Lazarus: A SSTO Hypersonic Vehicle Concept Utilizing RBCC and HEDM Propulsion Technologies

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***Lazarus* is an unmanned single stage reusable launch vehicle concept utilizing advanced propulsion concepts such as rocket based combined cycle engine (RBCC) and high energy density material (HEDM) propellants. These advanced propulsion elements make the *Lazarus* launch vehicle both feasible and viable in today's highly competitive market. The *Lazarus* concept is powered by six rocket based combined cycle engines. These engines are designed to operate with HEDM fuel and liquid oxygen (LOX). During atmospheric flight the LOX is augmented by air traveling through the engines and the resulting propellant mass fractions make single stage to orbit (SSTO) possible. A typical hindrance to SSTO vehicles are the large wings and landing gear necessary for takeoff of a fully fueled vehicle. The *Lazarus* concept addresses this problem by using a sled to take off horizontally. This sled accelerates the vehicle to over 500 mph using the launch vehicle engines and a propellant cross feed system. This propellant feed system allows the vehicle to accelerate using its own propulsion system without carrying the necessary fuel required while it is attached to the sled.**

***Lazarus* is designed to deliver 5,000 lbs of payload to a 100 nmi x 100 nmi x 28.5° orbit due East out of Kennedy Space Center (KSC). This mission design allows for rapid redeployment of small orbital assets with little launch preparation. *Lazarus* is also designed for a secondary strike mission. The high speed and long range inherent in a SSTO launch vehicle make it an ideal global strike platform.**

Details of the conceptual design process used for *Lazarus* are included in this paper. The disciplines used in the design include aerodynamics, configuration, propulsion design, trajectory, mass properties, cost, operations, reliability and safety. Each of these disciplines was computed using a conceptual design tool similar to that used in industry. These disciplines were then combined into an integrated design process and used to minimize the gross weight of the *Lazarus* design.

Nomenclature

α	=	angle-of-attack, °
AFRSI	=	Advanced Flexible Reusable Surface Insulation
CAD	=	computer aided design
CER	=	cost estimating relationship
c_L	=	coefficient of lift
DDT&E	=	design, development, test, & evaluation
DoD	=	Department of Defense
DSM	=	Design Structure Matrix
EMA	=	electro-mechanical actuators

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ESR	=	ejector scram-rocket
GLOW	=	gross lift-off weight
GRC	=	Glenn Research Center
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
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
RBCC	=	rocket based combined-cycle
RCS	=	reaction control system
RLV	=	reusable launch vehicle
SSTO	=	single-stage-to-orbit
TFU	=	theoretical first unit
TPS	=	thermal protection system
TUFI	=	Toughened Unipiece Fibrous Insulation
UHTC	=	Ultra-High Temperature Ceramic

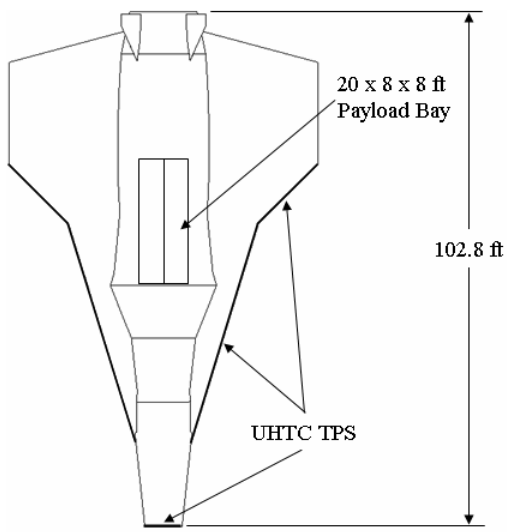
I. Introduction

MANY different single-stage to orbit (SSTO) launch vehicle concepts have been proposed in the search for a space shuttle replacement. Each of these vehicles had promised to reduce costs, turn around time, and increase reliability over current launch vehicles. Now that the Vision for Space Exploration has been adopted by NASA most of NASA's time and money is devoted to classical ETO vehicles such as the Ares I and Ares V launch vehicles. Unfortunately these vehicles have much the same shortcomings as their predecessors the space shuttle and evolved expendable launch vehicles. These vehicles will require months of notice for a launch and cost hundreds of millions of dollars per launch. Currently there is no available vehicle to quickly and reliably inject a small payload to orbital velocities without the use of these costly expendable rockets.

The United States Department of Defense has become increasingly reliant on space based assets. This reliance will force the DoD to investigate and invest in a vehicle which will provide the department with assured and timely access to space. The *Lazarus* vehicle concept is designed to meet the requirement to launch a small payload to orbital velocities with little notice and for a fraction of the cost of existing launch vehicles. This SSTO vehicle is accomplished through the use of rocket based combined cycle (RBCC) engines. These engines combine the space-based performance of traditional rockets with the atmospheric performance of ramjet/scramjet engines. Lazarus further improves on RBCC performance with the use of HEDM propellants. GRC and NASA Marshall Space Flight Center (MSFC) are also currently working on HEDM propulsion development and testing. Experiments in the formation of solid hydrogen particles in liquid helium have been performed[1]. Studies using gelled hydrogen and metallized gelled hydrogen fuels have shown potential in significantly increasing payload delivery capability and/or reducing GLOW[2,3]. 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.

The use of HEDM fuels and an RBCC engine allow a SSTO vehicle to become feasible. *Lazarus* is a single-stage, fully reusable vehicle. *Lazarus* takes off horizontally with the assistance of a rail based sled. This sled contains propellant tanks that feed the vehicle during its take-off roll. *Lazarus* accelerates to 500 mph while using fuel in the sled. This sled not only benefits the overall performance of the vehicle by eliminating the need to carry takeoff propellant, but also allows the vehicle to have significantly smaller wings and landing gear. The result is a much smaller dry weight for the vehicle and a lower mass ratio. Once the vehicle reaches 500 mph it releases from the sled and accelerates using the ejector mode of the RBCC engines. This continues through Mach 3.0 when the ramjet starts. The ramjet propels the vehicle to Mach 6 when the engine transitions to a scramjet mode. The scramjet powers the vehicle through Mach 10 when the rocket engine starts and the vehicle operates in scram-rocket mode. This continues until the atmosphere becomes too sparse ($q<50$psf) and the vehicle transitions into a traditional rocket. The vehicle continues in rocket mode until main engine cutoff (MECO) when the vehicle is in a 40 nmi x 100 nmi x 28.5° orbit. The vehicle then coasts until reaching apogee. Once at apogee, the main engines are used again to perform an orbital maneuvering burn to transition into the vehicle into a 100 nmi x 100 nmi x 28.5° orbit.

A full multi-disciplinary conceptual design process is used to create the *Lazarus* concept. This design process is completed using a disciplinary design tool for each of the following disciplines: external configuration and CAD was completed using ProEngineer, aerodynamic analysis with CBAERO[4], propulsion design and selection was completed using REDTOP[5], ramjet and scramjet performance using SCCREAM[6], trajectory optimization used POST[7], mass estimation and sizing was completed using mass estimating relationships[8] (MERs), Non-recurring cost estimating was conducted using NAFCOM cost estimating relationships (CERs), vehicle ground operations analysis using AATe, vehicle safety and reliability estimation using GT-Safety II, and a lifetime cost compilation using an Excel based cost complier. Each of these tools was used to analyze their respective disciplines and was iterated to close the *Lazarus* concept.



Vehicle Characteristics	
Lazarus	
Gross Weight:	180,000 lbs
Ascent Propellant Weight:	127,000 lbs
LOX:	87,000 lbs
HEDM:	40,000lbs
Payload Weight (LEO):	5,000 lbs
Ascent MR:	3.413
$(T/W)_{veh}$:	0.6
Sled	
Sled Gross Weight	78,000 lbs
Sled Propellant Weight:	24,000 lbs
Stack	
Gross Weight on Rails	257,000 lbs
Total Propellant	156,000 lbs
LOX:	110,000 lbs
HEDM:	46,000lbs

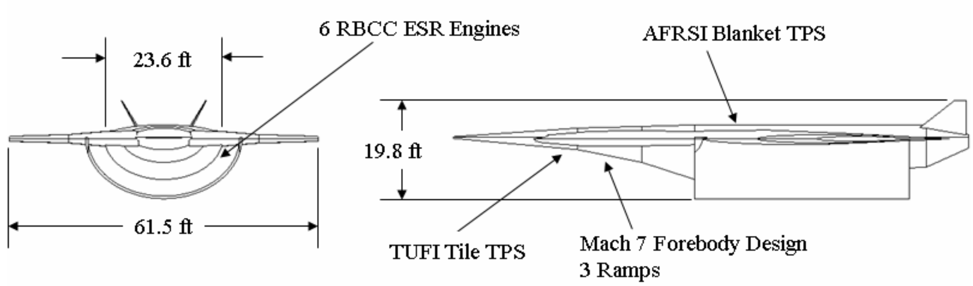


Figure 1. *Lazarus* Concept Configuration

II. Lazarus Configuration

A. Overview

Lazarus is a single stage to orbit, fully reusable space plane with a conical forebody and highly swept wings and two vertical tails. *Lazarus* is propelled by six HEDM/LOX RBCC engines. The vehicle consists of four main tanks (two for HEDM and two for LOX), associated structure, landing gear, a payload bay, avionics, and inspace maneuvering system. The HEDM tanks are conformal with the conical shape of the vehicle while the Lox tanks are elliptical calendars positioned on either side of the payload bay. The underside of the vehicle has a three ramp forebody to precompress the air entering the underslung RBCC engines. This forebody is optimized to provide shock coalescence on the lip at Mach 7.

Figure 2. *Lazarus* Concept

Lazarus is assisted in its takeoff by the use of a horizontal rail based sled. This sled provides the propellant necessary for the ground based portion of the trajectory via a crossfeed system similar to the system utilized by the space shuttle for propellant transfer between the external tank and the orbiter. This sled provides the propellant to accelerate the vehicle to 500 mph on the ground (Mach 0.66). The velocity provided by the sled has an added benefit in that the wing of Lazarus can now be sized for landing instead of takeoff, which results in a much smaller wing. The landing gear of the vehicle also incurs a benefit from the sled based launch. The landing gear for the vehicle is sized for the reduced weight of landing rather than the gross weight of the vehicle. A further benefit of this configuration is that the main propulsion of the *Lazarus* vehicle is started long before the vehicle actually leaves the ground. This allows for ground based aborts due to engine failures.

The baseline *Lazarus* is designed to deliver 5,000 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 *Lazarus* is designed to be 2030. The baseline airframe life is designed to be 1,000 flights with a baseline engine life of 500 flights for the RBCC engines. For the economic analysis it is assumed that one rail facility will be constructed at KSC, but other facilities may come online once the concept is flight proven.

Lazarus utilizes several additional advanced technologies currently under development. Propulsion technologies such as RBCC engines and HEDM fuels are assumed to be enabling technologies for the vehicle concept. 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 the vehicle is covered with Toughened Unipiece Fibrous Insulation (TUFI) TPS tiles while the leeward side of the vehicle is covered with Advanced Flexible Reusable Surface Insulation (AFRSI) blankets. The main fuselage and wing structure of *Lazarus* is made of titanium-aluminide while the LOX 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. The sled that assists *Lazarus* for takeoff uses proven technologies such as high speed rails[9], and shuttle based propellant transfer system.

B. Mission Profile

Lazarus takes off horizontally from a launch installation at KSC. This sled based launch accelerates the sled and the vehicle via the main rocket engines and propellant supplied from the sled. At the beginning of the roll the total stack (sled+vehicle) has a combined thrust to weight ratio of 0.42. Once the vehicle stack reaches 500 mph the sled releases the vehicle at an angle of attack of 7 degrees for liftoff. The vehicle continues under ejector mode ,powered by 6 LOX/HEDM gas generator engines each providing 17,967 lbs of thrust, through transonic and supersonic regimes until Mach 2.9. At Mach 2.9 the ejector rockets throttle down to reduced the acceleration as the ramjet starts at Mach 3.0. With the ejector off and the ramjet powering the ascent, *Lazarus* 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 RBCC engines switch to scramjet mode by decreasing the backpressure to obtain super sonic combustion. *Lazarus* continues in scramjet mode flying the dynamic pressure profile until Mach 10. At this point, the vehicle pulls up off the dynamic pressure flight profile and starts the rocket engines again. The vehicle flies this scram-rocket mode from Mach 10 until the dynamic pressure drops below 50 psf. This dynamic pressure signals the minimum atmospheric pressure in which the scram-rocket can operate. When the dynamic pressure drops below 50 psf the air ducts to the engines are closed and the vehicle continues in rocket mode until it enters a 40 nmi x 100 nmi x 28.5° orbit and the dynamic pressure is below 1 psf (signifying minimal drag). When this is satisfied main engine cut-off (MECO) occurs. The vehicle coasts until apogee where the vehicle performs a ΔV, using the main HEDM engines, to get into a 100 nmi circular orbit. Once in orbit, the vehicle can deploy its payload to either orbit the earth, or loiter until the proper entry interface is necessary to hit a specific target. Once the payload is released *Lazarus* can de-orbit and performs an unpowered, autonomous landing at the launch site.

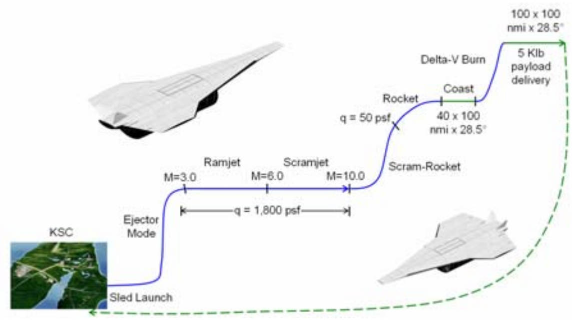


Figure 3. *Lazarus* Mission Profile

III. Multidisciplinary Design Process

The conceptual design process involves the combination of many different design disciplines. These disciplines are treated as individual contributing analyses to the entire vehicle design. Each of these contributing analyses are coupled which makes a difficult design problem. This coupling requires iteration between the disciplines to close the vehicle design. This coupling is graphically represented as a design structure matrix (DSM). Each of the contributing analyses (design disciplines) is represented as a box in the DSM and the links between the boxes are the coupling variables that are passed between the disciplines. Links leaving the right hand side of the boxes represent data that is passed downstream, while links leaving the left hand side represent information that is required upstream in the design process.

The DSM for the *Lazarus* design involves two different iteration loops. The first iteration loop is between the propulsion, trajectory, and weights and sizing disciplines. This iteration loop closes the performance aspects of the vehicle. For *Lazarus*, the main iteration loop between propulsion, trajectory, and weights & sizing required 8 iterations to converge. This convergence rate is typical of conceptual vehicle design processes of this type. Convergence is defined as a less than 0.1% change in overall vehicle mass ratio and mixture ratio from one iteration to the next. The second iteration loop is between operations, reliability, and life cycle costs. This loop uses the converged physical design and creates the operations, reliability, and costs of the closed design.

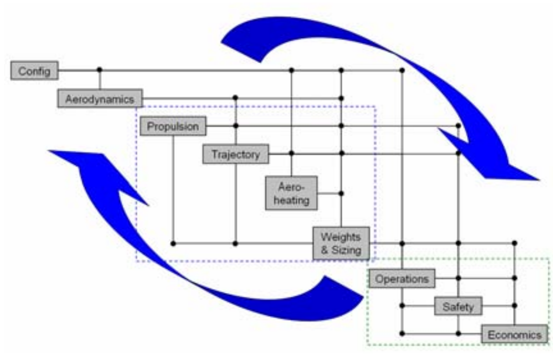


Figure 4. *Lazarus* Design Structure Matrix

Table 1. *Lazarus* Disciplinary Design Tools

Discipline	*Analysis Tool*
Configuration & CAD	Pro/E, Excel
Aerodynamics	CB Aero
Ramjet/Scramjet Propulsion	SCCREAMv6
Rocket Propulsion	REDTOP
Ascent Trajectory	POST 3-D
Weights & Sizing	MS Excel
Operations	AATe
Safety & Reliability	GT Safety II
Cost	NAFCOM-99
LCC	MS Excel

Each discipline has its own conceptual design tools associated with it. Table 1 provides a listing of each discipline and its associated design tool or tools. Configuration, propulsion, trajectory, and reliability are all analyzed with their respective disciplinary tool. Weights and sizing is composed of a series of MERs that are summarized and internally closed in an MS Excel workbook. Cost CERs are based upon NAFCOM and are also summarized in a MS Excel workbook.

IV. Lazarus Baseline Results

A. Internal Configuration and Layout (CAD)

The baseline *Lazarus* configuration is 102.79ft (nose-to-tail) with a gross weight of 179,700 lbs. The total fuselage volume is 9,455 ft^3. The maximum fuselage width is 21.3 ft and the height of the vehicle from cowl to top of vertical stabilizer is 19.8 ft. The payload bay is 20 ft. long, 8 ft. wide, and 8 ft. tall. Propellant tanks, landing gear, engine structure, and the payload bay are packaged on using Pro/Engineer, a solid modeling Computer Aided Design (CAD) package.

An important output of the configuration discipline is the propellant packaging efficiency (PEF). 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. 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. 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, yet the propellant tanks, etc. must scale. The PEF curve fit is created from three different CAD layouts at three different lengths (72, 109, and 145 ft). 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 packaging efficiency for *Lazarus* is 55.6%.

Figure 5. *Lazarus* External CAD Image

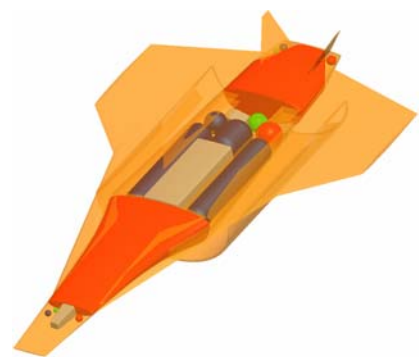


Figure 6. *Lazarus* Internal CAD Image

The internal volume of the vehicle is dominated by the main propellant tanks. The two integral HEDM tanks are in the fore and aft of the body in order to utilize as much volume as possible for the relatively low density fuel (15% the density of LOX). The three non-integral LOX propellant tanks are located on either side and behind the payload bay in the mid-fuselage. These tanks are elliptical cylinders to utilize as much of the internal volume as possible, without occurring the costs associated with conformal tanks. A LOX density of 71.3 lbs/ft^3 and a HEDM density of 10.7 lbs/ft^3 are assumed for tank volume calculations. 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[2]. The remaining internal components shown in the CAD model are the two main landing gear compartments in the mid-fuselage, the nose landing gear compartment, and the OMS and RCS propulsion systems. The main landing gear is located in the wing and extends down beside the RBCC engine cowl. The landing gear compartments sized using historical gear and tire sizes for aircraft of comparable size and weight[10]. The OMS and RCS systems have separate tanks from the main propulsion. This is done so that the propellants can be used easily when the main tanks are dry in orbit. The Helium pressurant tanks for this system are also shown in this layout.

B. Aerodynamics and Aeroheating

The forebody of *Lazarus* consists of a three ramp, Mach 7, elliptical conic forebody on the windward side. 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 mid-fuselage is designed to allow the appropriate volume for the main LOX and HEDM tanks as well as the payload bay.

The wings are sized for a landing speed of 150 mph using the lift coefficients obtained from CBAERO aerodynamics software. The wings are sized for landing rather than takeoff because the velocity provided by the sled at takeoff reduces the wing size below that necessary for landing on traditional landing gear. Therefore the wing is sized for landing and the angle of attack at liftoff is adjusted to provide the correct lift necessary. 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 1,465 ft^2. At take-off, the vehicle has a coefficient of lift (c_L) of 0.21 at an angle-of-attack (α) of 7°. This seemingly low lift coefficient is obtained because of the realatively high takeoff speed provided by the sled. The wing is a double delta with sweeps of 73° for the strake and 45° for the leading edge of the wing.. The theoretical aspect ratio of the wing is 1.87 and the taper ratio is 0.20. The vertical tail fins are sized to have a total planform area of 2.5% of the total theoretical wing planform area and are at an angle to provide stability in the pitch, yaw, and roll axis.

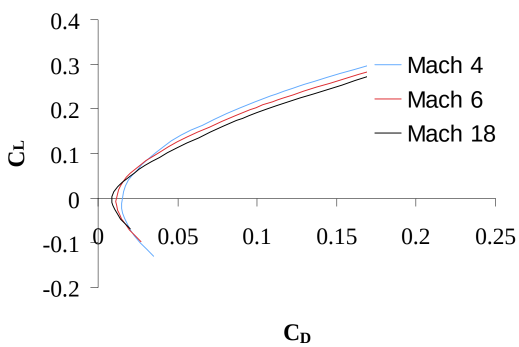


Figure 7. *Lazarus* Drag Polars

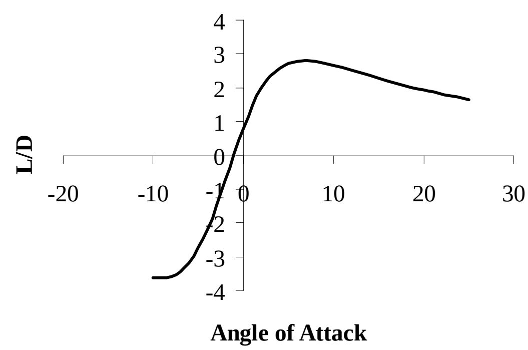


Figure 8. *Lazarus* Aerodynamics at Mach 6.0

Figure 7 shows the drag polars for the entire hypersonic regime from Mach 4 to Mach 18. This curve is representative for the hypersonic aerodynamics of the Lazarus vehicle. Figure 8 shows the lift to drag ratio of the *Lazarus* vehicle for changing angles of attack at Mach 6.0.

CBAERO creates tables of lift and drag coefficients as a function of Mach number, dynamic pressure, 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

Lazarus uses six LOX-HEDM ejector scram-rocket (ESR) engines to inject the vehicle into a 100 nmi x 100 nmi x 28.5° orbit. The propulsion system analysis is performed using the “Simulated Combined Cycle Rocket Engine Analysis Module” (SCCREAM[11]). SCCREAM provides 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 9 shows the internal engine layout and the station identifications used by SCCREAM.

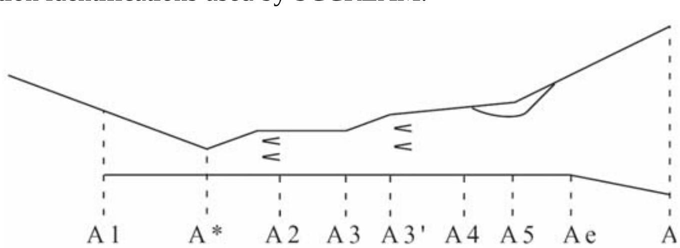


Figure 9. *Lazarus* ESR Engine Configuration

The HEDM fuel used is liquid hydrogen with a methane gellant and solid aluminum (60% by weight) metallic additive. This aluminum additive serves to vastly improve the fuel density from a liquid hydrogen density of 4.43 lbm/ft^3 to a liquid HEDM density of 10.66 lbm/ft^3.

The engines are mounted underneath the midbody of the vehicle and use *Lazarus*' three ramp, Mach 7 forebody to compress the air flowing into the engine inlet. The engine cowl has a height of 1.85 feet in order to achieve shock-on-lip at Mach 7. Each engine has an average width of 3.55 feet which provides a total inlet area of 6.6 ft^2 per engine. Table 2 provides key design and performance characteristics for the rocket engine primary. The installed engine sea-level static (SLS) thrust-to-weight is 22.0. In ramjet and scramjet modes, the following efficiencies were assumed: 90.0% mixer efficiency, 95.0% combustor efficiency, and 98.0% nozzle efficiency. Each engine utilizes a variable internal geometry to achieve improved performance (thrust and I_{sp}) over static internal geometries for a wide range of mach numbers.

Table 2. *Lazarus* Rocket Engine Primary Data

Item	*Value*
SLS Thrust (per engine)	18,000 lbs
SLS I_{sp}	332.9 sec
Vacuum I_{sp}	467.7 sec
Rocket O/F	4.2
Chamber Pressure	2,800 psia

Figure is a plot of thrust and I_{sp} as a function of time from takeoff to orbital insertion. Please note that thrust and I_{sp} are measured from cowl-to-tail. As seen in Figure 10, at takeoff the six ESR engines are providing nearly 130,000 lbs of thrust in air-augmented rocket (AAR) mode. This translates to a takeoff vehicle thrust-to-weight of 0.6. *Lazarus* remains in AAR mode until Mach 3 (at 135 seconds in Figure 10) where it transitions into ramjet mode. This transition is modeled in POST as a ramping down of the AAR throttle and a ramping up of the ramjet mode throttle. *Lazarus* flies in ramjet mode until Mach 6 (at 180 seconds in Figure 10) where it transitions into scramjet mode. During this transition, the internal engine ramps are adjusted to achieve optimal scramjet performance. The engine is initially choked at the start of scramjet mode and as a result has a low thrust and high Isp (shown in Figure 10 from 180-240 seconds) *Lazarus* flies in scramjet mode until Mach 10 (at 320 seconds in Figure 10) where it transitions into scram-rocket mode by relighting the rocket engine primary. *Lazarus* flies in scram-rocket mode, performing a zoom maneuver between 380 and 410 seconds, until a dynamic pressure of 50 psf (at 480 seconds in Figure 10) at which point the engine inlet closes and the trajectory continues in all-rocket mode until orbital insertion at 540 seconds.

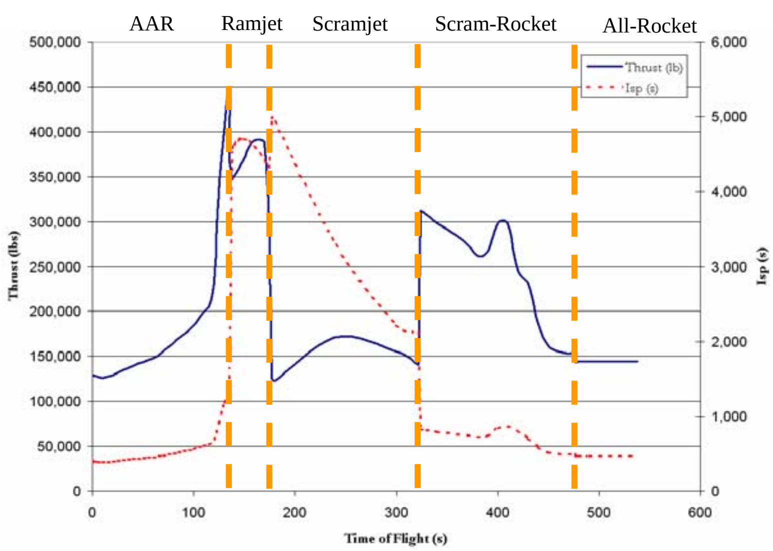


Figure 10. Lazarus Thrust and I_{sp} vs. Time

D. Performance (Trajectory Optimization)

The *Lazarus* trajectory is optimized to give the minimum the mass ratio of the vehicle by changing the pitch angles used during the flight. This is accomplished by maximizing the final weight of the vehicle given an initial weight. The constraints on the trajectory are a maximum dynamic pressure (2050 psf), a maximum acceleration (3 g's), a minimum angle of attack (-10), a maximum dynamic pressure at MECO (1 psf), and a final orbit of 40 nmi x 100 nmi x 28.5° orbit. The trajectory analysis is performed by the Program to Optimize Simulated Trajectories (POST 3-D), a three degree-of-freedom trajectory simulation tool.

The trajectory begins at the end of the sled takeoff roll (the sled propellant usage is estimated using a worst case delta-V approximations). At this point the angle of attack is fixed to 7° to provide enough lift to take-off yet not exceed the 3 g max acceleration constraint on the trajectory. The trajectory continues on in ejector mode and begins to fly a dynamic pressure table of 1800 psf. 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[12]. 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 ejector begins to ramp down at Mach 2.9 to limit the acceleration of the vehicle as the ramjet starts at Mach 3.0. The ramjet transitions into a scram-jet at Mach 6.0. *Lazarus* continues to fly a dynamic pressure boundary throughout ramjet and scramjet modes from Mach 3.0 to Mach 10.0. This technique is used to provide optimal air-breathing engine performance.

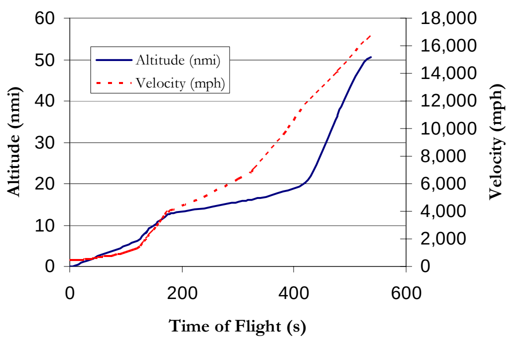


Figure 11. *Lazarus* Trajectory

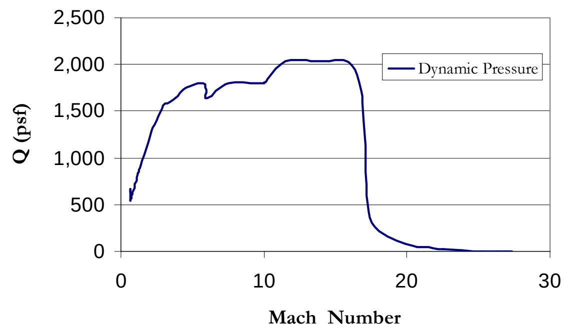


Figure 12. Dynamic Pressure vs. Mach #

Once the vehicle reaches Mach 10 the rocket engine is ignited again and the vehicle begins to operate in scram-rocket mode. At this point the vehicle climbs out of the constant dynamic pressure flight profile and begins to maneuver via a pitch angle table. These pitch angles are some of the dependant variables that are used to optimize the trajectory. The vehicle continues under scram-rocket mode until the dynamic pressure drops below 50 psf. At this point the dynamic pressure is too low to continue in scram rocket mode and the vehicle transitions to all-rocket mode. *Lazarus* continues to maneuver via the pitch tables in all rocket mode until the MECO criteria of a 40 nmi x 100 nmi x 28.5° orbit and a dynamic pressure of <1psf is reached. This dynamic pressure constraint is necessary to insure the drag is low enough at insertion to not reduce the apogee of the orbit. The main propulsion system 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 990 ft/sec of on-orbit ΔV.

The converged optimal baseline trajectory results in an ascent MR of 3.413. The ideal ascent ΔV provided by the propulsion systems is 31,527 ft/sec, including 5,087 ft/sec of drag losses (measured inertially). The engine mixture ratio is 4.2 while the overall vehicle mixture ratio (for packaging) is 2.15. This mixture ratio is smaller than the mixture ratio for the engines since LOX is being obtained from the air. *Lazarus* propellant weights are broken down in Table 3.

Table 3. *Lazarus* Propellant Breakdown

Fuel	*Value*
Ascent HEDM	40,300 lbs
Ascent LOX	86,700 lbs
Lazarus Mass Ratio	3.413
Lazarus Mixture Ratio	2.151
Sled HEDM	4,400 lbs
Sled LOX	18,400 lbs
Sled Mass Ratio	1.09
Sled Mixture Ratio	4.2

E. Aerothermal Analysis

The thermal protection materials and unit weights for *Lazarus* are based upon analysis performed by CBAERO, to calculate the max heating rates and temperatures the trajectory data from POST is used. 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[13]. The heating rates and the overall temperature for the trajectory are given as Figure 13 and Figure 14. For these analyses the engines were not modeled and therefore the tail of the vehicle is much hotter than pictured.

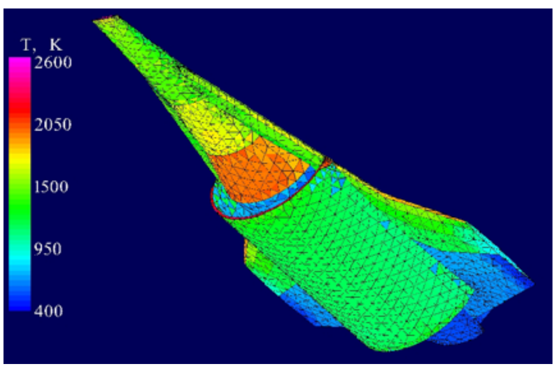


Figure 13. *Lazarus* Temperature Gradients

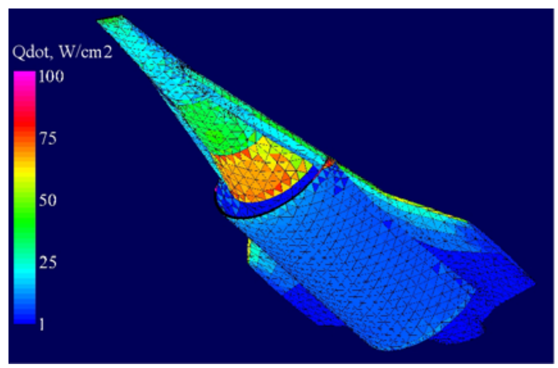


Figure 14. *Lazarus* Heat Rates

For *Lazarus*, the TPS design features TUFI tiles on the windward side of the vehicle, AFRSI blankets on the leeward side, and UHTC on the nose and wing & tail leading edges. The remainder of the exposed wings 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 reference14.

F. Mass Properties

A spreadsheet model containing 87 parametric MERs is used to estimate the size and weight of both *Lazarus* and the launch assist sled. The vehicle weights are broken down into a 28 category, 3 level weight breakdown structure (WBS). 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.

Table 4. *Lazarus* Summary WBS

WBS Item	*Weight*
Wing & Tail Group	5,100 lbs
Body Group	13,500 lbs
Thermal Protection System	3,700 lbs
Landing Gear	1000 lbs
Main Propulsion System	5,500 lbs
OMS/RCS Propulsion	670 lbs
Primary Power	760 lbs
Electrical Conversion & Dist.	2,300 lbs
Surface Control Actuation	230 lbs
Avionics	1,600 lbs
Environmental Control	1,900 lbs
Dry Weight Margin (15%)	5,400 lbs
Dry Weight	**41,600 lbs**
Payload Carried	5,000 lbs
Residual, Reserve, and Unusable Propellants	2,200 lbs
Insertion Weight	**52,700 lbs**
Ascent Propellant	127,000 lbs
Gross Weight	**179,700 lbs**

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. Once the vehicle is "closed" within the mass properties discipline, meaning the MR and mixture ratio for the vehicle 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 vehicle changes by less than 0.1% from one iteration to the next. Each dry weight component includes a 15% growth margin to take into account the likelihood of weight increases as the design matures.

As seen in Table 4, the baseline *Lazarus* design has a gross weight of 179,700 lbs and a total dry weight of 41,600 lbs. The vehicle's fuselage is 102.8 ft from tip-to-tail. The figures below show the gross and dry mass breakdown of the *Lazarus* concept. As expected the biggest component of the dry mass is the fuselage of the vehicle followed by the main propulsion system. The dry weight margin is 15% of the sum of the components of the dry weight. This results in only 13% of the dry weight since the dry weight includes this margin. The biggest component of the gross weight of the vehicle is the ascent LOX. Even with airbreathing engines the rocket mode still dominates the propellant consumed and therefore a large amount of LOX must be taken on the vehicle.

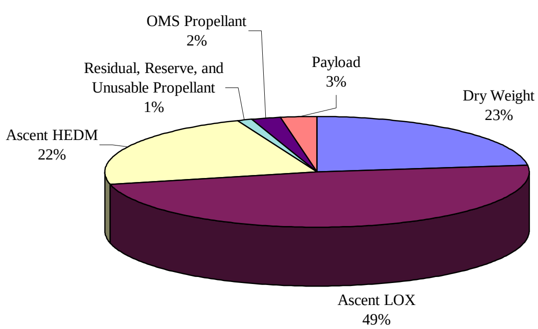


Figure 15. *Lazarus* Gross Weight Breakdown

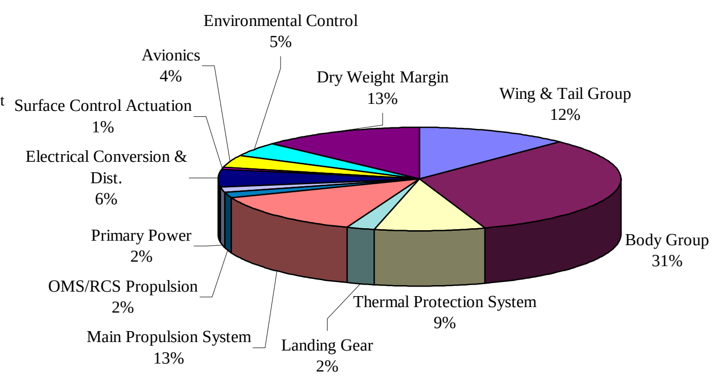


Figure 16. *Lazarus* Dry Weight Breakdown

The overall vehicle dimensions are very similar to that of the SR-71 high performance aircraft. In fact *Lazarus* is only 6,000 lbs heavier and is 4 ft shorter. A comparison of *Lazarus* to the SR-71 and an F-18 fighter aircraft is shown as Figure 17.

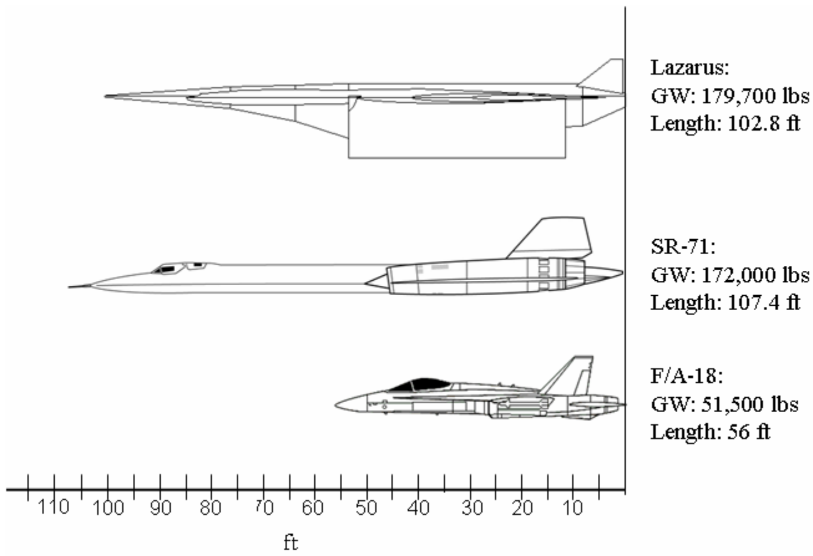


Figure 17. Comparison of *Lazarus* to Current High Performance Aircraft

G. Operations

Lazarus is designed to be a highly operable and highly reusable space transportation system. The Architectural Assessment Tool – enhanced (AATe), developed at KSC[15], is used to assess the *Lazarus* space transportation system for its operational impacts, mainly costs and ground cycle times[16]. In AATe's determination of ground cycle time, the number of vehicles in the fleet is not taken into account.

Lazarus 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. An estimated operating crew of 280 "touch" labor personnel is required for the vehicle. A single *Lazarus* vehicle is capable of flying 20 flights per year with a ground cycle time of 6.1 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 $100,000 per flight in FY$2006. The ground support facilities for the *Lazarus* concept are an estimated $280 M in FY$2006. This does not include the sled system which is assumed to be operational by the IOC of 2030.

H. Safety & Reliability

Lazarus is designed to be a highly safe and reliable space transportation system. *Lazarus* 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.

Lazarus uses RBCC engines that have a failure rate of 1 in 5,000. The vehicle can lose two of the six RBCC engines without losing the vehicle. *Lazarus* has an IVHM system to quickly warn of any developing problems so proper action can be taken to avoid system failures. The design avoids the use of potentially unsafe high pressure hydraulic actuators in favor of electro-mechanical actuators. The predicted loss of mission for the *Lazarus* vehicle is

1 in 1,244 flights, and the predicted loss of vehicle is 1 in 2,654 flights. This translates into a loss of vehicle reliability of 0.9996.

I. Cost and Economics

The cost estimating for the *Lazarus* design is calculated using weight-based cost estimating relationships (CERs). These CERs are used to estimate the development and production costs for each of the items in the weight breakdown structure. These CERs are based upon data from the NASA Air Force Cost Model (NAFCOM) for cost estimating. 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. A summary of the non-recurring costs for *Lazarus* are included as Table 5 (All costs presented in FY 2006 dollars).

Table 5. *Lazarus* Non-Recurring Cost Breakdown

Non-Recurring Costs	$M FY2006
DDT&E (Airframe)	$3,989
DDT&E (Engine)	$725
DDT&E Total	**$4,714**
Acquisition (Airframe)	$786
Acquisition (Engine)	$330
TFU	**$1,115**
Cost to First Vehicle	**$5,829**
Ground Facilities	$282
Total Non-Recurring Cost	**$6,111**

The design, development, testing, and evaluation cost for *Lazarus* is $4.714 B. The cost to first (and only) *Lazarus* vehicle is $5.829 B. The total non-recurring costs are $6.111 B, this includes the cost to first vehicle and the ground facilities necessary for the operation of *Lazarus* not including the sled construction and upkeep costs.

Recurring cost estimation is performed by AATe. Recurring costs including labor and materials costs required to maintain and operate the vehicle, propellant costs, and site fees. 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[16]. Materials costs include the cost required for routine replacement of vehicle components. Propellant costs are calculated using the following unit costs for the three main propellants: $0.10/lb of LOX and $2.00/lb of HEDM. The final recurring cost item is a site fee of $100,000 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 *Lazarus* is estimated to cost $5.51M. A summary of the recurring costs for the *Lazarus* is included as Table 6.

Table 6. *Lazarus* Recurring Cost Breakdown

Recurring Costs	$ FY2006
Average Number of Flights per Year	12
Fixed Operations Cost per Year	$31 M
Variable Operations Cost per Year	$2.707 M
Propellant Cost per Flight	$101,000
Site Fee per Flight	$100,000
Total Recurring Cost per Flight	**$5.51 M**
$/lb to Orbit	**$5,176**

The cost to orbit of a pound of payload is just over $5,000. This is equivalent to the price of the EELV program, but *Lazarus* provides anytime access to space. Breakdowns of the recurring and non-recurring costs for Lazarus are included below. These figures show that the majority of the recurring costs are associated with the labor force and materials necessary to fly the vehicle, while the propellants and site fees are small in comparison. The results from the non-recurring cost pie chart are also as expected since the DDT&E of the airframe is the most expensive item.

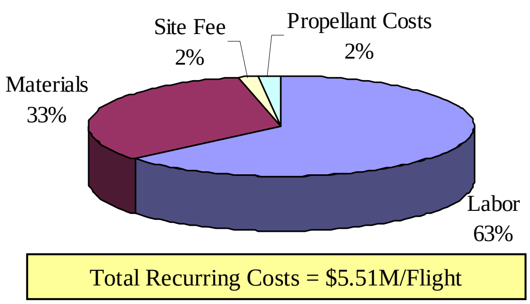


Figure 18. *Lazarus* Recurring Costs

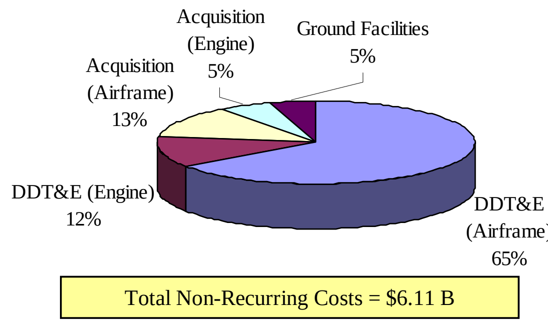


Figure 19. *Lazarus* Non-Recurring Costs

A life cycle cost analysis is also performed on *Lazarus.* This analysis involved the compilation of costs over the 25 year lifetime of the vehicle. For this cost analysis it is assumed that one vehicle is necessary for the 25 years of the program at a modest 12 flights per year. It is assumed that the design, development, testing and evaluation (DDT&E) costs will be spread evenly over the 25 years of the program and that the sled is costed separately from the vehicle. An inflation rate of 2.1% per year is assumed to get the total cost of the program. This is shown in Table 7.

Table 7. Life Cycle Cost of *Lazarus*

Economics	$FY2006
Life of Program	25 yrs
Average Number of Flights per Year	12
Total Number of Flights	300
Inflation Rate	2.10%
Total Program Cost	**$10,001 M**
Average Cost per Flight	**$33.34 M**
Average $/lb to Orbit	**$6,667**

This table shows the total program cost is $10 B, but that cost covers over 300 flights and 1.5 million pounds of payload to LEO.

V. Conclusions

Lazarus is an unmanned single stage reusable launch vehicle concept utilizing advanced propulsion concepts such as rocket based combined cycle engine (RBCC) and high energy density material (HEDM) propellants. These advanced propulsion elements make the Lazarus launch vehicle both feasible and viable in today's highly competitive market. Lazarus is designed to deliver 5,000 lbs of payload to a 100 nmi x 100 nmi x 28.5° orbit due East out of Kennedy Space Center (KSC). This mission design allows for rapid redeployment of small orbital assets with little launch preparation. The Lazarus concept is powered by six rocket based combined cycle engines. These engines are designed to operate with HEDM fuel and liquid oxygen (LOX). A typical hindrance to SSTO vehicles are the large wings and landing gear necessary for takeoff of a fully fueled vehicle. The Lazarus concept addresses this problem by using a sled to take off horizontally. This sled accelerates the vehicle to over 500 mph using the launch vehicle engines and a propellant cross feed system. This propellant feed system allows the vehicle to accelerate using its own propulsion system without carrying the necessary fuel required while it is attached to the sled.

Economics results show that over a 25 year program the total cost is $10 B. That that cost covers over 300 flights and 1.5 million pounds of payload to LEO. That equates to about $ 6,700/lb. That cost is approximately the cost of a traditional EELV, but the advantage of *Lazarus* is the responsive launch capability. This responsive capability will be vital to replace damaged satellites or deploy weapons quickly and with little advanced notice.

Acknowledgments

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