AIAA 95-3531

Lifting Body - An Innovative RLV Concept

Robert I. Baumgartner and John D. Elvin
Lockheed Martin Skunk Works
1011 Lockheed Way
Palmdale, CA 93599-7241

AIAA 1995 Space Programs and Technologies Conference
September 26-28, 1995/Huntsville, Al

AIAA 95-3531

LIFTING BODY - AN INNOVATIVE RLV CONCEPT

R. I. Baumgartner * and J. D. Elvin †

Lockheed Martin Skunk Works
Palmdale, CA

ABSTRACT

This paper describes the development of Lockheed Martin's Lifting Body Reusable Launch Vehicle (RLV) concept. The design evolution and trade studies leading to the lifting body concept are presented. Lockheed Martin's current RLV design concept is described. A Linear Aerospike rocket engine has been selected to power the lifting body RLV concept. The Linear Aerospike design concept and integration benefits are presented. Initial aerodynamic and aerothermodynamic wind tunnel tests and analysis have been performed on this concept. The tests and analysis have confirmed the superior characteristics of the lifting body shape.

NOMENCLATURE

ac	Aerodynamic Center
ACRV	Advanced Crew Return Vehicle
BMI	Bismaleimide
c.g.	Center of Gravity
GLOW	Gross Lift Off Weight
Isp	Specific Impulse
LEO	Low Earth Orbit
LMSW	Lockheed Martin Skunk Works
LOX	Liquid Oxygen
LH_2	Liquid Hydrogen
OML	Outer Mold Line
Pi	Polyimide
RLV	Reusable Launch Vehicle
SSTO	Single Stage to Orbit
TPS	Thermal Protection System
T/W	Thrust-to-Weight

* LMSW SSTO/X-33 Chief Engineer, Senior Member AIAA
† LMSW Senior Engineer, Member AIAA

INTRODUCTION

The launch of Sputnik in 1957, herald the dawn of a new age -- the Space Age. Since the launch of Sputnik, the advancement of technology has led to vast improvements in all fields of transportation except one, Space Transportation. Figure 1 illustrates this point. Our country's principal means of launching payloads to orbit, four decades after Sputnik, are the same expendable launchers we initially developed in the 1950's.

Vehicle	**1957 Technology**	**1997 Technology**
Automobile	**Volkswagon Bug**	**Electric Car**
Airliner	**Douglas DC-7C**	**Boeing 777**
Fighter	**F-100C**	**F-22A**
Bomber	**B-52**	**B-2**
Space Launch	**Thor(Delta)**	**Delta**
	Atlas	**Atlas**
	Titan	**Titan**

Fig. 1 Transportation Technology Advancement

Over the last 10 years, numerous national studies have examined our space launch capability and have concluded our space launch systems are expensive, labor intensive, delay prone, and not competitive. In 1993, NASA conducted a study of space transportation options (reference 1) and concluded that a new, fully reusable, Single Stage to Orbit (SSTO) launch system offered the best approach to achieving a true national need -- affordable access to space.

As discussed in reference 2, both fully and partially reusable launch vehicle concepts have been proposed in the past. While vehicle technology has advanced, driving SSTO vehicle requirements have not changed with time. A SSTO must be a structural/volumetric efficient design. To achieve orbit, vehicle dry weight cannot be more than approximately 10% of the vehicle Gross Liftoff Weight (GLOW). To ease the mass fraction challenge, the SSTO requires a high installed propulsion performance (high installed average specific impulse (Isp) and engine thrust/weight). The SSTO's aerodynamic shape must provide adequate stability and control across the full range of mach numbers and fuel states encountered. The SSTO should have cool, benign reentry aerothermodynamic characteristics allowing the use of affordable thermal protection materials.

Lockheed Martin has conducted RLV vehicle studies for over 30 years. Some of the more notable studies included the 1 1/2 stage lifting body based Star Clipper (1965 - 1968), the winged body, horizontal take-off, horizontal landing Trans Atmospheric Vehicle (TAV)

SSTO (1983 -1988), and the conical, vertical take-off, vertical landing X-Rocket SSTO (1988). In the early 1990's, Lockheed Martin began to reexamine the potential of SSTO. We initially focused on four key questions: What should the SSTO mission concept be? What is the correct payload capacity? What is the best vehicle concept? Will the state of the art support an SSTO system?

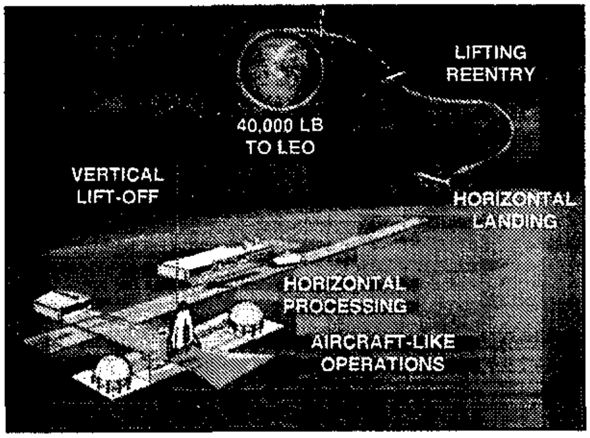


Fig. 2 Mission Concept

This Mission Concept selected for our RLV studies is shown in Figure 2. Vertical takeoff/horizontal landing were selected because these are well known, proven approaches. In addition, horizontal landing allows horizontal processing and aircraft, like operations and support. Our mission studies concluded that approximately 40,000 lb. of low earth orbit (LEO) payload capability was required to satisfy the National Launch System mission model of future DoD, NASA, and commercial missions.

Figure 3 compares the lifting body SSTO against the wing-body, conical vertical takeoff and landing, and two stage to orbit approaches. Our system studies concluded that the lifting body was a superior SSTO concept. The lifting body SSTO concept offered the potential to eliminate known problems of our previous study configurations. In particular, the synergistic lifting body SSTO approach eliminates the parasitic add-ons of our previous configurations (wings or fuel for landing). The lifting body has superior volumetric efficiency, aerodynamic stability and aerothermodynamic characteristics allowing the use of off the shelf materials.

CONCEPT EVOLUTION

The key to the success of a Skunk Works program is the utilization, or "harvesting", of existing technology innovatively integrated to achieve dramatic performance results. An example of this is the leveraging of capsule-type reentry vehicle analyses produced during the Advanced Crew Return Vehicle (ACRV) program. During this study, Lockheed Martin engineers discovered that by combining a large forebody radii of curvature with a smooth toroidal extension on the windward aeroshell yields tailorable hypersonic lift to drag ratio's. Static as well as dynamic stability for this shape was achievable with small control surfaces. This approach affords lower reentry temperatures due to these large radii; a must for robust fully reusable vehicle thermal protection system (TPS).

System		Pros	Cons
Wing-Body VHTL SSTO		• Simple Tanks • Well Studies Aerodynamics • High Hypersonic L/D	• Parasitic Weight of Wings • Difficult Integration of Large Payload Bay • High Landing Speed • Aero Stability Across Mach Range
Conical VTVL SSTO		• Light Structure	• Requires Atmospheric Restart of Main Engines • Parasitic Weight of Landing Fuel • Difficult Integration of Large Payload Bay
Lifting-Body VTHL SSTO		• High Volumetric Efficiency • No Parasitic Add Ons • Integrated Propulsion Performance • Lowest Reentry Temperatures • Best Aerodynamic Stability • Lowest Landing Speed • Lightest SSTO	• More Complicated Structural Arrangement • More Difficult Propulsion Integration
Wing-Body VTHL TSTO		• Light System Weight	• Highest System Cost

Fig. 3 RLV Architectue Comparison

Our work on the ACRV program was the genesis of the lifting body SSTO design. Figure 4 shows the evolution of the lifting body SSTO concept from the earliest concepts to the current baseline. Our initial SSTO design concept drew heavily upon the lessons learned from our ACRV and HL-20 design studies. The first body shape of the lifting body RLV resembled a Boston Whaler sea going craft. It incorporates the ACRV large round nose, deep hull, and straight sides. Cool reentry heating temperatures enabled the use of a metallic TPS. Conformal propellant tanks were used for the primary load bearing structure. The payload bay nested between tanks and was partially exposed on the leeward surface for accessibility.

We performed an aerodynamic analysis on our ACRV based initial concept and concluded it would never balance throughout the flight envelope with the weight of the required rocket engines at the end of the vehicle. The logical solution was to reduce the area forward of the center of gravity (c.g.) and incorporate a swept planform, reminiscent to the lifting bodies studied extensively in the sixties by the Air Force, NASA, and industry contractors. This led to configuration K4, shown in Figure 4. Inherent to delta planforms is a 2/3 body chord ac and a similar c.g. Compared to our initial conformal propellant tanks, configuration K4 incorporated lighter semi exposed conical LH_2 tanks and an aft multilobe LO2 tank. Although the semi exposed tanks were light, Navier Stokes aerodynamic CFD analysis predicted flow separation in the channel between the tanks and the payload bay. This led to the incorporation of a smooth outer mold line (OML) over the vehicle. Further refinements shown in Figure 4 have led to the current L1M baseline. This emphasis of these refinements were optimizing tank and propellant feed arrangements, incorporating aerodynamic shaping techniques to optimize stability, and propulsion integration.

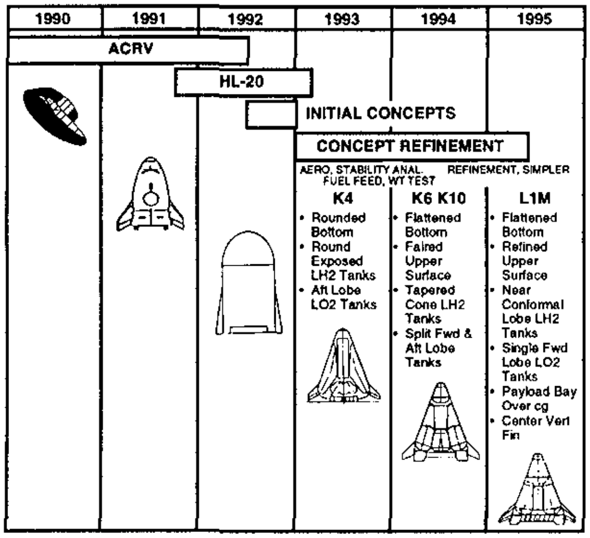


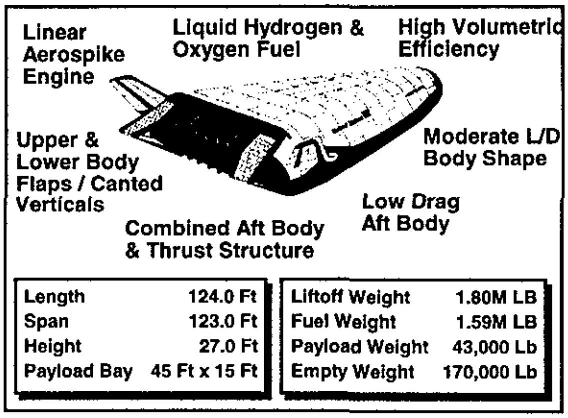
Fig. 4 Lifting Body SSTO Evolution

Aerodynamic shaping included increasingly larger radii (i.e. flattening) for the bottom surface to maintain aerodynamic qualities of a delta wing and compression sharing near the fins to move the aerodynamic center aft by sharpening the windward side closure panel radii as they go aft. This has an added benefit in that it also contributes to hypersonic directional stability. Adding camber to the leeward body surface moves the body volumetric center forward and increases the body contribution to lift. The volumetric efficiency of the lifting body shortens the length of any given vehicle propellant loading reducing the projected side area and therefore the required directional control surface requirements. These and other techniques are instrumental in developing a synergistic OML for the RLV which exhibits acceptable flying qualities over a broad flight regime.

Our design studies concluded that the linear aerospike has the highest performance with the lowest risk of any of the advanced RLV propulsion concepts. Developed by Rocketdyne in the early '70's for the Space Shuttle engine competition, the aerospike was extensively ground tested in the late 1960's and early 1970's. The altitude compensation afforded by the "inside out" nozzle and the higher installed engine thrust-to-weight (T/W) are but two of the advantages of this engine. Integration of a linear engine into a delta shape simplifies the thrust structure and preserves a more forward center of gravity through reduced weight and weight moment of the short, compact aerospike engine.

VEHICLE CONCEPT

Figure 5 shows the features, dimensions, and weights of our current vehicle concept. The internal arrangement of the baseline concept (Figure 6) dubbed configuration L1, features a delta shaped planform, a blunt forebody and smooth upper and lower surface contours. The thickness to length ratio of the vehicle is optimized within the constraints of payload bay length and propellant volume requirements. The aerospike engine integrates into the aft body tank closures and provides structure for the attachment of the fins.



Length	124.0 Ft
Span	123.0 Ft
Height	27.0 Ft
Payload Bay	45 Ft x 15 Ft

Liftoff Weight	1.80M LB
Fuel Weight	1.59M LB
Payload Weight	43,000 Lb
Empty Weight	170,000 Lb

Fig. 5 Lifting Body SSTO Design Concept

The payload bay cavity is nestled between the two LH_2 tanks and is 15 feet in diameter and 45 foot long. Performance requirements developed in market analyses size the LEO payload capacity at 43,000 lb.

Propellant tanks for the RLV consist of one main Al-Li multilobe LOX tank in the forward portion of the vehicle and two main composite multilobe LH_2 tanks which begin at the LOX tank closure and end at the linear aerospike engine. Primary structural loading is

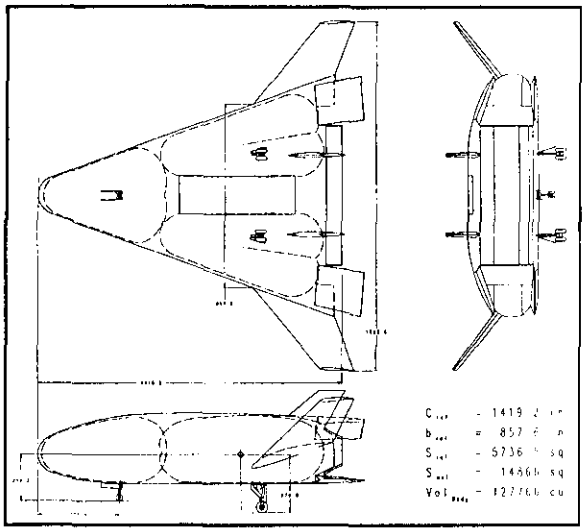


Fig. 6 Lifting Body Arrangement

carried by these tanks. In addition to the main tanks there is an auxiliary tank system for the Orbital Maneuvering System. This is located below the payload bay cavity forward of the aerospike engine. The Main Propellant System (MPS) feed lines are routed internally between the payload bay cavity and the auxiliary tank system.

The cylindrical, mid-body payload bay is located on, and axially aligned with, the vehicle centerline. The payload bay is placed over the vehicle landing c.g. to provide minimal trim changes between payload in or out. The payload bay doors are integrated into the upper body surface. The payload bay walls are the large insulated LH_2 tanks on ether side. Because of the LH_2 tank structure, the payload bay doors do not have to carry structural loads. The thrust and intertank structure form the payload bay ends. Common payload interfaces and structural load paths are accomplished by the Airborne Support Equipment, which is unique to each payload class. This approach eliminates the need for the vehicle to design-in worst on worst requirements for payload accommodations.

Between the LOX tank and the payload cavity is contained a single forward primary subsystem bay. Operational considerations, such as accessibility to systems, routinely checked between flights, are a critical element of the ongoing design evolution process. Distributed subsystems are placed adjacent to required openings, such as the payload cavity and the landing gears bays, to facilitate a minimum number of intrusions into the OML for routine maintenance and vehicle checkout. The main landing gear is placed on a lobe of the LH_2 tanks and retract to the vehicle centerline. The nose gear is located on the crease of the LOX tank and retracts aft.

Due to the lifting body's large body radii and low planform loading, reentry heating is lower than wing body or conical shapes. This enables the consideration of several lightweight material combinations for the primary structure and TPS. Lower reentry temperatures allow the engineers an opportunity to incorporate design drivers, other than temperature, into the heatshield trade space, such as maintainability. The result is the application of an optimal mix of composite and metallic materials for primary structure and TPS resulting in a robust, easily maintained system.

Body flaps trail from the upper and lower surfaces of the vehicle outboard of the linear aerospike engine on each side. The flaps can be deflected trailing edge up or trailing edge down. Various combinations of flap deflection will generate pitch, roll, and yaw moments for aerodynamic control and trim during descent.

Canted vertical tails are employed for aerodynamic stability and control. The leading edges of the tails are swept aft to an angle inside the shock wave during atmospheric re-entry to minimize aerodynamic heating. Primary yaw authority is provided by rudders mounted on the tail surfaces.

The GLOW goal for the SSTO is 1.8 million pounds with greater than 25,000 lb. payload delivered to International Space Station Alpha. Nominal orbital insertion weight, for the baseline mission to Space Station Alpha, is approximately 220,000 lb. Fluctuations in vehicle size and weight are anticipated during the design iteration process. However, the ratio of inserted weight (vehicle dry weight plus payload plus on orbit fluids) to GLOW must remain below approximately 12.0% to achieve SSTO. This requires that the vehicle dry mass fraction must be maintained below 10%.

STRUCTURE

As discussed above, dry mass fraction is a critical element to achieving SSTO. Structural mass fraction is the largest portion of this quantity and must be minimized for mission performance. The goal of structural design is to integrate all vehicle systems into a single unit of high structural efficiency. The method used to accomplish this task has often been referred to as a mix of art and engineering.

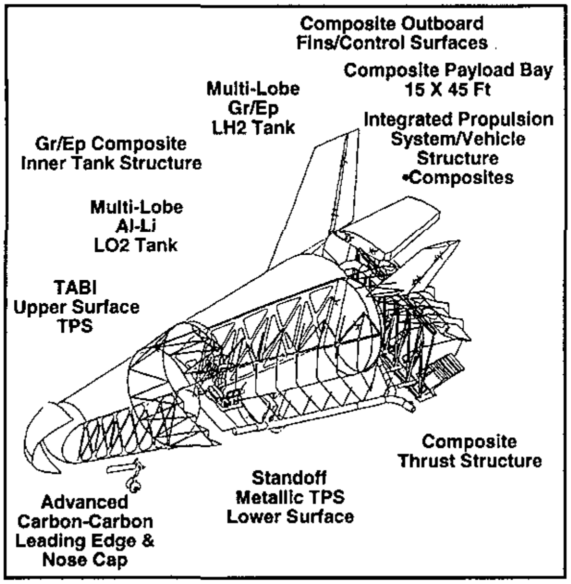


Fig. 7 Lifting Body Structural Arrangement

The SSTO structure arrangement shown in Figure 7 consists of propellant tanks, aeroshell, and connecting support structure. The aeroshell includes the TPS. The propellant tanks of the LMSW SSTO vehicle concept are designed and sized to react stack column loads, flight and landing body bending loads in combination with tank pressure. Vehicle structural continuity and integrity are provided by structural connections between the propellant tanks. This is accomplished with an intertank truss structure between the LOX and LH_2 tanks and a truss network between the LH_2 tanks and engines. Further, these truss structures bound the fore and aft ends of the payload bay and provide lateral continuity between left and right halves of the vehicle. The TPS is supported by the aeroshell which is considered secondary structure.

The approach to minimizing the dry mass fraction of the lifting body configuration is to minimize the difference between the secondary aeroshell and the primary propellant tanks or, in other words, making the tankage as nearly conformable as possible. This has two effects:

- Maximizing packaging efficiency
- Minimizing parasitic standoff structure to support the aeroshell.

A basic review of pressure vessels and associated weights has shown, two dimensionally, that several smaller circular tanks are equal in weight to one larger circular tank of equal volume and pressure. Further as discussed in reference 3, a multilobed tank is equal in weight to a circular tank, including cross tie, sized to the same conditions. These basic relationships imply that many circular tanks of varying diameter can be stacked together to approach an arbitrary cross sectional shape or a single tank of multiple lobes can efficiently package odd sections for the same weight. Theoretically, the tankage weight of a lifting body could equal that of, what appears to be, the more efficient circular fuselage of a wing-body vehicle. The challenge of tanks for the lifting body becomes the extension in the third dimension, particularly when the change in one dimension does not coincide with the change in the other dimension (i.e. planview versus elevation cut).

The TPS is a non structural system which has the capability to distribute air loads to the primary structure. The TPS systems must be free to expand inplane both thermally and mechanically. Three basic TPS regions have been identified with two attachment scheme for each region. The three regions, each with a unique TPS concept, are: the very hot edges, the hot windward surface and the relatively cool leeward surface. The TPS is either conformal to the primary structure or supported off the primary structure with aeroshell support members. The latter attachment arrangement is to fasten several TPS panels to an open lattice which are supported at the corner by columns that carry direct pressure load or provide lateral stability. The lattice is so arranged and shaped in non-conformable regions to provide aerodynamic contours.

The intertank truss structure connects the single multilobe forward LOX tank to the two (left and right) multilobe LH_2 tanks. The intertank is continuous across the full breadth of the vehicle which coincides with the forward close-out to the payload bay and provides a compression member that reacts kick loads from the thrust load carried by the LH_2 tanks.

The thrust structure is part of a multifunctional transverse structure at the aft end of the vehicle which connects the linear thrust engines to the LH_2 tank, acts as the carry through structure for the fins, distributes hold down/hoist loads, provides the tension tie between LH_2 tanks, and is the aft close-out for the payload bay. By far, the largest loads come from the engine thrust at launch. This load is gathered, beamed, and redistributed to the hydrogen tank by this three dimensional truss network. The network includes the engine expansion ramps and mounting structure. On the forward side, the LH_2 tanks provide shear continuity and beam caps for the carry through structure. Within regions not coincident with existing functional structure (i.e. payload region), a three dimensional truss network is added to complete spanwise continuity of this multifunctional member. In planview the two beam coincide with the fin structure for minimum weight.

Hot/Cold Structures Trades A first order trade study was initiated to determine whether the lifting body structure of the LMSW SSTO should be designed and sized hot or cold. The principle driver is all-up weight. Considering limitations established by enabling technologies and manufacturing, the question became: Does the TPS weight decrease faster than the increase in airframe weight with increasing TPS backside temperature?

Candidate material categories varied from cool/warm plastics to hot metals. Included were Gr/Ep/BMI/PI, titanium, stainless steel, and nickel steel. Preliminary analysis has shown the critical strength sizing condition of the primary structure (i.e. tanks and connecting members) to be during the ascent phase and the hot descent is relatively benign for sizing. Metallic alloys were selected for comparison based on specific mechanical properties of strength and stiffness at room temperature. For the thermoset composite material candidates, mechanical properties were considered equal at room temperature with adjustments made for hot aeroshell support structure sizing. The backside temperature used for TPS sizing was determined based on reusable considerations of matrix micro cracking or metallic creep buckling. For the purpose of the study, cryo insulation was considered on the interior of the tankage.

The weight build-up of Hot/Cold trade included structural elements of: LOX and LH_2 tankage, intertank and thrust structure, and aeroshell support structure including portions of the fin carry through structure. The build-up of the LH_2 tanks included the barrel, longeron, aft ring and aft dome. TPS weight was calculated separately by Rohr Incorporated, and included the heat shield support lattice.

The results of the trade concluded that moderately warm graphite composite structure, on the order of 350°F, offered the lowest all-up weight. It was found that for structural materials above 350°F, the TPS weight did not decrease enough to compensate for the increase in density of higher heat capacity materials. Further, it was found that moderately warm composite structure was well within the state of the art.

Materials Materials of the baseline LMSW SSTO primary airframe is a mix of advance metallics and advanced composite materials. The forward LOX tank is of welded aluminum-lithium alloy 2195 and is supported by an intertank truss structure of IM7/APC2 thermal formed tubes that connect to the LH_2 tanks of tow placed IM7/977-2. The multifunctional thrust truss structure that ties the engines to the two LH_2 tanks is a mix of tubes made from graphite/epoxy and a boron/graphite/epoxy hybrid.

The principal driver in selecting materials was weight performance with reusability. The advancement in material technology since the design of the Space Shuttle has been with advanced composite materials. The specific properties advantages of composites made them the winner over metallics for the weight critical SSTO vehicle. This is not to say that all composite issues relative to a RLV have been demonstrated, but that enough technology and design/manufacturing experience has been gained in the last two decades, combined with specific research, to produce a viable airframe in the next century.

AERODYNAMIC DESIGN

Building a RLV as a delta lifting body, as opposed to a wing-body layout, makes good aerodynamic use of the propellant tankage surface area. A number of benefits are also gained; either directly from the lifting body shape or indirectly from accommodating a highly desirable linear aerospike propulsion system and a mild reentry thermal loading.

As shown in Figure 6, the tankage in the form of multilobed cells forms a low aspect ratio lifting body that carries approximately 80% of the lift. The payload bay center can be readily placed on the vehicle empty c.g. which is also coincident with the landing aerodynamic center. Note that these delta configurations have a relatively small ac shift, less than 5% from low speed to hypersonic. Thus trim shifts are small for either speed change or payload; in versus out. In comparison, the long forward fuselage of a wing-body is a minority player in lift at low speed, but produces significant forces hypersonically via impact flow. Thus the ac shift can be large, typically in the range of 20%.

A lifting body delta shape is very compact longitudinally. This feature helps in establishing directional stability. Also a basic hemispheric lower body shape has been flattened aft both horizontally and vertically. These flattened areas provide more hypersonic flow impact area to aid in pitch and directional characteristics. Side fins are used to achieve

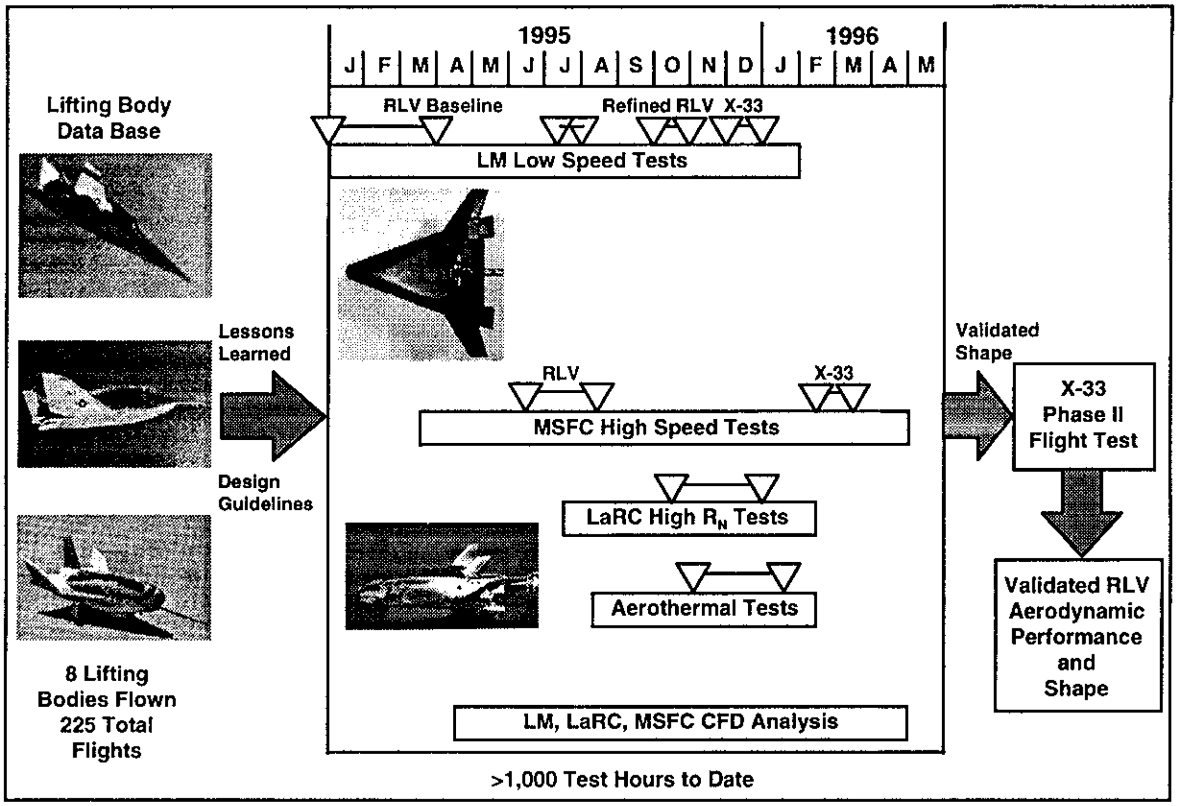


Fig. 8 Lifting Body Aerodynamic Development Plan

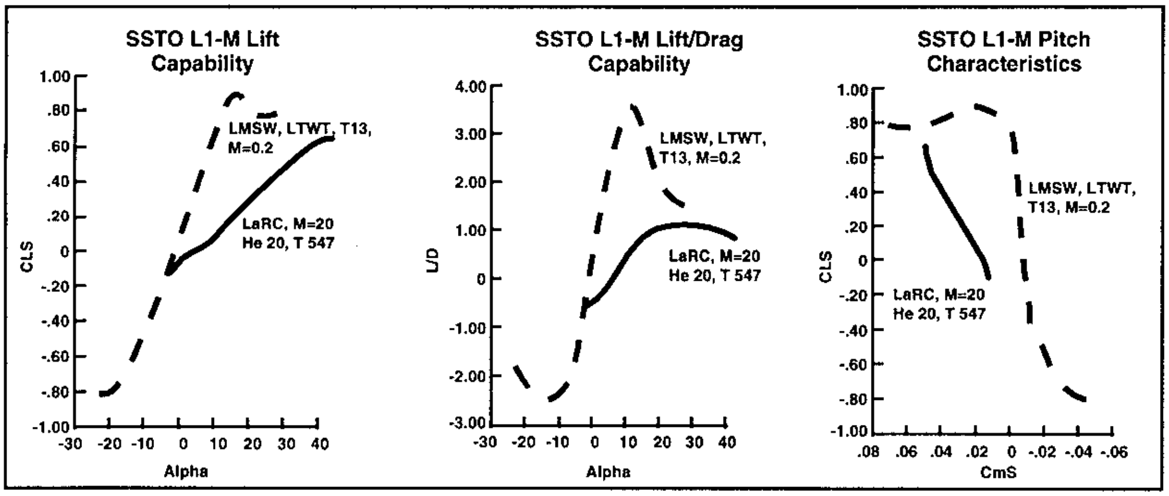


Fig. 9 Lifting Body Aerodynamics

most of the required low speed directional characteristics. A center fin or twin verticals are used to establish low speed neutral directional stability from the level already provided by the side fins alone. The center vertical(s) rudder is used for pure yaw control. Side fins are primarily sized to bring the basic body low speed lift to drag ratio of approximately 2.5 up to a more suitable level of near 4. These fins provide part of the pitch balance and also give excellent roll damping. The fins are canted to avoid significant reentry heat loads.

Given the large lifting area, the equivalent wing loading is approximately 40 psf. This relatively low loading coupled with a maximum lift coefficient, C_L, of approximately 0.9 yields approach and landing speeds in line with small commercial jet aircraft.

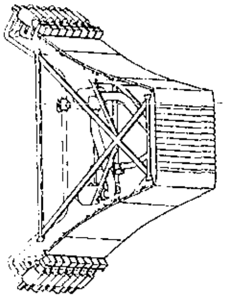
As shown in Figure 8, the general arrangement of the delta lifting body RLV and the body flaps in particular draw from X-24 and HL-20 experience. These flaps do a number of things. First, they provide a sharp trailing edge to stabilize the upper surface and lower surface flow separation points around the base area. Secondly, they provide pitch and roll control function. Third, both the upper and lower flap areas provide additional attached flow area at low speed to supersonic speeds that contributes both to lift and pitch stability. Lastly, the lower body flaps provide the hypersonic impact area for both lift and pitch trim.

Aerodynamic inputs to the design process have proceeded in 4 steps as charted in Figure 8. First, aerodynamic data were compiled using empirical drag estimates, vortex lattice (VORLAX) and hypersonic arbitrary body program (HABP) codes. Secondly, a low speed wind tunnel configuration development program was run in the Lockheed Martin Skunk Works low speed low turbulence wind tunnel (LTWT) facility using a plastic 1/120 scale model formed by stereo lithography. This model was easily recontoured by filing, plastic filler and new parts made from thin circuit board stock. Significant configuration changes were accomplished in hours rather than days or weeks. Changes were made to achieve fully attached upper body flow and to match side fin aerodynamic parameters (root incidence, twist, sweep, area, airfoils) to the local body flow angularity. Third, a high speed test program was run at Marshall Space Flight Center (MSFC) 14-inch Trisonic Wind Tunnel to fully characterize the design from low speed to Mach 5. A plastic stereo lithography model has also run at the LaRC Mach 20 Helium tunnel. Fourth, new design iterations are now being formulated based on the findings of the testing to date, and flight simulations.

Aerodynamic test results are encouraging as shown in Figure 9. The low speed maximum C_L is 0.9 and the L/D is 3.7. The reentry measured hypersonic C_L is 0.6 with a L/D of 1.1. At low speed the configuration is nearly pitch balanced with neutral controls and is approximately 1% pitch unstable with the c.g. at 66 % of centerline length. Hypersonic data with controls faired shows 5% pitch unstable. Approximately 10 degrees down lower body flap will trim the vehicle at hypersonic speeds and give neutral pitch stability.

PROPULSION

As shown in Figure 10, the lifting body RLV/SSTO vehicle's main engine is a pump fed, linear aerospike engine that provides propulsive thrust by burning a mixture of liquid hydrogen and liquid oxygen propellants. The rocket engine's Gas Generator cycle combines a very high thrust to weight ratio while still providing relatively high specific impulse. Rocketdyne's linear aerospike engine is designed to provide high performance, minimum propulsion installation weight and long life in a simple robust installation. The aerospike 'spike' nozzle, opens to the atmosphere, which allows for automatic performance adjustment as the vehicle ascends. The aerospike's design flexibility allows high vehicle integration to occur, reducing vehicle weight and cost. It's flexibility allows the vehicle designer to fill the vehicle's base with engines, thereby reducing base drag on ascent and eliminating heat sheilding allowing a smaller, lower cost vehicle to be designed.



Gas Generator Cycle	
Nominal Thrust, lbf	
Sea Level	299,000
Vacuum	377,000
Specific IMpulse, sec	
Sea Level	361
Vacuum	455
Chamber Pressure, psia	2,300
Propellants	Lox/LH2
Mixture Ratio	6.0:1
Throttling for TVC	± 30%
Weight	3,400

Fig. 10 Baseline Linear Aerospike Engine

Figure 11 illustrates the key features of the linear aerospike nozzle. The truncated planar spike nozzle utilizes secondary flow to pressurize the nozzle base region, and thus compensate for the shortened length. The secondary flow is provided by the engine's turbine drive gas which, after expanding through the turbines, is exhausted into the base. This serendipitous use of the turbine drive gases permits the simple generator cycle to match the performance of complex topping cycle engines.

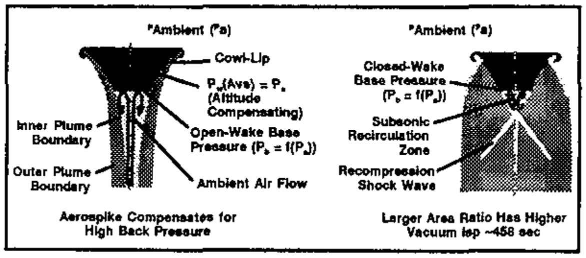


Fig. 11 Aerospike Nozzle Flow

The high pressure primary flow gases which produce the major portion of the engine thrust are exhausted from modular thrusters against the surface of an external expansion ramp. The primary flow continues to expand beyond the nozzle surface and encloses a subsonic, recirculating flow field in the base region. The pressure acting upon the nozzle base contributes additional thrust to the nozzle and with the introduction of the secondary flow further increases the base pressure.

The outer surface of the primary flow is a free jet boundary, which is influenced by ambient pressure. This ambient pressure favorably influences nozzle performance at low altitudes. At sea level the relatively high ambient pressure compresses the primary flow field. This compression increases the static pressure on the nozzle wall. At high altitudes the outer free jet boundary expands to the Prandtl-Meyer turning angle at the exit of the modular thruster, as shown in Figure 11. The ambient pressure influence prevents the nozzle from overexpanding at sea level allowing the use of high area ratio nozzles for high vacuum Isp.

The linear aerospike engine allows use of a unique thrust vector control (TVC) scheme whereby differential thrust control is accomplished by adjusting the propellant flows between the upper and lower engine segment thrust cells. This provides capability for both pitch and roll control through the use of electromechanical actuated three-way showerhead valves. Vehicle yaw control is accomplished by varying the output of individual turbo pumps and therefore the engine thrust. This simple control architecture eliminates the necessity for gimbals, actuators, hydraulic plumbing and the increased power required to move the engines for thrust vector control. The aerospike engine can be closely coupled to the aft end of the vehicle to shorten the thrust structure without the attendant gimbals joints, thus effectively moving the c.g. forward and driving the vehicle empty weight down.

The highly integrated Lifting Body/Linear Aerospike configuration has the benefits of:

- altitude compensating nozzle, high vacuum specific impulse with minimal sea level degradation.
- reduced vehicle base area thus decreasing the base drag and reducing the need for base heat shielding, saving weight.
- distributed thrust loads, leading to a lighter thrust structure over comparative bell installations.
- low torque valves for differential thrust vectoring; no flexible feed lines, interconnects, or hydraulics, for improved operability.
- truncated nozzle, less weight aft, more fwd c.g. for improved trim requirements.
- small individual thrusters, inexpensive, shorter design cycle.

AEROTHERMAL DESIGN

Space vehicle flight at high speeds and altitudes produces high skin temperatures due to aerodynamic heating. Skin temperatures over the surface of the vehicle depends on a number of variables such as flight path, vehicle configuration, altitude, and others. The aerodynamic heating produced during ascent, abort, and reentry phases needs to be known to ensure that proper thermal protection is provided for the vehicle.

For the missions considered here, the reentry phase generates the highest aerodynamic heating rates (reference 4), and thus drives most of the thermal protection system design.

The reentry trajectory selected for the RLV was specifically tailored to minimize the peak heat rate during reentry. The lifting body's low planform loading allows a cooler reentry than Space Shuttle. Comparative reentry trajectories are illustrated in Figure 12, with the corresponding peak windward temperatures along the RLV centerline shown in Figure 13.

To improve the circumferential temperature distribution evaluations, reentry surface temperature/heat transfer measurements are being performed in a NASA Langley wind tunnel using a quantitative phosphor Thermography technique (reference 5). A typical result obtained with this technique is illustrated in Figure 14.

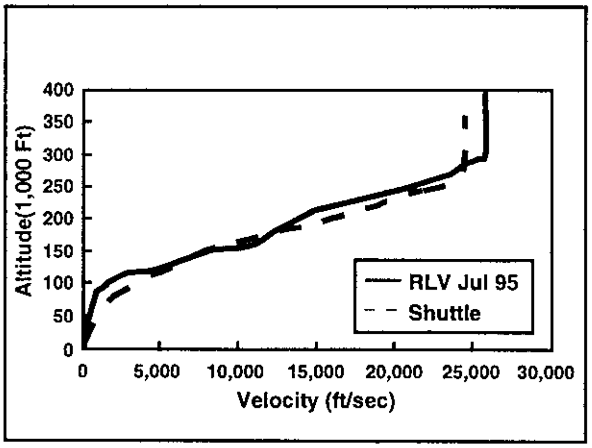


Fig. 12 Comparative Reentry Trajectories

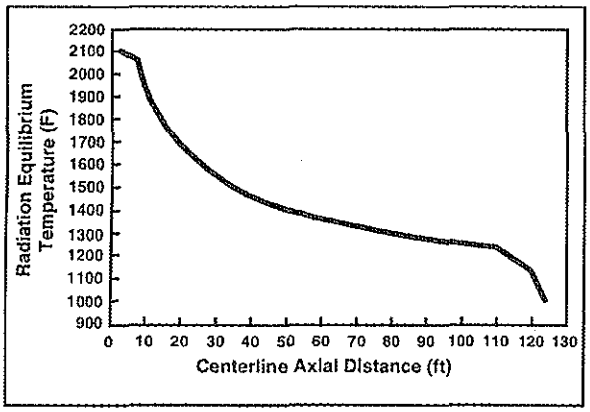


Fig. 13 Peak Centerline Reentry Temperature

This figure shows the cool, monotonic decreasing reentry temperatures of the lifting body RLV devoid of high temperature shock interactions.

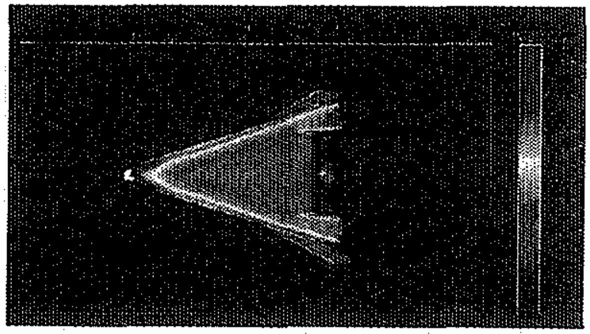


Fig. 14 RLV Reentry heating Distribution

The lower RLV surface temperatures reached during reentry allow use of a well-characterized, conventional and durable TPS system as illustrated in Figure 15. Oxidation resistant carbon-carbon (ORCC) was selected as the leading candidate for the highest temperature regions encountered such as the nose cap and leading edges. ORCC was selected because it provides superior oxidation resistance and has higher temperature capability as compared to Advanced Carbon-Carbon (ACC-4), Carbon-SiC, and SiC-SiC materials.

For temperatures under 1800°F, Inco-617 was selected for its high temperature creep performance, thermo-mechanical and chemical stability. For temperatures under 1300°F, Ti-1100 was selected because it is a production-ready titanium alloy.

For the comparatively low temperatures encountered on most of the leeward side of the vehicle, conventional insulation blankets consisting of PBI, AFRSI and TABI were selected for use.

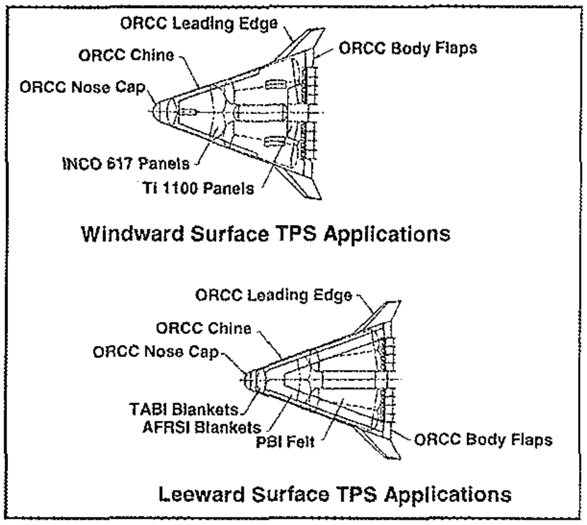


Fig. 15 TPS Application

SUMMARY

Numerous studies have concluded that our current expendable launch systems are not competitive with foreign expendable launchers. A new fully reusable SSTO launch system would bring about a dramatic reduction in launch cost. With the advancements since the Space Shuttle was developed, the technology for a fully reusable SSTO launch system is within reach. The NASA X-33 Advanced Technology Demonstration (ATD) program will demonstrate the technology required for RLV before the end of this century. An integrated lifting body RLV concept has been developed that harvests current and near term technology. The lifting body approach eliminates the parasitic add-ons such as landing fuel and wings while providing superior aerodynamic stability, payload, integration, reentry aerothermodynamics, and integrated propulsion. The lifting body benefits have been confirmed by test and analysis.

ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration, Marshall Space Flight Center, under a Cooperative Agreement Contract NCC-8-73. The authors wish to express appreciation to the Lockheed Martin Team Staff who contributed to this project. In particular, we would like to thank Michael Rankin, J. Scott Reaser, Al Kudirka, Paul Landry, and Bryan Kreimendahl of the Lockheed Martin Skunk Works for their work in developing the lifting body concept; John Vinson of Rocketdyne for his support in optimizing the Lifting Body/Aerospike concept; Barry Strauss of Rohr Incorporated, for his continual work on maintainable Thermal Protection Systems; and Kathryn

Wurster of NASA LaRC for the aerothermodynamic expertise she has contributed to our design team. Last but not least, we are indebted to Christina Van Dyk and Carol Miller for their time and effort in publishing this paper.

BIBLIOGRAPHY

1. NASA Access to Space Study Final Report, May 1993.

2. Space Shuttle, The History of Developing the National Space Transportation System, Dennis R. Jenkins, Walsworth Publishing Company, 1992.

3. Analysis and Design of Flight Vehicle Structures, E.F. Bruhn, Tri-State Offet Company, 1965.

4. SSTO RLV L1-M Baseline Update, Lockheed Martin Skunk Works, July 31, 1995, LMSW # DU-95-1013.

5. Surface Temperature/Heat Transfer Measurement Using a Quantitative Phosphor Thermography System, G.M. Buck, January 1991, AIAA-91-0064.