab
School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA, 30332-0150
timothy_kokan@ae.gatech.edu

The *Aztec* reusable launch vehicle (RLV) concept is a two-stage-to-orbit (TSTO) horizontal takeoff, horizontal landing (HTHL) vehicle. The first stage is powered by ten JP-5 fueled turbine-based combined-cycle (TBCC) engines. The second stage is powered by three high energy density matter (HEDM)/liquid oxygen (LOX) staged-combustion rocket engines. The HEDM fuel is a liquid hydrogen-based propellant with a solid aluminum and methane gel additive.

***Aztec* is designed to deliver 20,000 lbs of payload to a 100 nmi x 100 nmi x 28.5° orbit due East out of Kennedy Space Center (KSC). The second stage separates at Mach 8 and continues to the target orbit while the first stage flies back to KSC in ramjet mode. For the above payload and target orbit, the gross lift-off weight (GLOW) is estimated to be 690,000 lbs and the total dry weight for both stages is estimated to be 230,000 lbs. Economic analysis indicates that the *Aztec* recurring launch costs will be approximately $590 per lb. of payload delivered to the target orbit. The total non-recurring cost including design, development, testing and evaluation (DDT&E), acquisition of the first vehicle, and the construction of launch and processing facilities is expected to be $13.6B. All cost figures are in FY$2004 unless otherwise noted.**

Details of the *Aztec* design including external and internal configuration, aerodynamics, mass properties, first and second stage engine performance, ascent and flyback trajectory, aeroheating results and thermal protection system (TPS), vehicle ground operations, vehicle safety and reliability, and a cost and economics assessment are provided.

Nomenclature

α	=	angle-of-attack, °
AFRSI	=	Advanced Flexible Reusable Surface Insulation
ASTP	=	Advanced Space Transportation Program
CAD	=	computer aided design
CER	=	cost estimating relationship
c_L	=	coefficient of lift
DDT&E	=	design, development, test, & evaluation
DSM	=	Design Structure Matrix
EMA	=	electro-mechanical actuators
GLOW	=	gross lift-off weight
GRC	=	Glenn Research Center

* Graduate Research Assistant, School of Aerospace Engineering, Student member AIAA.
† Associate Professor, School of Aerospace Engineering, Associate Fellow AIAA.

HEDM	=	high energy density matter
HTHL	=	horizontal takeoff, horizontal landing
IOC	=	initial operating capability
Isp	=	specific impulse, sec
KSC	=	Kennedy Space Center
LCC	=	life cycle cost
LOX	=	liquid oxygen
LRU	=	line replacement unit
MECO	=	main engine cutoff
MER	=	mass estimating relationship
MR	=	mass ratio (gross weight / burnout weight)
MSFC	=	Marshall Space Flight Center
OMS	=	orbital maneuvering system
PEF	=	propellant packaging efficiency
q	=	dynamic pressure, psf
RCS	=	reaction control system
RLV	=	reusable launch vehicle
RTA	=	Revolutionary Turbine Accelerator
TBCC	=	turbine-based combined-cycle
TFU	=	theoretical first unit
TPS	=	thermal protection system
TSTO	=	two-stage-to-orbit
TUFI	=	Toughened Unipiece Fibrous Insulation
UHTC	=	Ultra-High Temperature Ceramic

I. Introduction

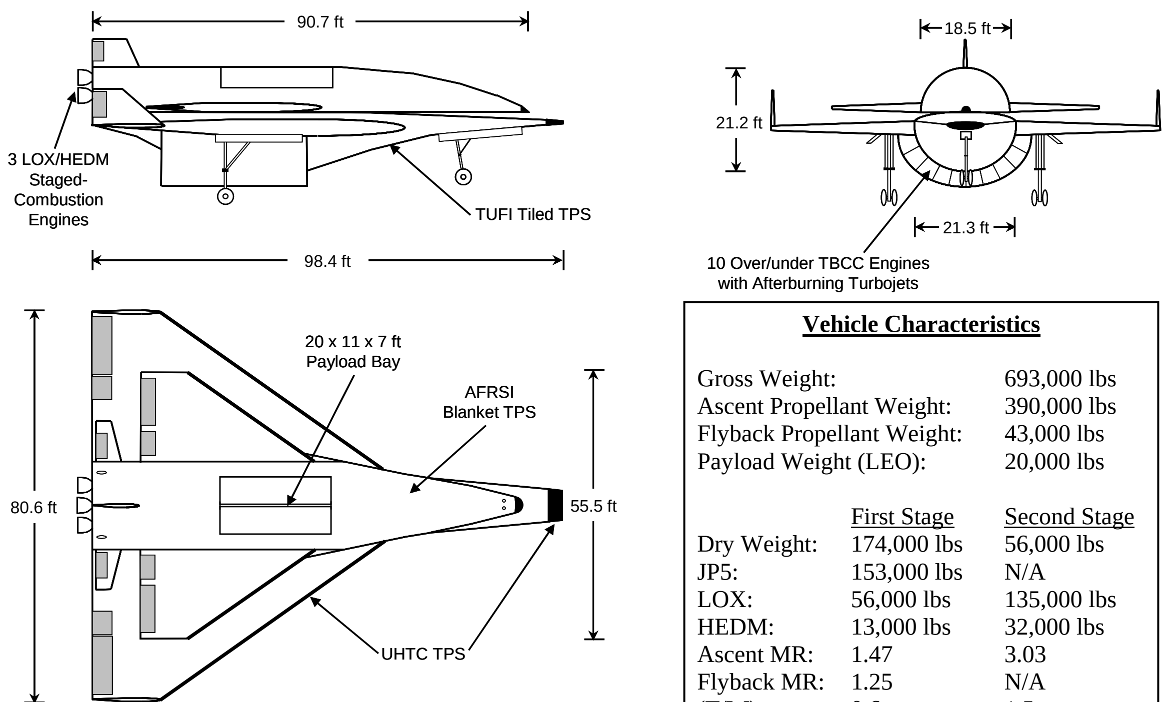
NASA Glenn Research Center (GRC) is currently working to develop and demonstrate a reusable turbine-based propulsion system as part of NASA's Advanced Space Transportation Program (ASTP)[1]. TBCC engines are multimode engines that provide significant benefits over conventional rocket engines. These engines use atmospheric oxygen along with on-board fuel as propellants. This is an important advantage over rocket engines in that the oxygen, which makes up a significant portion of the gross weight of a conventional launch vehicle, does not need to be carried along in propellant tanks on a TBCC-powered vehicle. Operational benefits such as reduced turnaround time, improved reusability, and improved versatility for launch and landing sites are also possible with TBCC propulsion systems[1].

GRC and NASA Marshall Space Flight Center (MSFC) are also currently working on HEDM propulsion development and testing. MSFC has performed a series of small-scale, hot fire tests on several new hydrocarbon-based HEDM propellants such as quadricyclane, 1-7 Octadiyne, AFRL-1, and CINCH[2]. Based upon this round of small-scale tests, MSFC is planning a larger scale engine test program to further demonstrate the performance of these new fuels.

The research at GRC has focused more upon hydrogen-based HEDM propellants. Experiments in the formation of solid hydrogen particles in liquid helium have been performed[3]. Studies using gelled hydrogen and metallized gelled hydrogen fuels have shown potential in significantly increasing payload delivery capability and/or reducing GLOW[4,5]. Gelled hydrogen fuel consists of liquid hydrogen with solid, frozen particles of a different fuel added to form a gel structure in the hydrogen. Methane is an example of a potential gellant particle used in conjunction with hydrogen. Metallized gelled propellants introduce metallic particles, such as aluminum, into the gellant. The result is a higher specific impulse (I_{sp}) engine, with significantly higher fuel density over standard hydrogen fuel.

These new technologies, each with very promising benefits for future reusable launch vehicles, are incorporated into *Aztec*. *Aztec* is a two-stage, fully reusable vehicle with a TBCC first stage and a HEDM rocket second stage. The first and second stages take off horizontally and each lands horizontally. The first stage TBCC engines operate in three distinct modes: afterburning turbojet, ramjet, and scramjet. The TBCC engines are in an over-under configuration with the upper flow path being the low speed turbojet path while the lower flow path is for the high speed ramjet and scramjet modes. The engine operates in turbojet mode from takeoff to Mach 2.5. In the transonic region, from Mach 0.8 to Mach 1.5, the second stage HEDM rocket engines are used in conjunction with the first stage turbojets. This extra thrust in the transonic region is needed due to the fact that turbojet thrust suffers and drag increases significantly. From Mach 2.5 to Mach 6, the first stage engine operates in ramjet mode. This engine then transitions to scramjet mode and operates in this mode from Mach 6 to Mach 8. At Mach 8, the second stage separates and the first stage turns around and flies back in ramjet mode. The second stage HEDM rocket engines are then relit and propel the second stage to a 50 nmi x 100 nmi x 28.5° orbit. Upon reaching this orbit, the second stage engines are shut off and the vehicle coasts until reaching apogee. Once at apogee, the second stage main engines are used again to perform an orbital maneuvering burn to transition into the target 100 nmi x 100 nmi x 28.5° orbit.

A full multi-disciplinary vehicle design was performed for *Aztec*. Disciplines analyzed include: external and internal configuration with the solid modeling tool Pro/Engineer, aerodynamic analysis with APAS / HABP, mass estimation using standard industry mass estimating relationships (MERs), turbojet performance using T-BEAT, ramjet and scramjet performance using SCCREAM, rocket engine performance using REDTOP, ascent trajectory optimization using POST, flyback trajectory analysis using an Excel spreadsheet model, aeroheating analysis using Miniver, thermal protection system (TPS) sizing using TCAT, vehicle ground operations analysis using AATe, vehicle safety and reliability estimation using GT-Safety II, vehicle non-recurring cost estimation using NAFCOM-derived cost estimating relationships (CERs), and an economics assessment using CABAM. An excellent description of each of these design tools can be found in reference 6.



Vehicle Characteristics

Gross Weight:		693,000 lbs
Ascent Propellant Weight:		390,000 lbs
Flyback Propellant Weight:		43,000 lbs
Payload Weight (LEO):		20,000 lbs
	First Stage	Second Stage
Dry Weight:	174,000 lbs	56,000 lbs
JP5:	153,000 lbs	N/A
LOX:	56,000 lbs	135,000 lbs
HEDM:	13,000 lbs	32,000 lbs
Ascent MR:	1.47	3.03
Flyback MR:	1.25	N/A
$(T/W)_{veh}$:	0.6	1.5

Figure 1. ***Aztec*** **Concept Configuration**

II. The *Aztec* Concept

A. Overview

Aztec is a two-stage, fully reusable vehicle with a conical forebody first stage, highly swept wings on both the first and second stage, and twin vertical winglets on the first stage (see Figure 1). The first stage has ten JP-5 fueled TBCC engines in an over-under configuration (see Figure 1). The first stage holds three propellant tanks: a JP-5 tank for the TBCC engines, a HEDM tank, and a LOX tank for cross-feeding propellants to the second stage. The cross-fed propellants are used when the second stage engines are firing during flight through the transonic region. The first stage has a three ramp forebody to precompress the air entering the underslung TBCC engines.

The second stage is powered by three LOX/HEDM fueled staged-combustion engines. The HEDM propellant used is a hydrogen-based fuel doped with solid methane and aluminum to increase the propellant density. This allows for a more compact second stage that is able to integrate more easily with the first stage.

The baseline *Aztec* is designed to deliver 20,000 lbs of payload to a 100 nmi x 100 nmi x 28.5° orbit due East out of Kennedy Space Center (KSC). The initial operating capability (IOC) for *Aztec* is designed to be 2025 with a technology freeze date of 2018. The baseline airframe life is designed to be 1,000 flights for both stages and the baseline engine life is designed to be 500 flights for both the airbreathing and rocket engines.

Aztec utilizes several additional advanced technologies currently under development. Ultra-High Temperature Ceramic (UHTC) TPS is used on the wing and tail leading edges, the nose, and the cowl leading edge in order to avoid actively cooling these high temperature areas. The remainder of the windward side of both vehicles is covered with Toughened Unipiece Fibrous Insulation (TUFI) TPS tiles while the leeward side of both vehicles is covered with Advanced Flexible Reusable Surface Insulation (AFRSI) blankets. The main fuselage and wing structure of both vehicles is made of titanium-aluminide while the LOX, JP-5, and HEDM main propellant tanks are made of graphite-epoxy composites. To avoid using heavy hydraulic actuators and the subsequent heavy, high pressure hydraulic fluid lines, electro-mechanical actuators (EMAs) are used for control surface actuation on both stages.

B. Mission Profile

Aztec takes off horizontally from a KSC spaceport in Florida (see Figure 2). *Aztec* uses its ten TBCC first stage engines to provide the required takeoff thrust. The takeoff thrust-to-weight is 0.6, with each afterburning turbojet engine providing approximately 41,600 lbs of sea-level static thrust. *Aztec* operates in this mode up to approximately Mach 0.8. At this point, the second stage HEDM rocket engines are lit in order to provide additional thrust to accelerate through transonic. The second stage rockets are needed due to the fact that the turbojet thrust suffers slightly through transonic and the overall vehicle drag increases significantly. The HEDM rocket engines are kept on until approximately Mach 1.5 and are then shut off until just prior to second stage separation.

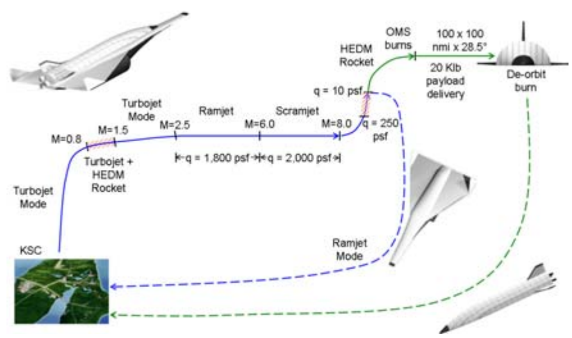


Figure 2. *Aztec* Mission Profile

Figure 3. Second Stage Separation and Ascent

At Mach 2.5 the first stage TBCC engines switch to ramjet mode. This is done by closing off the low speed turbojet flow path and opening up the high speed ramjet/scramjet flow path. *Aztec* enters a 1,800 psf dynamic pressure (q) flight profile and flies along this constant pressure boundary up to Mach 6. At Mach 6, the TBCC engines switch to scramjet mode by decreasing the backpressure to obtain super sonic combustion. *Aztec* then flies on a 2,000 psf dynamic pressure profile while in scramjet mode. This increase in dynamic pressure can be accomplished because the static pressure within the combustor reduces significantly once the normal shock is removed, thus allowing for a higher dynamic pressure while not increasing engine weight.

Aztec flies in scramjet mode until Mach 8. At this point, the vehicle pulls up off the dynamic pressure flight profile. At a dynamic pressure of 250 psf, the second stage engines are relit to provide the necessary thrust to reach the staging dynamic pressure of 10 psf. Staging occurs at approximately Mach 8.2, a flight path angle (γ) of 10.7°, and an altitude of approximately 215,000 ft. Upon separation, the second stage continues its ascent (see Figure 3). The first stage then turns around while slowing down and descending, and returns to the launch site in ramjet mode.

The second stage continues its ascent and enters into a 50 nmi x 100 nmi x 28.5° orbit. Main engine cut-off (MECO) occurs at perigee. The second stage coasts until apogee where the vehicle performs a ΔV, using the main HEDM engines, to get into a 100 nmi circular orbit. The payload bay doors are opened and the payload released. The second stage finally de-orbits and performs an unpowered, autonomous landing.

III. Multidisciplinary Design Process

The conceptual design of a reusable launch vehicle involves many disciplines. These disciplines are highly coupled with one another. Figure 4 is a design structure matrix (DSM) for the *Aztec* conceptual design process.

A DSM provides a very concise, structured means of representing the disciplines involved and the interactions between disciplines. The links between the discipline boxes represent data flow from one discipline to another. The links in the upper right represent data flow downstream while the links in the lower left represent the data flow upstream. Upstream data flow requires iteration in order to converge the design. The conceptual vehicle design has two main iteration loops: one between propulsion, trajectory, aeroheating, and weights & sizing, and the other between ground operations, safety & reliability, and economics.

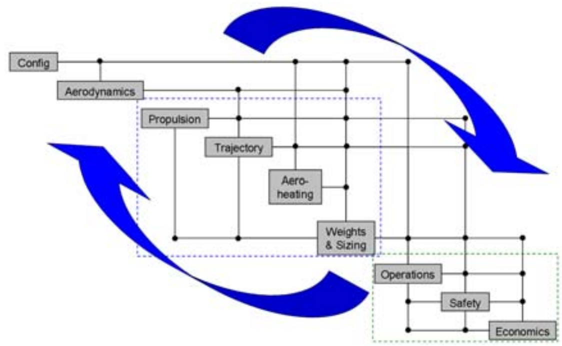


Figure 4. *Aztec* Design Structure Matrix

For *Aztec*, the main iteration loop between propulsion, trajectory, aeroheating, and weights & sizing required 10 iterations to converge. This convergence rate is typical of conceptual vehicle design processes of this type. Convergence was defined as a less than 0.1% change in overall vehicle mass ratio and mixture ratio from one iteration to the next. The second stage was reconverged at each iteration of the first stage main convergence loop. Second stage convergence required 3-5 iterations each time. Although this method requires iteration between the first and second stage, a more optimal staging point can be found as opposed to simply specifying the staging condition ahead of time.

Each discipline has one or more conceptual design tools associated with it. Table 1 provides a listing of each discipline and its associated design tool or tools.

Table 1. *Aztec* Disciplinary Design Tools

Discipline	*Analysis Tool*
Configuration & CAD	Pro/E, MathCAD
Aerodynamics	APAS (UDP, HABP)
Turbojet Propulsion	T-BEAT
Ramjet/Scramjet Propulsion	SCCREAMv6
Rocket Propulsion	REDTOP
Ascent Trajectory	POST 3-D
Flyback Trajectory	MS Excel
Aeroheating	MINIVER
Weights & Sizing	MS Excel
Operations	AATe, Arena
Safety & Reliability	GT Safety II
Cost	NAFCOM-99
Economics	CABAM

IV. Baseline Design Results

A. Internal Configuration and Layout (CAD)

Aztec's first stage has a length of 98.4 ft (nose-to-tail) for the baseline configuration. The baseline first stage fuselage volume is 8,200 ft^3. The maximum first stage fuselage width is 21.3 ft and the maximum vehicle height, including engine cowl and landing gear, is 18.0 ft. The second stage has a length of 90.7 ft with a total fuselage volume of 9,500 ft^3. The maximum fuselage width for the second stage is 18.5 ft with a maximum vehicle height, including the landing gear, of 11.0 ft. The payload bay on the second stage is 20 ft. long, 11 ft. wide, and between 6 ft. and 8 ft. tall. The height varies because the top of the payload bay conforms to the rounded top of the second stage fuselage.

Propellant tanks, landing gear, engine structure, and the payload bay are packaged on both stages using Pro/Engineer, a solid modeling Computer Aided Design (CAD) package. First and second stage internal and external views of *Aztec* are shown in Figures 5, 6, 7, and 8.

An important output of the configuration discipline is the propellant packaging efficiency (PEF) of each stage. The PEF is defined as the percentage of fuselage volume occupied by the main propellant tanks. This packaging efficiency term is fed into the weights & sizing discipline to calculate the total propellant volume.

In order to remove the configuration discipline from the main design loop, a curve fit of packaging efficiency as a function of vehicle length is performed. Packaging efficiency changes as vehicle length changes because certain internal components such as the payload bay must retain their size no matter how the size of the vehicle changes. The PEF curve fit is created from three different CAD layouts at three different lengths. A second order curve fit of these three points is then created in order to allow rapid calculation of PEF as vehicle length changes. This curve fit equation is then used in the weights & sizing discipline. The converged first stage packaging efficiency for *Aztec* is 65.5% while the second stage packaging efficiency is 55.1%. The second stage has a lower packaging efficiency because a significant percentage of the internal fuselage volume is occupied by the payload bay.

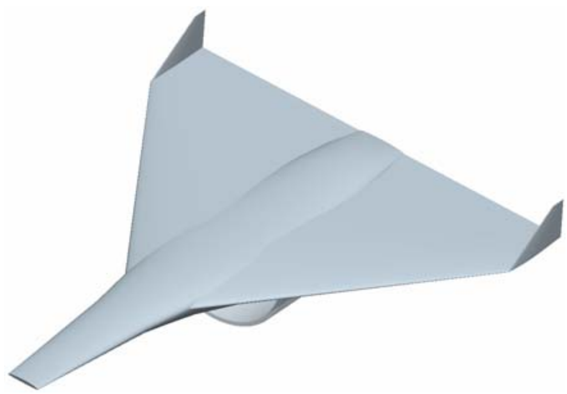


Figure 5. *Aztec* First Stage External CAD Image

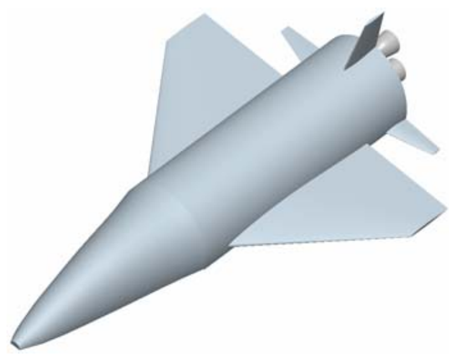


Figure 6. *Aztec* Second Stage External CAD Image

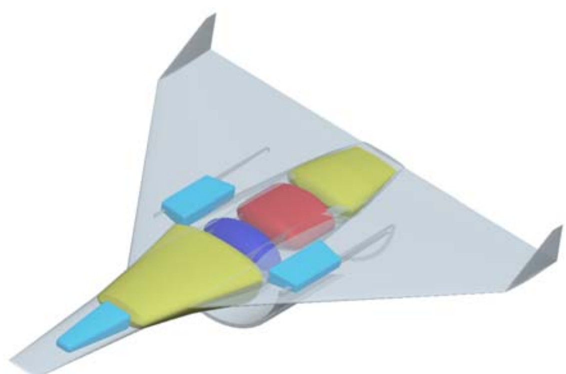


Figure 7. *Aztec* First Stage Internal CAD Image

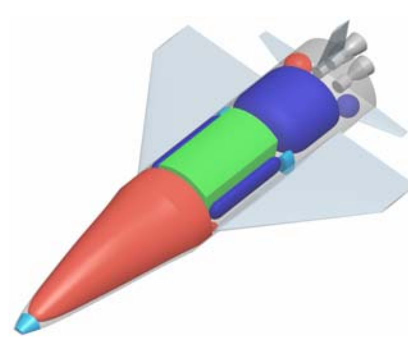


Figure 8. *Aztec* Second Stage Internal CAD Image

The internal volume of the first stage is dominated by the four main propellant tanks. The non-integral HEDM propellant tank, which holds fuel that is cross-fed to the second stage during transonic flight, is located in the first stage midbody in Figure 7. The non-integral LOX propellant tank, which is also cross-fed to the second stage in the transonic region, is located in the midbody of the first stage in front of the HEDM tank. The partially-integral JP-5 tanks used to fuel the TBCC engines on the first stage are located in the forebody and aftbody. A LOX density of 71.3 lbs/ft^3, a JP-5 density of 50.1 lbs/ft^3, and a HEDM density of 10.7 lbs/ft^3 are assumed for each stage. The HEDM propellant is comprised of liquid hydrogen, solid methane, and solid aluminum. The propellant is 60% aluminum by weight in order to increase the overall propellant density[4]. The remaining internal components shown in the first stage CAD model are the two main landing gear compartments and the nose landing gear compartment. The main landing gear is located in the wing and extends down beside the TBCC engine cowl.

The internal volume of the second stage is dominated by the main propellant tanks and the payload bay. The partially-integral HEDM propellant tank is located in the forebody in Figure 8. The midbody of the second stage is filled by the large payload bay. There are three main non-integral LOX tanks; two cylindrical tanks beside the payload bay in the midbody and one larger LOX tank with an elliptical cross-section located just behind the payload bay. The three main rocket engines can be seen in the back of the vehicle. Also included in the CAD model are the LOX and HEDM propellant tanks for the orbital maneuvering system (OMS) and reaction control system (RCS). The remaining components shown in the CAD model are the two main landing gear compartments located beside the large main LOX propellant tank and the nose landing gear located in front of the main HEDM propellant tank. The landing gear compartments for both vehicles are sized using historical gear and tire sizes for aircraft of comparable size and weight[7].

B. Aerodynamics

Aztec's first stage consists of a three ramp, Mach 5.5, elliptical conic forebody on the windward side. The initial half-angle is 5.0° which transitions eventually to a half-angle of 18.0° just before the cowl inlet. The leeward side of the forebody is a much shallower-angled elliptical conic whose volume is used for packaging of the main propellant tanks. The midbody is designed to allow the appropriate volume for the main LOX and HEDM tanks while still allowing room for TBCC engine turbomachinery. The figure below is a three view of the *Aztec* aerodynamic model constructed in APAS, including both stages.

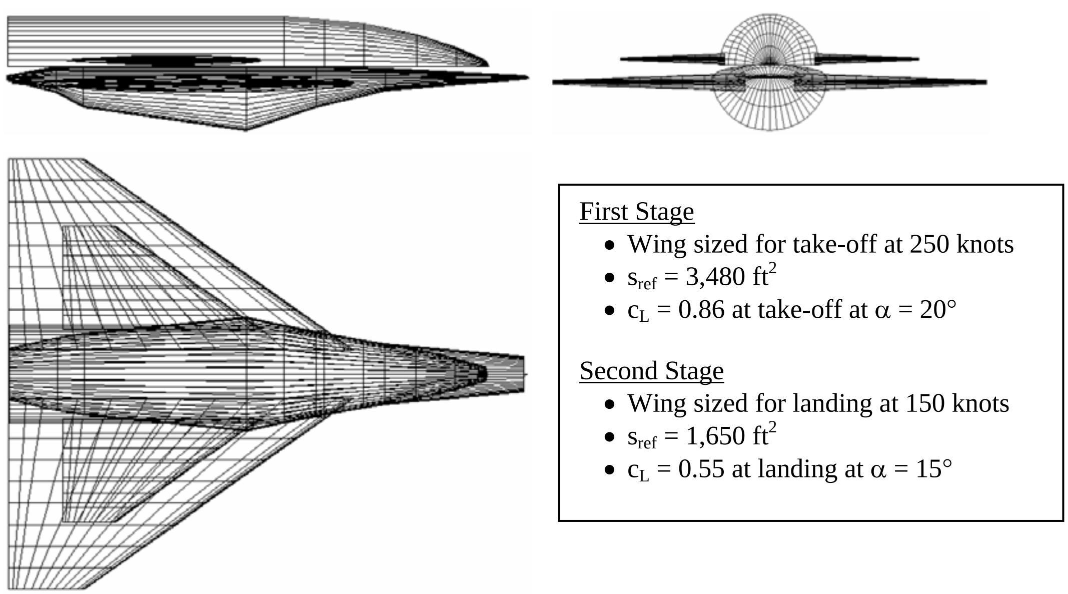


Figure 9. *Aztec* APAS Model: Three View

The first stage wings are sized for a take-off speed of 250 knots using the APAS aerodynamics software[8]. The wings are positioned to provide static stability throughout the flight regime. The baseline configuration has a theoretical wing planform area (s_{ref}) (extending into the fuselage) of 3,480 ft^2. At take-off, the first stage has a coefficient of lift (c_L) of 0.86 at an angle-of-attack (α) of 20°. The wing has a 55° leading edge sweep and is a 5%

thick biconvex airfoil. The theoretical aspect ratio of the wing is 1.87 and the taper ratio is 0.20. The vertical tipfins are sized to have a total planform area of 2.5% of the total theoretical wing planform area.

The second stage wings are sized for landing at a speed of 150 knots, also using the APAS aerodynamics software. The second stage baseline configuration has a theoretical wing planform area (s_{ref}) (extending into the fuselage) of 1,650 ft^2. At landing, the second stage has a coefficient of lift (c_L) of 0.55 at an angle-of-attack (α) of 15°. The wing has a 55° leading edge sweep and is a 5% thick biconvex airfoil. The theoretical aspect ratio of the wing is 1.87 and the taper ratio is 0.20. Second stage control surfaces are designed primarily to provide control authority during reentry and landing and provide little function during ascent.

APAS creates tables of lift and drag coefficients as a function of Mach number and angle of attack. This aerodynamic data is formatted for use in the POST 3-D trajectory analysis program. During vehicle convergence, the vehicle is scaled photographically which allows the assumption of constant aerodynamic coefficients during scaling. This assumption allows the removal of the aerodynamics discipline from the main engineering design loop, and thus aerodynamic analysis only needs to be done once at the beginning of the design process.

C. Propulsion

Aztec uses ten JP-5 TBCC engines on the first stage. Each engine consists of a low speed afterburning turbojet mode and a high speed ramjet/scramjet mode in an over-under configuration. The afterburning turbojet mode is designed using T-BEAT, an in-house Georgia Tech turbine-based design and analysis tool[9]. The ramjet and scramjet modes are designed and analyzed using SCCREAM, the “Simulated Combined Cycle Rocket Engine Analysis Module”[10]. Both T-BEAT and SCCREAM provide tables of engine performance data including thrust, thrust coefficient, and I_{sp} as a function of altitude and Mach number for use by POST 3-D.

Figure 10 is an example over-under TBCC configuration. The upper section contains the afterburning turbojet engines while the lower section is used for ramjet and scramjet modes. Mode changes are performed by actuating doors at the inlet and exit of the engine to open and close airflow for the lower and upper sections. These actuating doors are indicated by dotted lines in Figure 10.

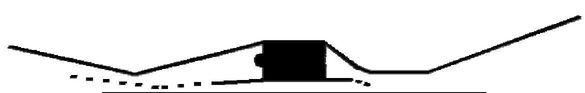


Figure 10. Over-Under TBCC Engine Configuration

Aztec uses the ten TBCC engines to accelerate the vehicle to the Mach 8.0 staging point. The engines are located underneath the first stage and receive precompressed air from the three ramp forebody. The engine cowl has a height of 3.6 feet in order to provide a Mach 5.5 shock-on-lip condition for the three forebody shocks. Each engine has an average width of 3.3 feet which provides a total inlet area of 12.0 ft^2 per engine. Table 2 provides some key TBCC engine design characteristics for the afterburning turbojet low speed mode.

Table 2. Afterburning Turbojet Characteristics

Item	*Value*
SLS Thrust (per engine)	41,600 lbs
SLS I_{sp}	1,990 sec
Compressor Pressure Ratio	22
Max Turbine Inlet Temp (°R)	3,400
Max Afterburner Temp (°R)	3,900
Compressor Efficiency	0.94
Turbine Efficiency	0.96
Burner Efficiency	0.99
Engine Installed T/W	6.0

For the high speed ramjet and scramjet modes, the following efficiencies were assumed: 90.0% mixer efficiency, 95.0% combustor efficiency and 98.0% nozzle efficiency.

Figure 11 and Figure 12 are plots of first and second stage thrust and I_{sp} as a function of Mach number from takeoff to the Mach 8.0 staging point. Note that the thrust and I_{sp} are measured from cowl-to-tail. All forebody pressures in front of the cowl are included in the aerodynamic drag computed by APAS. SCCREAM uses forebody geometry information, however, to determine mass capture into the engines.

As seen in Figure 11, at takeoff the ten afterburning turbojet engines are providing over 410,000 lbs of thrust which translates into a takeoff thrust-to-weight of 0.6. As stated previously, in the transonic region the second stage rockets are turned on in order to provide additional thrust to overcome the increase in drag. With both the first and second stage propulsion systems firing, *Aztec* punches through transonic. Once through transonic, the second stage engines are turned off and the first stage afterburning turbojet engines accelerate *Aztec* to the Mach 2.5 transition to ramjet mode.

Aztec's second stage uses three LOX-HEDM staged-combustion engines. The engines are used at two distinct points during the ascent trajectory: first during the transonic region in order to provide additional thrust to overcome the added transonic wave drag, and second after separation to accelerate the second stage from the Mach 8.0 staging point to a 50 nmi x 100 nmi x 28.5° orbit.

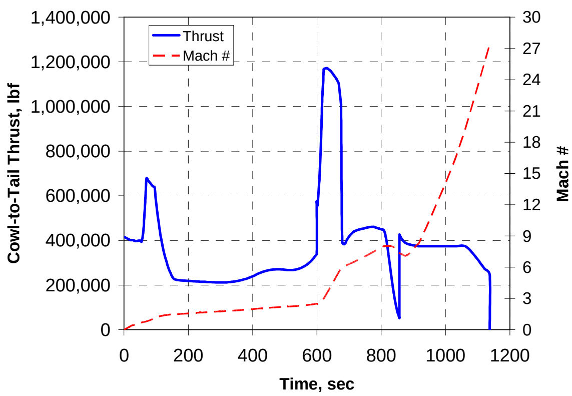


Figure 11. First and Second Stage Thrust and Mach # vs. Time

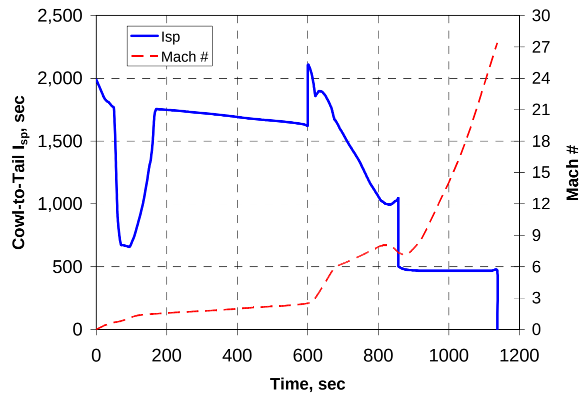


Figure 12. First and Second Stage I_{sp} and Mach # vs. Time

Table 3 provides key design and performance characteristics of these rocket engines. The engines are designed with a chamber pressure of 3,000 psia with a mixture ratio of 4.2. This mixture ratio was selected based upon previous research performed on using high energy density propellants for launch vehicle propulsion systems[4].

Table 3. Second Stage Rocket Engine Characteristics

Item	*Value*
Vacuum Thrust (per engine)	125,000 lbs
Vacuum I_{sp}	468.8 sec
O/F	4.2
Expansion Ratio (ε)	80
Chamber Pressure	3,000 psia
Exit Area (per engine)	12.5 ft^2
Engine Uninstalled T/W	64.8

The rocket engine propellants are a hydrogen based HEDM fuel and LOX. The HEDM fuel is comprised of liquid hydrogen, solid aluminum, and a methane gellant. The fuel is 60% by mass aluminum. The solid aluminum particles are added to the fuel mixture primarily to increase overall fuel density. In calculating the fuel density, Equation (1) is used[4].

$$\rho_{fuel} = \frac{1}{\frac{1-ML}{\rho_{LH_2}} + \frac{ML}{\rho_{Al}}} \qquad (1)$$

ML is the metal loading (in this case, 0.6), ρ_{fuel} is the calculated fuel density, ρ_{LH2} is the liquid hydrogen density of 4.43 lbs/ft^3, and ρ_{Al} is the solid aluminum density of 178.80 lbs/ft^3. As is proposed in reference 4, the methane gellant density is not used in the fuel density calculation.

This results in a fuel density of 10.7 lbs/ft^3 which is significantly higher than the normal boiling point liquid hydrogen density of 4.43 lbs/ft^3. The calculated vacuum I_{sp} of 468.8 sec is based upon a quoted I_{sp} of 439.9 sec[4] for an engine with an expansion ratio of 40, a chamber pressure of 2,250 psia, and an I_{sp} efficiency of 0.94. The I_{sp} efficiency takes into account nozzle, engine cycle, reaction, and combustor inefficiencies. By increasing the chamber pressure and expansion ratio[11], and assuming a higher I_{sp} efficiency (smaller losses due to nozzle boundary layer effects, engine cycle inefficiencies, and reaction and combustor inefficiencies) for this advanced engine design, the calculated I_{sp} of 468.8 is obtained.

D. Performance (Trajectory Optimization)

Aztec's trajectory is optimized such that the final weight of a given stage is maximized by changing the pitch angles during both turbojet mode and pull-up for the first stage and throughout the second stage trajectory subject to several constraints. The constraints on the first stage trajectory are a maximum wing normal force, a maximum dynamic pressure, a staging dynamic pressure, and a minimum staging flight path angle. The constraint on the second stage trajectory is the target 50 nmi x 100 nmi x 28.5° orbit. The trajectory analysis is performed by the Program to Optimize Simulated Trajectories (POST 3-D)[12], a three degree-of-freedom trajectory simulation tool.

From takeoff to Mach 2.5, *Aztec's* trajectory is controlled by changing pitch angles as a function of Mach number. Of interest in this region of the trajectory is the means by which *Aztec* flies through transonic. As was mentioned in the previous section, at Mach 0.8 the second stage rocket engines are turned on in order to provide additional thrust to overcome the added drag. These engines stay on until Mach 1.5 where they are throttled down and shut off. The turbojet engines are then used to accelerate *Aztec* to the Mach 2.5 transition point to ramjet mode.

As seen in Figure 14, *Aztec* flies a dynamic pressure boundary throughout ramjet and scramjet modes from Mach 2.5 to Mach 8.0. This technique is used to provide optimal air-breathing engine performance. In ramjet mode, the dynamic pressure is ramped up to a constant 1,800 psf. The dynamic pressure is increased to 2,000 psf upon transition to scramjet mode. This can be done due to the fact that the normal shock that exists in the engine during ramjet mode is expelled upon transition to scramjet mode. As a result, the static pressure in the engine decreases significantly.

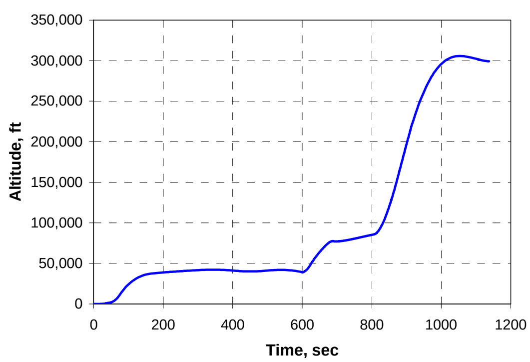


Figure 13. Altitude vs. Time

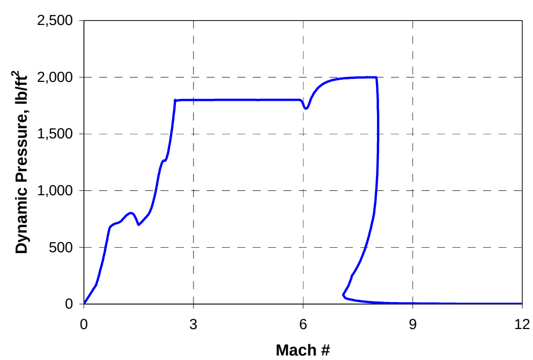


Figure 14. Dynamic Pressure vs. Mach #

The static pressure in the engine is related to the dynamic pressure boundary flown and affects the structural weight of the engine. The higher the static pressure in the engine, the heavier the engine structure is required to be. The dynamic pressure boundary is constrained through the use of a linear feedback control guidance scheme in which the dynamic pressure is held to the specified boundary by varying the angle-of-attack of the vehicle[13].

At Mach 8.0, *Aztec* comes off of the 2,000 psf dynamic pressure boundary and performs a pull-up maneuver before staging. At a dynamic pressure of 250 psf, the second stage engines are relit to provide the thrust necessary to reach the 10 psf dynamic pressure staging condition. The second stage then separates from the first stage and flies to the target 50 nmi x 100 nmi x 28.5° orbit while the first stage turns around and flies back to KSC in ramjet mode. The main propulsion system on the second stage is then used as the OMS propulsion system in order to circularize in the 100 nmi orbit. The LOX/HEDM OMS propulsion system can deliver 450 ft/sec of on-orbit ΔV.

The converged optimal baseline trajectory results in a first stage ascent MR of 1.473 and a second stage ascent MR of 3.034. The first stage flyback MR is 1.250. The ideal ascent ΔV provided by the first and second stage propulsion systems is 37,610 ft/sec, including 13,120 ft/sec of drag losses (measured inertially). The second stage mixture ratio is 4.2 while the first stage propellant weights are broken down in Table 4.

Table 4. First Stage Propellant Breakdown

Fuel	*Value*
Ascent JP-5	153,300 lbs
Flyback JP-5	43,400 lbs
LOX	55,900 lbs
HEDM	13,300 lbs

E. Aerothermal Analysis

The thermal protection materials and unit weights for *Aztec* are based upon analysis performed by MINIVER[14], the miniature version of the JA70 General Aerodynamic Heating Computer Code. MINIVER takes as input trajectory information from POST and geometric information from the CAD discipline.

From MINIVER, maximum radiation equilibrium temperatures are determined over the centerline of the vehicle. The maximum skin temperatures are then used to determine the appropriate TPS on different parts of the vehicle in order to provide acreage percentages for each TPS type. TPS unit weights are scaled from previous airbreathing launch vehicle designs flying similar trajectories and using similar technologies[15]. Table 5 provides TPS results for both the first and second stage.

Table 5. First and Second Stage TPS Breakdown

TPS	*First Stage*	*Second Stage*
Fuselage TUFI		
Unit Weight	1.59 lbs/ft^2	1.59 lbs/ft^2
Acreage	56%	39%
Fuselage AFRSI		
Unit Weight	1.67 lbs/ft^2	1.67 lbs/ft^2
Acreage	44%	61%
Nose and Wing UHTC		
Nosecap Weight	150 lbs	100 lbs
Wing LE Unit Weight	0.84 lbs/ft	0.84 lbs/ft

For *Aztec*, the TPS design features TUFI tiles on the windward side of both stages, AFRSI blankets on the leeward side, and UHTC on the nose and wing & tail leading edges of both stages. The remainder of the exposed wings on each stage is constructed of a high-temperature titanium-aluminide. This allows the wing to be designed as a hot structure, not requiring the tiles or blankets present on the fuselage. UHTC is used on the nose and wing & tail leading edges in order to avoid the use of active cooling in these areas. Information on these TPS materials is found in reference 16.

F. Mass Properties

A spreadsheet model containing 75 parametric MERs for each stage is used to estimate the size and weight of *Aztec*. The vehicle weights are broken down into a 28 category, 3 level weight breakdown structure (WBS) for each stage. MERs are parametric equations that take in some related sizing and/or performance design input(s) and compute the weight of the component. For example, the MER used to estimate wing weight takes, as input, the wing thickness ratio, taper ratio, exposed planform area, and the maximum wing loading force. These particular MERs have a NASA Langley heritage, but are adjusted to account for new materials and advanced construction methods.

The mass properties spreadsheet adjusts the vehicle length to match the MR from the trajectory optimization discipline. The required mixture ratio from the trajectory discipline, and the PEF curve created by the configuration and CAD discipline, together supply the necessary information to size the main vehicle propellant tanks. For a two stage vehicle, such as *Aztec*, the second stage is sized first and then the first stage is sized second. The second stage gross weight is considered to be the first stage payload weight. Once the vehicle is "closed" within the mass properties discipline, meaning the MR and mixture ratio for both the first and second stages matches the required MRs and mixture ratios from the trajectory optimization discipline, the results are sent back to the propulsion and trajectory disciplines to continue the iteration process around the main iteration loop. The design is considered converged when the MR and mixture ratio for the first stage and the MR for the second stage change by less than 0.1% from one iteration to the next.

Table 6 and Table 7 provide summary items from the full WBS for the first stage and second stage respectively. The full WBS is not included in this paper for brevity. Each dry weight component includes a 15% growth margin to take into account the likelihood of weight increases as the design matures.

Table 6. First Stage Summary WBS

WBS Item	*Weight*
Wing & Tail Group	21,100 lbs
Body Group	14,500 lbs
Thermal Protection System	6,900 lbs
Landing Gear	24,700 lbs
Main Propulsion System	75,800 lbs
OMS/RCS Propulsion	0 lbs
Subsystems & Other Dry Weights	7,900 lbs
Dry Weight Margin (15%)	22,600 lbs
Dry Weight	**173,600 lbs**
Payload Carried	249,200 lbs
Flyback Propellants	43,400 lbs
Residual, Reserve, and Unusable Propellants	4,100 lbs
Staging Weight	**470,300 lbs**
Ascent Propellant	222,500 lbs
Gross Weight	**692,800 lbs**

Table 7. Second Stage Summary WBS

WBS Item	*Weight*
Wing & Tail Group	6,900 lbs
Body Group	16,700 lbs
Thermal Protection System	6,800 lbs
Landing Gear	3,500 lbs
Main Propulsion System	7,200 lbs
OMS/RCS Propulsion	900 lbs
Subsystems & Other Dry Weights	6,800 lbs
Dry Weight Margin (15%)	7,300 lbs
Dry Weight	**56,100 lbs**
Payload Carried	20,000 lbs
OMS/RCS Propellants	3,200 lbs
Residual, Reserve, and Unusable Propellants	2,800 lbs
Insertion Weight	**82,100 lbs**
Ascent Propellant	167,100 lbs
Gross Weight	**249,200 lbs**

As seen in Table 6 and Table 7, the baseline *Aztec* has a gross weight of 693,000 lbs and a total dry weight of 230,000 lbs. The first stage dry weight is 174,000 lbs while the second stage dry weight is 56,000 lbs. The second stage gross weight is 249,000 lbs. The first stage fuselage is 98.4 ft from tip-to-tail, while the second stage fuselage is 90.7 ft from tip-to-tail.

G. Operations

Aztec is designed to be a highly operable and highly reusable space transportation system. The Architectural Assessment Tool – enhanced (AATe), developed at KSC[17], is used to assess the *Aztec* space transportation system for its operational impacts, mainly costs and ground cycle times[18]. In AATe's determination of ground cycle time, the number of vehicles in the fleet is not taken into account.

In order to take into account how the required fleet size affects the ground cycle time per vehicle, the Arena discrete event simulation tool is used. Arena models the *Aztec* fleet flow through the entire ground operations process. Figure 15 shows this ground operations flow path in Arena.

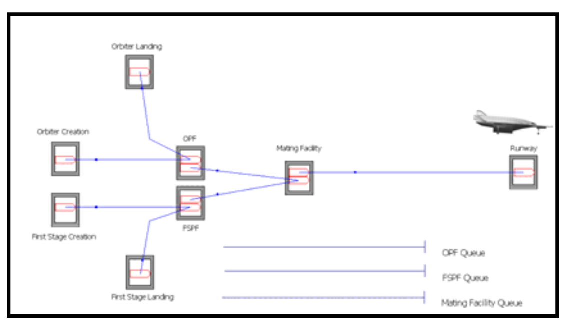


Figure 15. *Aztec* Ground Operations Flow Chart

The time spent at each facility is based upon that predicted by AATe for a fleet size of one vehicle. When additional vehicles are modeled by Arena within this ground operations flow, queues develop at certain facilities, such as the booster and orbiter processing facilities, thus increasing the ground cycle time per vehicle.

In order to determine the vehicle time spent at each facility for one vehicle, AATe takes into account both quantitative inputs and qualitative order of magnitude comparisons of *Aztec* to the Space Shuttle. Quantitative inputs include overall vehicle reliability, airframe life, payload weight, dry weight, vehicle dimensions, vehicle design life, and payload demand per year. Outputs include ground cycle time, facilities cost, labor costs, and LRU costs.

Aztec uses various technologies to reduce cycle time and operating costs. These technologies include integrated vehicle health monitoring systems (IVHM), built-in test equipment, and electro-mechanical actuators instead of hydraulic actuators. Toxic fluids are avoided for the OMS and RCS engines. Long life and reliable airframe and engine components are used to reduce maintenance costs. The airframe can fly 1000 flights before replacement while the engines can fly 500 flights before replacement. The turbojet and ramjet modes provide *Aztec's* first stage with flyback capabilities. They also enable *Aztec* to taxi on the runway and fly between sites under its own power. They also provide additional and safer abort scenarios during ascent.

Aztec is assumed to be operated by a commercial company using a future spaceport and runway at KSC. The spaceport infrastructure is assumed to be a shared asset provided by the federal or local government, much like an airport today. Spaceplane operators pay a user fee per flight, but are not required to pay for the spaceport design, construction, or maintenance, much like commercial airliners today.

An estimated operating crew of 660 "touch" labor personnel for the first stage and 540 for the second stage are required to operate a single *Aztec* vehicle based upon the economic flight rate of 17.0 flights per year. A single *Aztec* vehicle is capable of flying 20 flights per year with a ground cycle time of 15.8 days and an assumed mission time of 2 days. The user fee that the spaceplane operators must pay to the spaceport is estimated to be $50,000 per flight in FY$2004.

H. Safety & Reliability

Aztec is designed to be a highly safe and reliable space transportation system. *Aztec* safety and reliability analysis is performed by GT-Safety II, a top-level MS Excel-based spreadsheet tool used for determining safety and reliability metrics for RLVs. GT-Safety II required both quantitative and qualitative inputs. The quantitative inputs include information about the vehicle configuration (number of stages, number of engines, total amount of propellant), vehicle geometry (total vehicle wetted area, length, width, and height), and vehicle usage (crew per flight, passengers per flight, flights per year, and ground personnel touches per flight). The qualitative inputs are relative safety and reliability comparisons between the vehicle in question and the Space Shuttle. These include such features as launch abort options, propellant toxicity and volatility, and ground handling complexity.

Aztec uses highly safe and reliable engines and TPS on both the first and second stage. The first stage TBCC engines have a failure rate of 1 in 5,000 while the second stage rocket engines have a failure rate of 1 in 6,000. The first stage can lose three of the ten TBCC engines without losing the vehicle, while the second stage can lose one of the three rocket engines without losing the vehicle. Both stages have an IVHM system to quickly warn of any developing problems so proper action can be taken to avoid system failures. Both stages avoid the use of potentially unsafe high pressure hydraulic actuators in favor of electro-mechanical actuators.

These factors all help to make *Aztec* an extremely safe and reliable vehicle. *Aztec's* predicted loss of mission is 1 in 717 flights, and the predicted loss of vehicle is 1 in 2,431 flights. This translates into an *Aztec* reliability of 0.9996 in terms of loss of vehicle.

I. Cost and Economics

An analysis of *Aztec's* development, production, and operational costs and an assessment of the potential revenue stream are used to investigate the economic viability of *Aztec*. Development and production cost estimation is performed using the NASA-Air Force Cost Model (NAFCOM-99). This model contains a set of subsystem weight-based CERs for various vehicle component groups and also includes programmatic cost estimation for systems test hardware, integration, assembly & checkout, system test operations, ground support equipment, systems engineering & integration, and program management. Operational cost estimation is performed by AATe. These costs include facilities cost, labor costs, and LRU costs.

The assessment of potential revenue streams is performed using the Cost and Business Analysis Module (CABAM) developed at Georgia Tech. CABAM uses data from the NASA Commercial Space Transportation Study (CSTS) to approximate the price elastic behavior of potential markets[19]. Four different potential markets can be analyzed: commercial cargo, commercial passenger, government cargo, and government passenger. For each market, a curve of annual payload mass (or number of passengers) as a function of the price charged is used. For *Aztec*, only the two cargo markets are potential sources of revenue as *Aztec* is not designed to carry passengers. CABAM determines the market price per pound of payload delivered to orbit that results in a $0 net present value (NPV). In other words, CABAM determines the necessary price that needs to be charged in order to make up the initial costs of the venture plus some percentage in profit (commercial incentive return).

1. Business Model

Aztec will be operated by a commercial company, but much of the DDT&E costs will be paid for by the federal government. The government benefits from this investment in technology development, because the resulting reduction in launch costs will ultimately save the government, which is a heavy user of launch services, money in the long run. This will, in turn, eventually benefit taxpayers. As a result, the government is assumed to pay for 100% of the first stage TBCC engine development and 100% of the second stage HEDM engine development. In addition, the government also is assumed to pay for 25% of both the first and second stage airframe development. The government also is assumed to pay for launch facilities for the vehicle with the company paying a $50,000 user's fee per launch. The government is assumed to purchase the first vehicle produced. The government also guarantees commercial loans to the company so financing can be obtained at a reduced interest rate of 7.5%. The commercial company will pay for all production costs associated with building the vehicle. The company will also pay for all operating costs and all financing costs resulting from the aforementioned government loans.

An inflation rate of 2.1% and a tax rate of 30% are used for this economic analysis. The program starts in 2018 with initial operating capability (IOC) in 2025. The flight program will continue until 2045. A 20% cost margin is used for all DDT&E and TFU costs to account for potential cost increases during vehicle development and production.

2. Economic Results

Using the above inputs, the resulting Weighted Average Cost of Capital (WACC) plus the required commercial incentive return (2.5%) is 14.63% with a fleet size of a single vehicle. The resulting steady state flight rate is 17 flights per year, of which 4.9 flights per year are commercial (28.7% commercial). The vehicle operates for 20 years and flies for a total of 340 flights. The total Life Cycle Cost (LCC), without discount, is predicted to be $28.55B.

As seen in Table 8, the total cost from the start of the program to acquisition of the first vehicle is $13.64B. This cost includes airframe and engine DDT&E for both the first and second stages, acquisition of the first and second stage airframes, ten first stage TBCC engines, three second stage HEDM rocket engines, and the launch facility cost. Of this $13.64B, the government contributes $7.52B.

Table 8. *Aztec* Non-Recurring Cost Summary

Item	*First Stage*	*Second Stage*	*Total*
DDT&E - Airframe	$4,285 M	$3,871 M	
DDT&E - Engines	$1,076 M	$660 M	
Total DDT&E	**$5,361 M**	**$4,531**	**$9,892 M**
TFU - Airframe	$881 M	$791 M	
TFU Per Engine	$153 M	$89 M	
Total TFU*	**$1,953 M**	**$1,027 M**	**$2,980 M**
Facilities / GSE Acquisition			$766 M
Total for First Vehicle	**$7,314 M**	**$5,558 M**	**$13,638 M**

*Includes 85% learning curve effect for engine set

Recurring costs including labor and materials costs required to maintain and operate the vehicle, propellant costs, insurance costs, and site fees are shown in Table 9. Labor costs include the cost of employing people to work on a variety of vehicle operations including cargo processing, traffic control, launch and landing, integration, depot, support, logistics, and management[18]. Materials costs include the cost required for routine replacement of vehicle components or line replacement units (LRUs). Propellant costs are calculated using the following unit costs for the three main propellants: $0.10/lb of LOX, $0.07/lb of JP-5, and $2.00/lb of HEDM. Insurance costs are for limited liability coverage for the vehicle (hull insurance) and do not cover the payload or liability on public collateral injury. It is assumed that the government will provide indemnity as needed for those items. The final recurring cost item is a site fee of $50,000 per flight. As mentioned previously, this is a user fee that the spaceplane operators must pay to the spaceport. Including all these items, each flight of *Aztec* is estimated to cost $11.72M.

Table 9. *Aztec* Recurring Cost Summary

Item	*Value*
Launch Market Flight Rate Demand	17.0 Flights / Year
Fixed Labor Cost Per Year	$57.14 M
Variable Labor Cost Per Flight	$4.78 M
Fixed Materials Cost Per Year	$16.54 M
Variable Materials Cost Per Flight	$1.38 M
Propellant Cost Per Flight	$0.14 M
Insurance Cost Per Flight	$1.04 M
Site Fee Per Flight	$0.05 M
Total Recurring Cost Per Flight	**$11.72 M**

An economic summary of *Aztec* is shown in Table 10. The resulting market price per pound of payload delivered to a 100 nmi due east orbit is $7,102/lb. This price includes recurring costs, amortized DDT&E costs, financing costs, and company profit. Relative to current expendable launch vehicle prices which range from $4,000/lb to $5,000/lb, this result is disappointing. The result is more promising when compared to the Space Shuttle, but dramatic decreases in launch prices are unlikely with the engineering and economic assumptions used for *Aztec*.

Table 10. *Aztec* Economic Summary

Item	*Value*
Market Price Per Pound (to meet financial return where NPV = 0)	$7,102 / lb
Life Cycle Cost Per Pound (pre-Government Contribution)	$4,191 / lb
Life Cycle Cost Per Pound (post-Government Contribution)	$3,087 / lb
Recurring Cost Per Pound (operations + propellant + insurance + site fee)	$586 / lb
Recurring Operations Cost Per Pound (operations + propellant)	$531 / lb
Weighted Average Cost of Capital (WACC) + Incentive Return	14.63%
Flight Rate Per Year for Above Price (fractional)	17.0
% of Flights that are Commercial	28.7%
Number of Booster Units Acquired (Lifetime = 1,000 Flights)	1
Number of Orbiter Units Acquired (Lifetime = 1,000 Flights)	1
Number of TBCC Propulsion Units Acquired (Lifetime = 500 Flights)	10
Number of HEDM Propulsion Units Acquired (Lifetime = 500 Flights)	3
Total Life Cycle Cost (LCC) without Financing pre-Government Contribution	$28.55B
Total Government Contribution (DDT&E, Facilities Development, 1st Vehicle)	$7.52B

V. Conclusion

Aztec, a new TSTO hypersonic RLV utilizing TBCC and HEDM propulsion technologies, has been presented. *Aztec* is designed to deliver 20,000 lbs to a 100 nmi x 100 nmi x 28.5° orbit due East out of Kennedy Space Center (KSC). The gross lift-off weight (GLOW) was estimated to be 690,000 lbs and the total dry weight for both stages was estimated to be 230,000 lbs for this mission. Advanced propulsion systems, high strength and high temperature structural materials, composite propellant tanks, advanced TPS materials, and EMAs for control surface actuation are several of the advanced technologies incorporated into the *Aztec* design. The use of HEDM fueled second stage engines significantly decreased the physical size of the second stage and in turn decreased such key factors as the second stage dry weight and overall aerodynamic drag.

Economic results indicate that the *Aztec* launch price is on the high end of today's expendable launch vehicles that range between $4,000/lb and $5,000/lb. These results are disappointing in that dramatic improvements in launch cost are not obtained despite aggressive economic assumptions such has substantial government investments into airframe and engine DDT&E and government backed low interest loans.

Acknowledgments

This work was funded by the University Research, Engineering and Technology Institutes (URETI) Program. The authors would like to thank the members of the Space Systems Design Lab (SSDL) at the Georgia Institute of Technology.

References

[1]"Turbine-Based Combined Cycle (TBCC) Revolutionary Turbine Accelerator (RTA) Project." *NASA GRC.* URL: http://tbcc.grc.nasa.gov/ (17 Dec. 2003).

[2]Bai, S.D., P. Dumbacher, and J.W. Cole. "Development of Advanced Hydrocarbon Fuels at Marshall Space Flight Center." NASA/TP – 2002-211729, 2002.

[3]Palaszewski, B. "Solid Hydrogen Experiments for Atomic Propellants: Particle Formation Energy and Imaging Analyses." AIAA Paper 2002-4092, 2002. NASA/TM–2002-211915, 2002.

[4]Pelaccio, D.G., B. Palaszewski, and R. O'Leary. "Preliminary Assessment of Using Gelled and Hybrid Propellant Propulsion for VTOL/SSTO Launch Systems." AIAA Paper 97-3216, July 1997. NASA/TM–1998-206306, 1998.

[5]Palaszewski, B. "Metallized Propellants for the Human Exploration of Mars", Case for Mars IV Conference, Boulder, CO, June 1990.

[6]Bradford, J.E., Charania, A., Olds, J.R., and M. Graham. "*XCaliber*: A Vertical Takeoff TSTO RLV Concept With a HEDM Upperstage and a Scram-Rocket Booster." IAC Paper IAC-02-S.5.02, October 2002.

[7]Raymer, D.P. *Aircraft Design: A Conceptual Approach, Third Edition.* Reston, VA: American Institute of Aeronautics and Astronautics, 1999.

[8]Sova, G., and P. Divan. "Aerodynamic Preliminary Analysis System II, Part II – User's Manual." NASA CR 182077, April 1991.

[9]Bechtel, R.S. "T-BEAT: A Conceptual Design Tool for Turbine-Based Propulsion System Analysis." Georgia Tech Research Paper, Spring 2001.

[10]Bradford, J.E., J.R. Olds. "SCCREAM v.5: A Web-Based Airbreathing Propulsion Analysis Tool." AIAA Paper 99-2104, June 1999.

[11]Humble, R.W., Henry, G.N., and W.J. Larson, ed. *Space Propulsion Analysis and Design*. New York: McGraw-Hill Companies, Inc., 1995.

[12]Brauer, G.L., D.E. Cornick, and R. Stevenson. "Capabilities and Applications of the Program to Optimize Simulated Trajectories." NASA CR 2770, February 1977.

[13]Olds, J.R., and I.A. Budianto. "Constant Dynamic Pressure Trajectory Simulation in POST." AIAA 98-0302, January 1998.

[14]Engel, C.D., and S. Konishi. "MINIVER Upgrade for the AVID System." NASA CR 172213, August 1993.

[15]Olds, J.R., et al. "*Hyperion*: An SSTO Vision Vehicle Concept Utilizing Rocket-Based Combined Cycle Propulsion." AIAA paper 99-4944, November 1999.

[16]NASA Ames Thermal Protection Materials and Systems Branch, TPS-X Database Internet Site. http://asm.arc.nasa.gov.

[17]NASA, "An Operational Assessment of Concepts and Technologies for Highly Reusable Space Transportation – Executive Summary." Final Report of the NASA Integration Task Force, Operations, for the Highly Reusable Space Transportation Study, NASA Marshall Space Flight Center, November 1998.

[18]"Operations Cost Modeling and the Architectural Assessment Tool – Enhanced." IAA-99-IAA.1.1.01, 50th International Astronautical Congress, Amsterdam, the Netherlands, October 1999.

[19]Anon. "Commercial Space Transportation Study (CSTS) – Executive Summary." NASA Langley Research Center, Hampton, VA, April 1994.