THE K2X: DESIGN OF A 2ND GENERATION REUSABLE LAUNCH VEHICLE

R. Ewig, J. Sandhu, C. A. Shell, M. A. Schneider, J. B. Bloom, S. Ohno
University of Washington, Department of Aeronautics & Astronautics, Seattle, WA 98195-2400

Abstract

The K2X project was initiated at the University of Washington's Department of Aeronautics & Astronautics in response to a design competition announced by Kistler Aerospace Corporation in September of 1998. The goal of the competition was to solicit concepts for a possible next generation Kistler K-1 reusable launch vehicle, which might be used at Kistler's discretion. The K2X design was presented to Kistler in October, 1999.

The K2X (Kistler 2 Experimental) design is a Two-Stage-To-Orbit (TSTO), Vertical-Take-off, Horizontal-Landing (VTHL), autonomous, Reusable-Launch-Vehicle (RLV). The first stage utilizes lifting surfaces and air-breathing propulsion to return to the original launch site, where it performs a controlled horizontal landing. The second stage is a nearly cylindrical, hypersonic lifting body with small aerodynamic control surfaces, and uses parachutes and airbags for the final phase of its descent. Both stages use derivatives of the NK-33/43 LOX/Kerosene rocket engines developed for the Soviet Lunar program, and are currently in use on the K-1 RLV.

Several advanced technologies are incorporated into the design of both vehicle stages, including Hydroxyl Ammonium Nitrate (HAN) monopropellant based attitude control systems, ceramic vehicle thermal protection systems, and light weight composite structural design.

The economic viability of the K2X concept was included in the very first phase of the design and three target missions were identified: multiple satellite deployment in LEO, supply missions to the International Space Station, and injection of payloads into geosynchronous transfer orbit (GTO) using an expendable upper stage. The operations and performance of the completed design were also investigated and compared to the performance of other existing and near-term launch vehicles.

Vehicle Concept

The K2X is a Two-Stage-To-Orbit (TSTO), Vertical Take-off Horizontal Landing (VTHL), autonomous, Reusable Launch Vehicle (RLV). The first stage, referred to as the Launch Assist Platform (LAP)[1], is a winged craft, optimized for supersonic and subsonic cruise conditions. It utilizes two medium bypass ratio turbo-fan jet engines to return to the original launch site following separation. There it performs a controlled horizontal landing.

The second stage, referred to as the Orbital Vehicle (OV), is a nearly cylindrical hypersonic lifting body with small aerodynamic control surfaces. The entire forward section of the OV is detachable in order to facilitate payload processing. Following reentry and a short hypersonic glide phase, the OV uses parachutes and airbags to perform a soft landing at the original launch site.

Figure 1 shows an artist's illustration of the K2X RLV in low earth orbit.

Figure 1: Artist's illustration of the K2X.

Flight Profile for typical LEO Mission.

Figure 2 shows the flight profile for a typical Low Earth Orbit (LEO) mission of the K2X vehicle:

1. The mission begins with the vehicle being launched at the Kistler Aerospace Woomera Spaceport facilities in Australia.
2. At lift-off all engines of the first and second stage are ignited simultaneously. During this first phase of the ascent prior to separation, the main engine of the second stage (OV) is fueled with propellants stored in the tanks of the first stage (LAP). This enables the OV to leave the separation point with completely filled propellant tanks, yet allows the combined vehicle to achieve a high thrust to weight ratio at take-off to minimize gravity losses during the initial ascent.
3. Separation occurs at an altitude of approximately 53 km (174,000 ft).

First Stage (LAP)

4. Following separation, the LAP uses its attitude control thrusters to perform a 180 degree roll maneuver and reenters the atmosphere.
5. After reentry, the LAP performs a coordinated turn towards the launch site, and then continues to glide through the supersonic regime until an altitude of 3 km (10,000 ft) is reached. There the protective ramp in front of the two turbo-fan engines is lowered, and the engines are started using the wind milling effect of the oncoming air. The vehicle cruises the remaining distance to the launch site at Mach 0.45.
6. At the launch site, the LAP performs a controlled horizontal landing using a conventional runway.

Second Stage (OV)

4. The OV continues into orbit until Main Engine Cut Off (MECO) at an altitude of approximately 97 km (318,000 ft). When the desired apogee altitude is reached it uses its two Orbital Maneuvering System (OMS) engines to circularize the orbit. The payload is deployed axially through the nose of the vehicle.

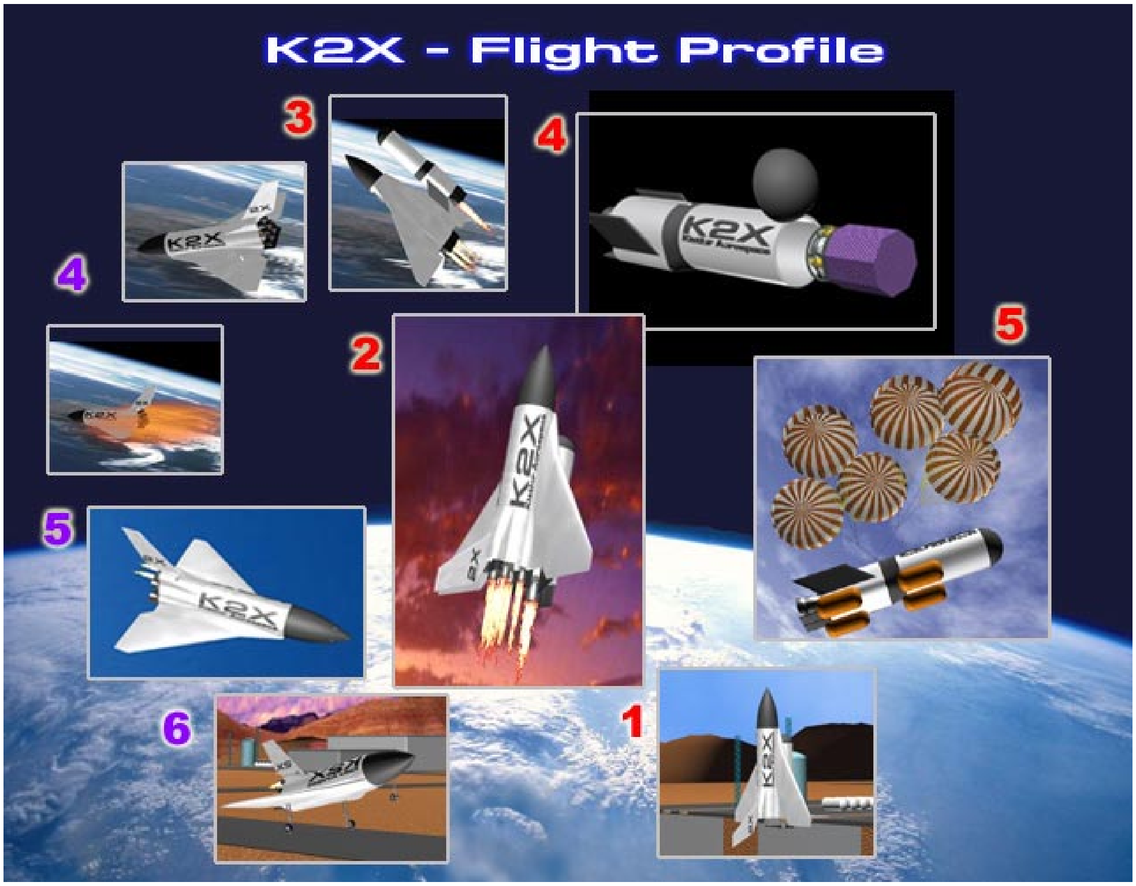

Figure 2: Flight profile of a typical K2X mission.

5. After staying in orbit for a sufficient time to align the reentry trajectory with the launch site (approximately 24 hours), the OV performs a deorbit burn, reenters in a gliding trajectory, and performs a soft landing at the original launch site, using parachutes and airbags.

Stage Sizing

For any given Δv requirement and vehicle configuration, there exists an optimum division of Δv contributions for each individual stage. The two stages of the K2X RLV are sized to operate at this optimum value. Since the launching of Low Earth Orbit (LEO) payloads is to be the most common task of the K2X vehicle, a Δv of 9.0 km/sec was chosen as the optimization point.

The Δv capability for each stage of the RLV is governed by the rocket equation, which relates the total Δv the stage can provide, to the specific impulse (I_{sp}) of its propulsion system, the initial mass, and the mass at burnout.[2] The payload mass fraction for the entire vehicle is given by the product of the values for the individual stages. Assuming structural mass fractions for the OV and LAP, the value of Δv fraction provided by the first stage can be found for which a maximum payload fraction for the entire vehicle will be achieved. Maximum payload mass fraction implies minimum launch pad mass for a given mission and payload mass.

The values of structural mass fraction were initially chosen to be 0.15 and 0.125 for the LAP and OV respectively.

Figure 3 shows a contour plot of the payload mass fraction versus the Δv fraction provided by the first stage (LAP) for different values of total Δv. The specific impulse values for the two stages are taken from the specifications for the NK-33/43 engines provided by Kistler Aerospace.[3] Since the analysis assumes a constant specific impulse during the entire ascent, the values used for the two engine types is the average of their respective vacuum and sea-level performance given in the cited reference.

At the chosen Δv of 9.0 km/sec, the ideal division of Δv between stages is such that the LAP has to provide 43 % of the total Δv.

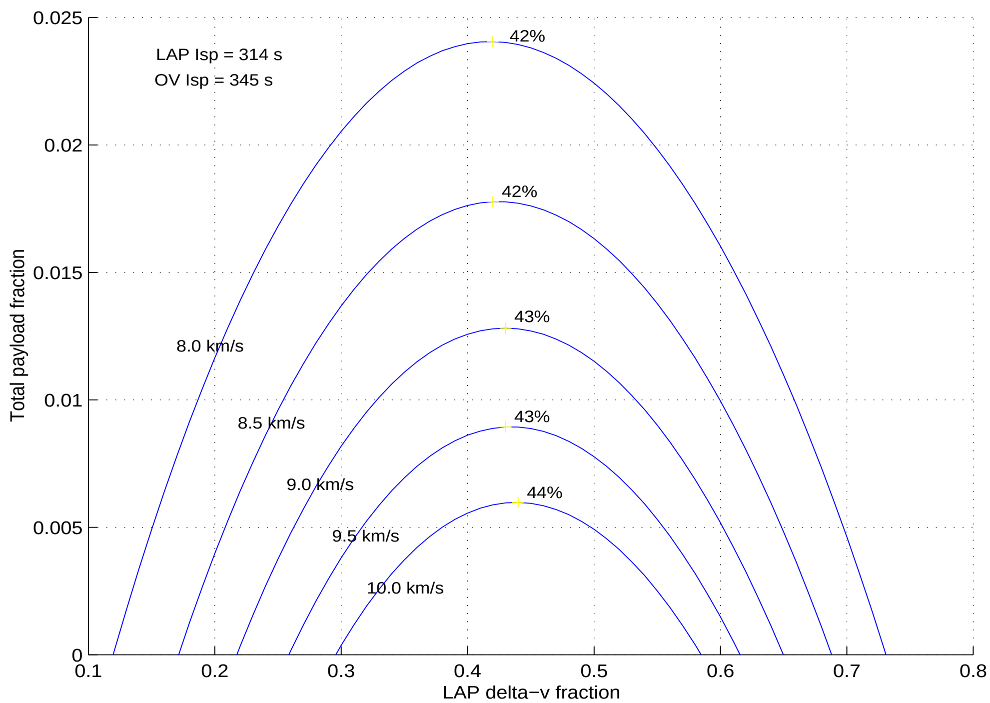

Figure 3: Total payload fraction vs. total Δv and Δv fraction of the LAP.

First Stage (LAP) Design

During the initial analysis of the two stage to orbit reusable vehicle concept, it quickly became apparent that the return of the first stage to the launch site is a driving factor in the vehicle design. In order to maximize payload capability for a given initial take-off mass, the LAP needs to travel a considerable distance downrange, before beginning its return trajectory. In order to travel back to the launch site in the most mass-economical manner, the LAP is designed similar to a supersonic aircraft, utilizing lifting surfaces and airbreathing propulsion to achieve maximum range capability for a minimum of propellant mass dedicated to the vehicle return. Figure 5 (next page) shows an exploded view of the LAP indicating the nomenclature for the various components.

LAP Mass Budget

Table 1 lists the basic mass breakdown of the LAP into structure and propellant. Any item contributing to the mass of the vehicle that is not part of the useful propellants for the ascent part of the trajectory is considered part of the structure mass in this breakdown.

Table 2 presents the distribution of the structural mass on ascent among the various sub-systems. The masses given represent the values as the vehicle sits on the launch pad.

Table 1: LAP basic mass breakdown.

Item	*Mass [kg]*
Propellant	482,167
Structure	85,075
Total	**567,242**

Table 2: LAP structural mass breakdown.

Item	*Mass [kg]*
Aerodynamic Surfaces	21,325
Jet Propulsion	19,000
Rocket Propulsion	17,962
Thrust Structure	10,670
Thermal Protection System	7,800
Landing Gear	3,500
Avionics	600
Attitude Control System	100
Growth Margin	5,520
Total	**85,075**

Aerodynamics

The LAP's aerodynamic design was based on a wind tunnel study done at NASA Langley Research Center[4]. In addition, several modifications were incorporated to further adapt the vehicle to its specific mission. Figure 4 shows a basic three view of the resulting design.

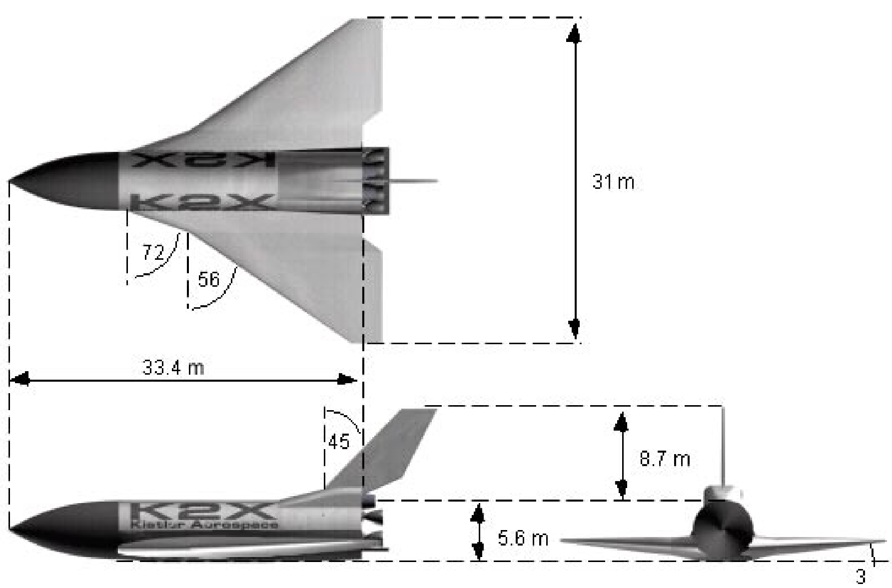

Figure 4: Three view of the first stage (LAP).

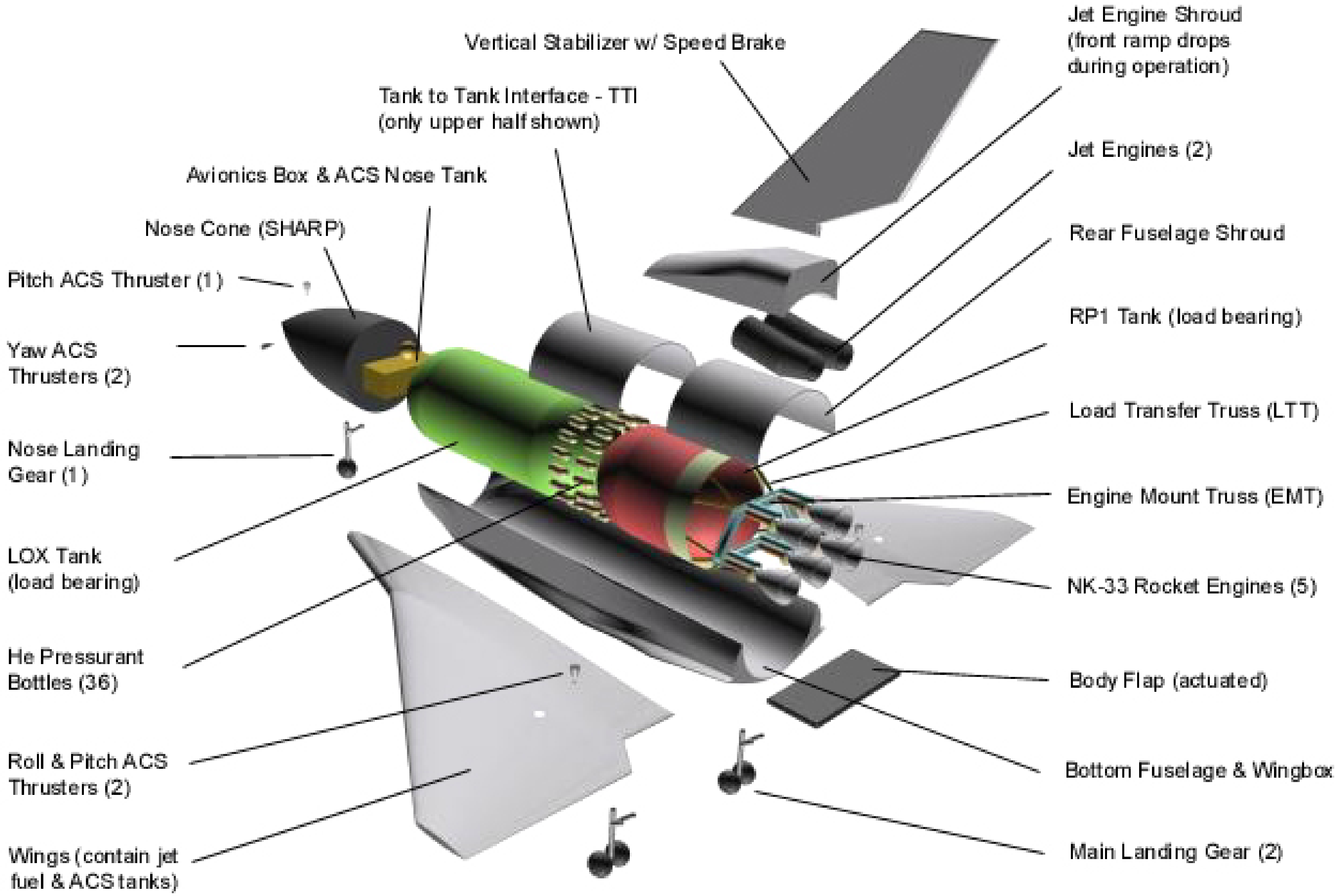

Figure 5: Exploded view of the K2X LAP indicating sub-component nomenclature.

Since the aerodynamic data available from the Langley model was brought into question by the additional modifications of the LAP, computational fluid dynamics capabilities were developed to verify the performance of the final configuration. All computations were performed on a parallel cluster of 15 DEC Alpha computers, using Metacomp Technology's CFD++ code.[5] Grid generation was achieved with ICEM CFD's Unigraphics to Grid conversion utilities. Due to the limited scope and time frame of this investigation, the geometry was simplified to speed up the grid generation process, and reduce computational time for a given run. As a result, the computational grid of 206,854 unstructured tetrahedral cells, did not account for rocket engine nozzles, body flap, or air-breathing engines. Also, grid density was not sufficient to model viscous effects.

Subsonic Cruise Analysis

Cases were run through an angle of attack range from zero to fifteen degrees, at Mach 0.45, and free stream conditions equivalent to a cruising altitude of 3,000 m (9,840 ft). Figure 6 shows the resulting lift and drag curves at these conditions.

At the chosen cruise velocity of Mach 0.45, an angle of attack of 8 degrees is required to maintain level cruise. The L/D ratio at this performance point is 3.64, the maximum L/D is achieved at an angle of attack of 11 degrees and has a value of 4.01. This indicates that further improvement in the LAP cruise range can be achieved by adjusting to a lower cruise velocity and higher angle of attack.

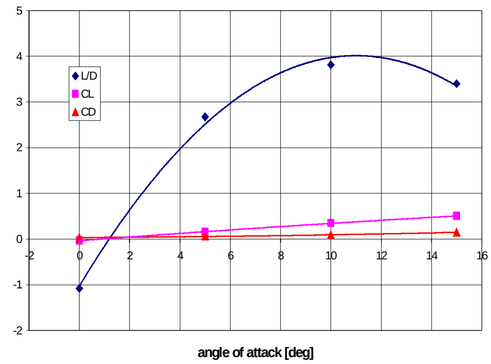

Figure 6: Non-dimensional lift and drag quantities for the LAP at cruise conditions.

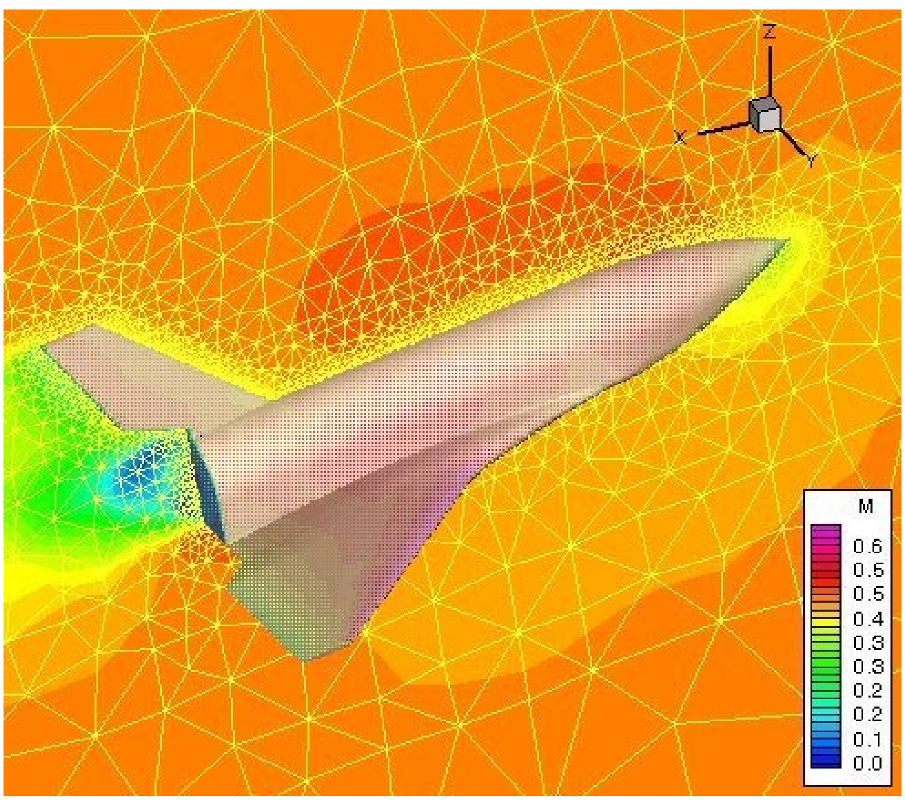

Figure 7: CFD flow visualization for the LAP under cruise conditions.

The reference area for both the C_L and C_D values is the wing plan form area of the LAP (one side), assuming the wing continues into the fuselage up to the centerline (265.1 m^2).

Figure 7 shows the flow field around the vehicle at the chosen cruise mode of 8 degrees angle of attack.

Another concern is the aerodynamic stability of the LAP under cruise conditions. Stability in the roll axis is easily adjusted by changing the dihedral angle of the vehicle. Stability in the pitch axis is more critical, especially since most of the structural mass of the LAP is located to the rear of the vehicle, leading to a C_g location at 62% of the vehicle length.

Figure 8 shows the location of the C_p on the vehicle roll axis as a function of angle of attack under cruise conditions.

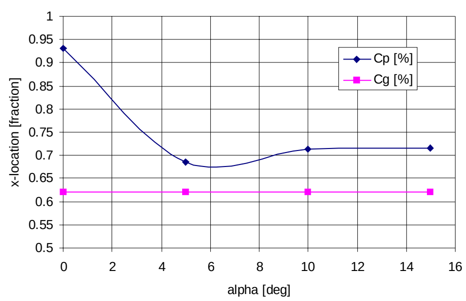

Figure 8: LAP C_p vs. C_g location under cruise conditions.

As can be seen, the center of pressure never moves in front of the vehicle C_g, and the LAP is thus aerodynamically stable. The location of the C_p varies such that it comes closes to the C_g at about 6 degrees angle of attack.

Reentry Aerodynamics

The same computational tools used in the subsonic cruise analysis were also utilized for the investigation of the supersonic characteristics of the LAP. The parameter of particular interest for this simulation was the maximum L/D the vehicle would be able to achieve under reentry conditions. Computations were performed for free stream conditions equivalent to 30 km (98,500 ft) altitude and Mach 10. Figure 9 shows the non-dimensional parameters of the vehicle versus angle of attack under reentry conditions.

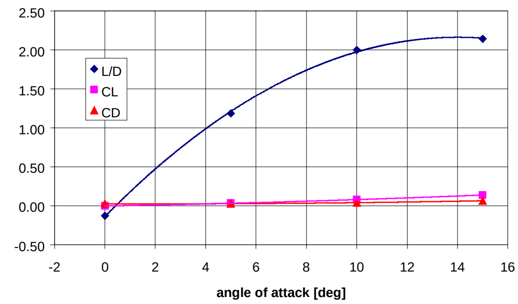

Figure 9: Non-dimensional lift and drag coefficients for the LAP at reentry conditions.

The maximum L/D is achieved at an angle of attack of 14 degrees and has a value of 2.17.

As in the subsonic case, the stability of the LAP (C_p vs. C_g location) was investigated for supersonic speeds as well.

Figure 10 shows that in the case of reentry the C_p repeats its earlier behavior of reaching its most forward location at an angle of attack of about 7 degrees. In this instance, the location is at 57% of the LAP roll axis and thus in front of the C_g, making the LAP aerodynamically unstable.

The LAP avoids this region of aerodynamic instability by not operating at angles of attack below 10 degrees until subsonic velocities are reached.

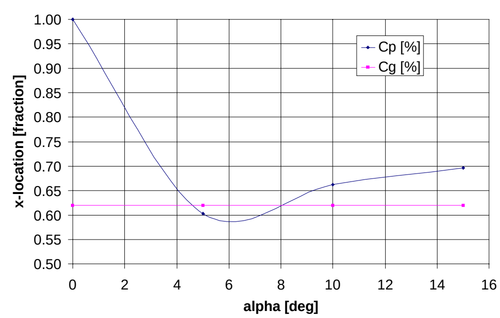

Figure 10: LAP C_p vs. C_g location at reentry conditions (Mach 10).

Figure 11 is a visualization of the flow field at supersonic speed.

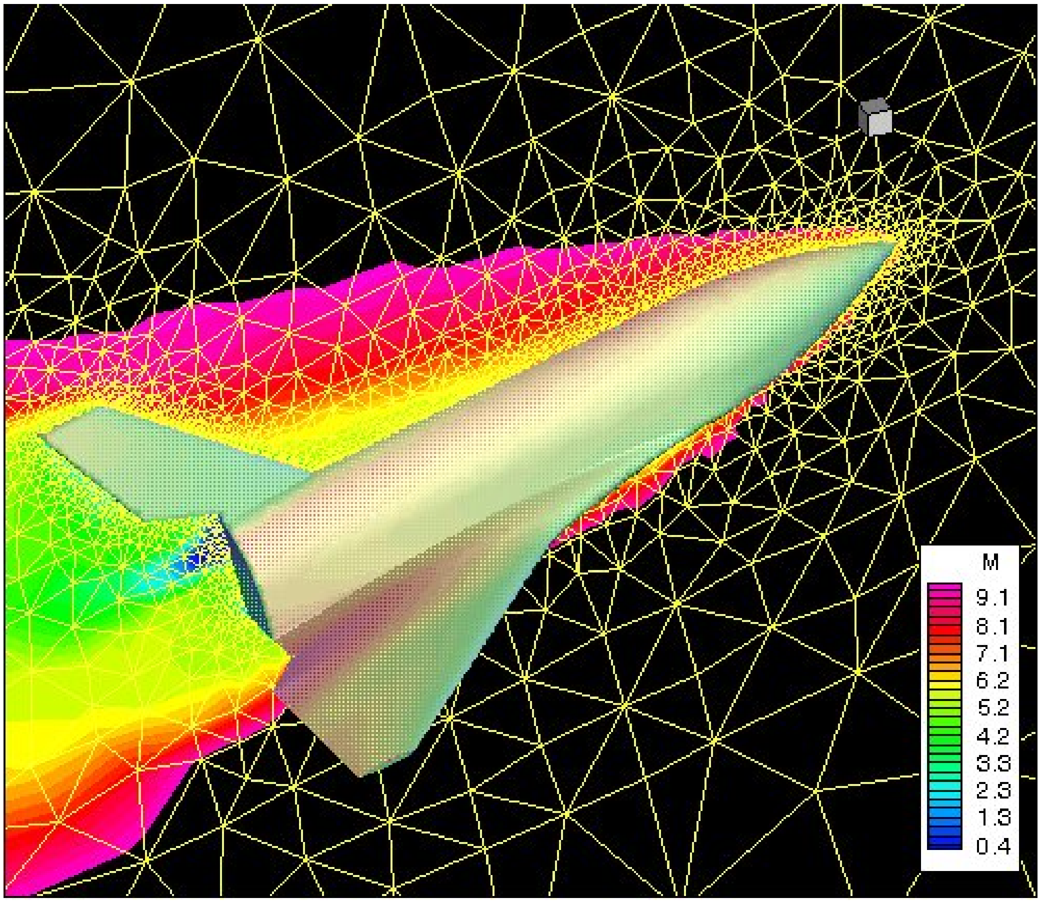

Figure 11: CFD flow visualization for the LAP at reentry.

Rocket Propulsion

The five main engines of the LAP are identical to those currently in use on the K-1 RLV. The Aerojet AJ26-58 engine is a modified version of the Russian NK-33 engine developed by ND Kuznetsov Scientific Technical Complex for the Russian Lunar program.[6]

Table 3: Specifications of AJ26-58 / NK-33.

Parameter	*Value*
Vacuum thrust	379,300 lb
Sea-level thrust	340,200 lb
Specific Impulse	331.3 sec
Chamber pressure	2109 psia
Mixture ratio	2.586
Length (total)	146 in
Diameter (nozzle exit)	59 in
Weight	3,104 lb
Area ratio	27
Throttling capability	50% - 114%
Gimbal range	± 6 degrees

The main propellant tanks of the LAP are located in a tandem arrangement. Both the LOX and RP1 tank are of cylindrical shape with hemispherical end caps. They also serve as the vehicle thrust structure, and part of the fuselage for the cylindrical section of the tanks.

The RP1 tank is located closer to the main engines and made of IM7/K3B composite, with a layer of titanium honeycomb to provide additional resistance against buckling under the axial thrust loads. The LOX tank is designed to be manufactured from aluminum alloy Al 2219, with the honeycomb stiffening layer made of the same material. The total masses of the RP1 and LOX tank are 823 kg (1,815 lb) and 3,973 kg (8,760 lb) respectively.

Attitude Control System

The LAP is equipped with a total of 5 attitude control thrusters. Two are located in the wings (roll/pitch-up), and three in the nose cone (pitch-down/yaw). These thrusters operate on a HAN based monopropellant. HAN is an oxygen rich salt, composed of hydroxylamine and nitric acid which can be made liquid by adding water. A HAN based monopropellant consists of HAN, water and a compatible fuel.[7]

HAN based monopropellants are aimed towards replacing toxic bipropellants and monopropellants used for the ACS of small spacecraft as well as launch vehicles. Primex Aerospace and NASA have already tested HAN with a resultant specific impulse of 195 s, and eventually have a goal of achieving a specific impulse of 300 s. It is expected that within the next few years HAN based monopropellants will be capable of providing an Isp of 247 s (using Glycine as fuel), equal to hydrazine performance. Three spherical titanium tanks with diaphragms are used to store the propellant: two in the wings of the LAP, and the third in the nose cone.

Thrusters were sized with assistance from Primex Aerospace as 150 lbf, axial, catalyst ignited individual modules with a specific impulse of 247 seconds.[8]

Airbreathing Propulsion

In order for the LAP to cover the return distance to the launch site after separation it will require to maintain level flight for a distance of approximately 500 km. During cruise the LAP produces thrust from two jet engines mounted on the sides of the vertical stabilizer (Figure 12). The Pratt & Whitney V2500 was identified as a suitable engine model. Table 4 lists the specifications.

Table 4: LAP jet engine specifications.[9]

Parameter	*Value*
Manufacturer	Pratt & Whitney
Model	V2500-A5
Mass (engine only)	5,690 lb
Bypass Ratio	5.4
TSFC at cruise	0.543 lb/hr/lb
Takeoff Thrust	22,000 – 33,000 lb
Fan Tip Diameter	63.5 inches
Length	126 inches
Price	US-$ 6 million

At the determined cruise conditions and for a nominal distance requirement of 500 km a total of 10,900 kg of jet fuel is required (21.7 kg/km).

In order to protect the engine fans and reduce drag during supersonic ascent and reentry parts of the trajectory, the engine inlets are covered with a supersonic ramp.

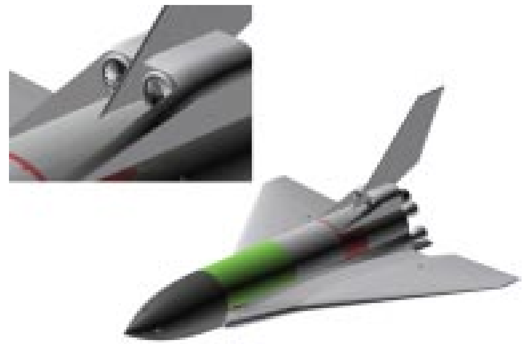

Figure 12: Illustration of LAP jet engines.

After subsonic speeds have been achieved, the ramp is lowered to expose the engine inlets to the flow. The oncoming air pressure is then used to start the engines.

LAP Thermal Protection System (TPS)

The first stage has three distinct TPS regions: the nose cone with a variety of materials using SHARP technology, the wing and vertical stabilizer leading edges protected with Advanced Carbon Carbon (ACC), and all remaining surfaces covered with composite flexible blanket insulation (CFBI).

NASA Ames, in conjunction with several small companies, has been developing new Ultra High Temperature Ceramics (UHTC). These materials have been successfully tested in ground-based arc jet facilities, and the first flight demonstration was successfully concluded in May, 1997. NASA has collaborated with Sandia National Laboratory and the U.S. Air Force to integrate a UHTC nose tip onto a reentry vehicle. These test vehicles are referred as Slender Hypervelocity Aerothermodynamic Research Probes (SHARP). Complex parts, including 1 mm radius leading edges, are readily machined using electrical discharge machining techniques. All data on UHTCs was adopted from the NASA Ames TPSX database.[10] The particular material chosen for the K2X nose tip construction is Hafnium Diboride Composite (A-7). HDC-A7 is an ultra-high temperature, multi-use ceramic matrix composite.

LAP Nose Cone Construction

The LAP nose cone is a layered construction, starting with UHTC at the tip, ACC for the first skirt, rigid AETB-12 tiles for the second skirt, CFBI for the remaining area and fuselage interface, and an insulating substrate of FRSI between the outer layer TPS and the underlying Aluminum structure (see Figure 13).

The choice of material is determined by the local radius of curvature of the cone, and the resulting heat flux into the vehicle.

Table 5 lists the material, local radius of curvature, and resulting wall temperature for the various components.

While it would be possible to continue the first ACC skirt all the way up to the fuselage interface, this was deemed prohibitively expensive and heavy. Thus the decision was made to use the AETB-12 tile to bridge the ACC to CFBI transition, even at the cost of added complexity and service requirements between flights.

Table 5: LAP nose cone material selections.

Component	*Material*	*Min Radius [m]*	*Chosen Radius [m]*	*Wall Temperature [K]*
Tip	UHTC (HDC-A7)	0.015	0.015	2805
Skirt 1	ACC	0.46	0.5	1847
Skirt 2	AETB-12 Tile	0.82	1.0	1658
Interface	CFBI	2.36	2.5	1467

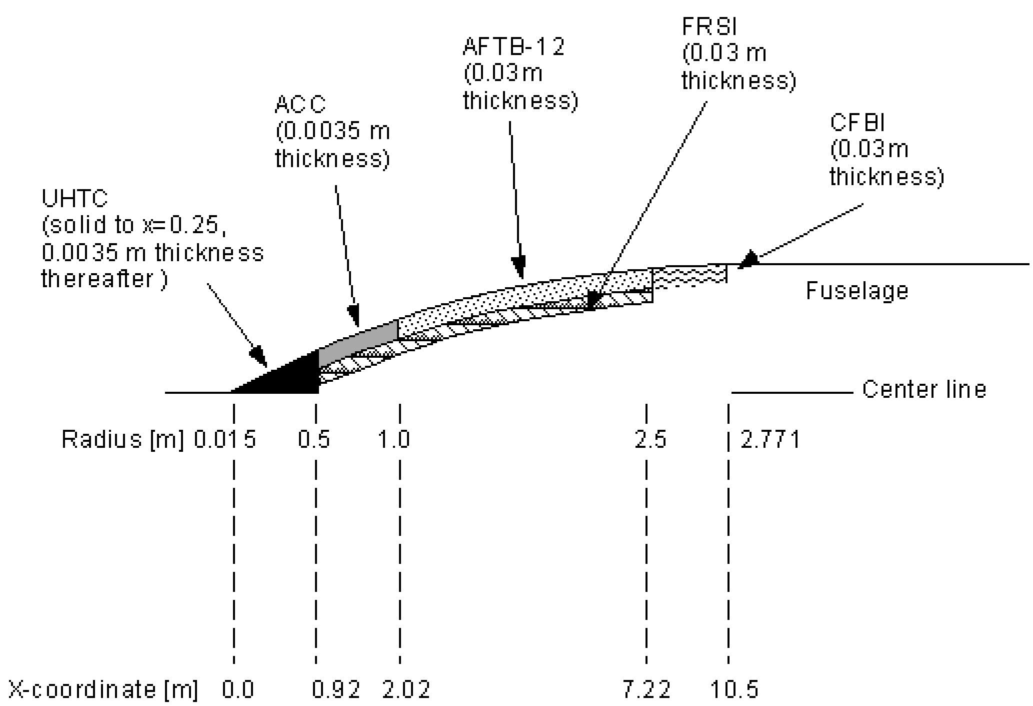

Figure 13: LAP nose cone construction schematic.

Second Stage Design

The second stage of the K2X RLV is referred to as the Orbital Vehicle (OV). Ease of payload processing, and simplicity of vehicle geometry for minimization of manufacturing and maintenance cost were the driving requirements in the OV's design. In addition, the desire of being able to return a payload of up to 4.5 metric tons from LEO back to the launch site had a large impact on the design. Figure 14 shows an exploded view of the OV with all its components.

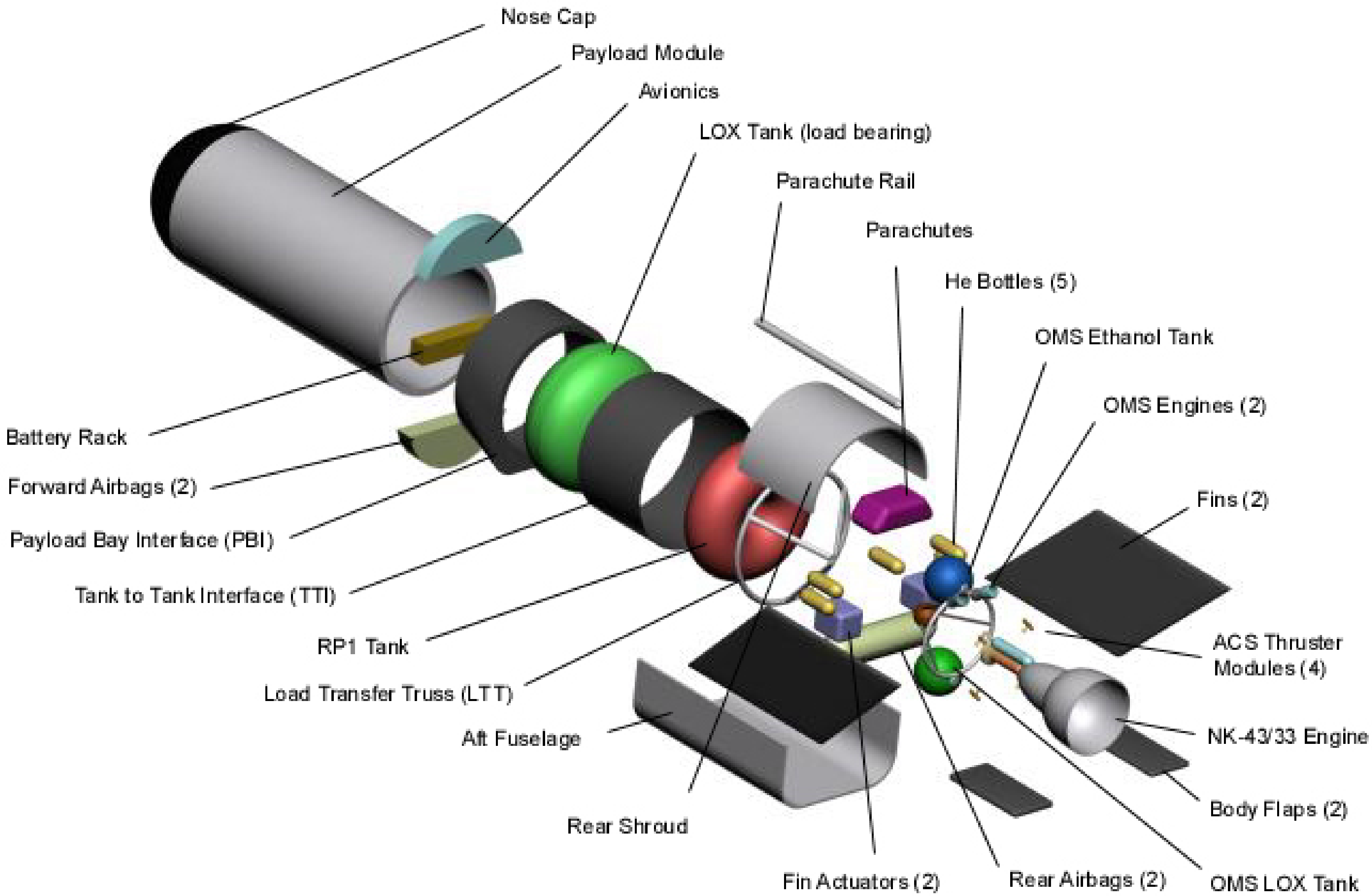

Figure 14: Exploded view of the K2X OV identifying sub-components and their nomenclature.

OV Mass Budget

The mass distribution of the OV varies with the particular mission. The target mission of delivering supplies to and from the International Space Station was chosen as the design reference. Table 6 lists the basic mass breakdown of the OV.

Table 6: OV basic mass breakdown.

Item	*Mass [kg]*	*Mass [lbs]*
Payload	11,500	25,350
Propellant	70,244	154,860
Structure	12,435	24,414
Total	94,179	207,630

Any item that is not payload or part of the useful propellants for the ascent part of the trajectory is considered structure mass in this breakdown. Table 7 presents the structural mass breakdown.

Aerodynamics

The K2X OV's aerodynamics are based on data from the Japanese HYFLEX.[11] HYFLEX (Hypersonic Flight Experiment) has been jointly developed by NAL (National Aerospace Laboratory) and NASDA (National Space Development Agency of Japan). The First J-I carrying a Hypersonic Flight Experiment (HYFLEX) Vehicle was successfully launched on February 12, 1996. Figure 15 shows a photograph of the HYFLEX vehicle.

Table 7 : OV structual mass breakdown.

Item	*Mass [kg]*
Main Propulsion	3,130
Payload Module	1,850
OMS Propulsion	1,695
Landing System	1,360
Thermal Protection System	1,200
Thrust Structure	941
Aerodynamic Surfaces	882
Avionics	360
Attitude Control System (ACS)	158
Margin	865
Total	12,435

Figure 15: Photograph of the Japanese HYFLEX (courtesy of NASDA).

Figure 16 shows a basic 3-view of the resulting design for the K2X OV.

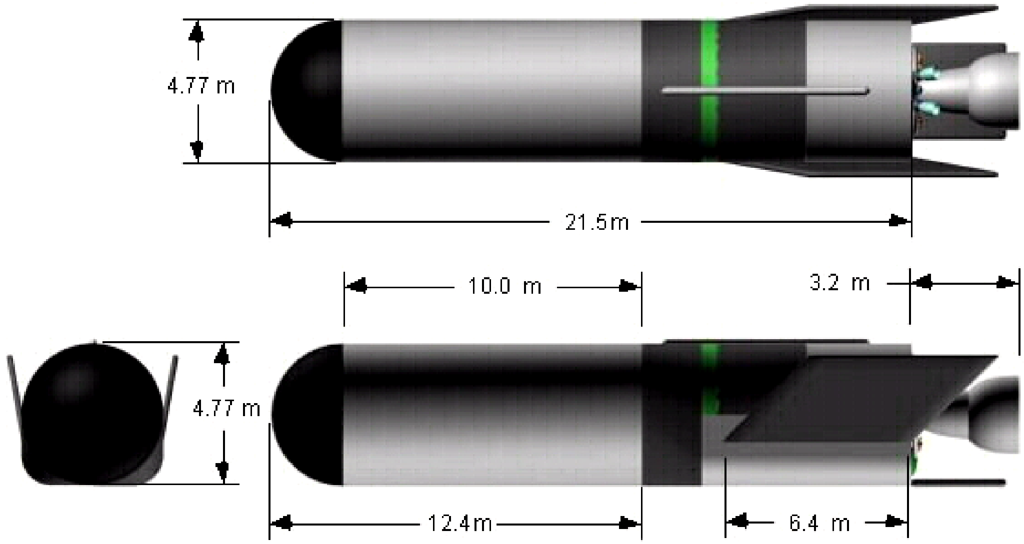

Figure 16: Three view of the second stage (OV).

OV Landing System

During re-entry the OV has some aerodynamic control, however, it is insufficient to complete a conventional horizontal landing. To enable the vehicle to land in a controlled fashion, the OV uses parachutes and airbags (Figure 17). In order to minimize cost, it was decided to use the existing landing system employed by the Kistler K-1 RLV.[12]

Figure 17: OV landing system (ISS mission configuration).

To maximize payload performance, a modular landing system is considered, providing two possible landing system configurations. Under normal mission operations, the OV will use the K-1's second stage parachutes and airbags. When the OV is returning a payload from orbit (ISS mission), the additional mass (4,550 kg return payload mass) during re-entry requires utilization of the K-1's first stage landing system. The commercial usefulness of reducing the K2X payload capability and increasing system complexity for all missions in order to accommodate a single customer (ISS return) may warrant further economic analysis.

Flight Profile without Return Payload

When the OV is not on a mission which requires returning a large payload back to the launch site, it uses the K-1's second stage landing system. This system is comprised of one (1) Drogue parachute, four (4) main parachutes, and four (4) airbag pairs made up of an inner and an outer airbag. The system does not include the parachute used on the K-1 due to the aerodynamic control surfaces present on the K2X OV design.

Once an acceptable free stream dynamic pressure (Q) is reached the drogue parachute is released. After the drogue parachute is fully deployed, pyrotechnic cutters fire to reorient the OV in a horizontal position. The OV continues to decelerate and cuts loose the Drogue parachute and subsequently releases the main three (3) parachute cluster. The main cluster remains open until touchdown. Just a few minutes prior to touchdown, the four (4) spherical airbag pairs are inflated. Upon impacting the Earth's surface, the outer airbags deflate to allow a maximum of 4 g's deceleration to the vehicle. The OV then rests on the full inner airbags until the recovery crew arrives to process the vehicle.

Flight Profile with Return Payload

In the case of the ISS mission where the OV is returning from orbit with a payload of up to 4,550 kg, the K-1 first stage landing system is employed. This second system follows a similar profile with the parachutes deployed at different Q and the main parachutes being two clusters of three instead of just the single cluster. Again the drogue parachute deploys at first and the main parachutes deploy once acceptable Q is reached. Instead of using the spherical airbags, this system uses cylindrical airbags to absorb the landing energy.

OV Propulsion

The Orbital Vehicle has a total of three propulsion systems: the main engine for ascent, the Orbital Maneuvering System (OMS), and the Attitude Control System (ACS).

Main Propulsion

The K2X vehicle concept uses all six available engines (5 on the LAP, 1 on the OV) during the first segment of the ascent trajectory. During this time period, all engines, including the one located on the OV are fed from propellant in the LAP's tanks. Only after the two vehicles have separated from each other will the OV's main engine be fueled by the OV's tanks.

One of the challenges with this approach is the optimization of the nozzle performance of the OV engine for a particular altitude, and the resulting performance loss when trying to operate it through the entire altitude range from sea-level up to vacuum. A variety of approaches have been suggested in the industry and academia to address this difficulty, from use of advanced engine technology, such as the Aerospike engine currently in development for the X-33 technology demonstrator, to simply ignoring it as is the case with the SSME. In the case of the K2X OV it was decided to use the original NK-43/33 engine core and only substitute the nozzle with an advanced dual-stage nozzle design, optimized for performance at both sea-level and vacuum conditions.

Figure 18: Photograph of an NK-43 engine.[6]

Of all the possible nozzle designs, the Multi-Position Nozzle and the Dual-Bell Nozzle are the two most useful candidates for the K2X OV. Both concepts can provide performance equivalent to that of using a NK-33 engine at sea-level and a NK-43 for vacuum performance. In addition, both concepts have been extensively researched.

The main difference between the Multi-Position Nozzle and the Dual-Bell Nozzle is that the first is optimized for size while adding the drawback of a heavier actuation mechanism and that mechanism's complexity.[13,14] The Dual-Bell Nozzle is considerably larger in overall physical dimensions, but also simpler, more reliable, and of lower mass. It is thus the ideal candidate for the K2X orbital vehicle, which has little constraint in external geometry, but stringent requirements in total mass and system reliability.

Extensive testing and research conducted by Rocketdyne indicates that the performance of the Dual-Bell Nozzle can be expected to be nearly identical to the use of an NK-33 engine at sea-level and an NK-43 from the staging point to complete vacuum, with only a modest mass penalty in exchange.[15] Table 8 summarizes the projected specifications of the resulting engine after the proposed modifications have been performed.

Table 8: Projected performance of an NK-33/43 engine, fitted with a Dual-Bell Nozzle.

Parameter	*Value*
Vacuum thrust	395,000 lb
Sea-level thrust	340,200 lb
Chamber pressure	2109 psia
Mixture ratio	2.586
Length (total)	220 in
Length (nozzle)	147 in
Diameter (nozzle exit)	59 in
Weight	3,585 lb
Area ratio	27 & 80
Throttling capability	50% - 114%
Gimbal range	± 6 degrees

As for the LAP, the OV also uses a mixture of RP1 and LOX for its main engine. The LOX tank is of cylindrical shape with ellipsoidal end caps. It also serve as the thrust structure, and part of the fuselage for the cylindrical section of the tank. The RP1 tank is toroidal and does not support any loads above its own weight and the contained propellant.

The RP1 tank is made of IM7/K3B composites, identical to the choice for the K2X LAP RP1 tank. The LOX tank is manufactured from AL2219 aluminum alloy, with a honeycomb stiffening layer made of the same material. The masses of the RP1 and LOX tank are 129 kg (285 lb) and 423 kg (933 lb) respectively.

<u>Orbital Maneuvering System (OMS)</u>

The orbital maneuvering system in the OV is responsible for orbit changes after MECO. The K2X OV employs the LOX/Ethanol engine currently used by the K-1. The OMS is sized to fulfill the following requirements:

- Circularization burn: needed to circularize from the elliptical transfer orbit into the desired circular orbit. The perigee altitude of the transfer orbit is 100km and the maximum apogee altitude is 1,200km.
- Deorbit burn: after 24 hours in orbit the OMS of the OV will perform one or multiple burns to place it in an elliptical orbit with apogee no higher than 475 km, and perigee at 60 km. At 60 km the OV enters the appreciable atmosphere and begins its reentry.

Table 9 lists the specifications of the OV OMS.

Table 9: LOX/Ethanol OMS specifications.[16]

Parameters	*Value*
Vacuum Thrust	3870 N
Mixture Ratio	1.5
Isp, Vacuum	307 s
Isp, Nominal	295 s
Gimbal Capabilities	± 6 degrees
Expansion to vacuum Ratio	100:1
Propellants	LOX / Ethanol
Mass (2 engines)	354 kg
Chamber Pressure	150 psia

Figure 19 shows the OMS structure and placement on the K2X OV.

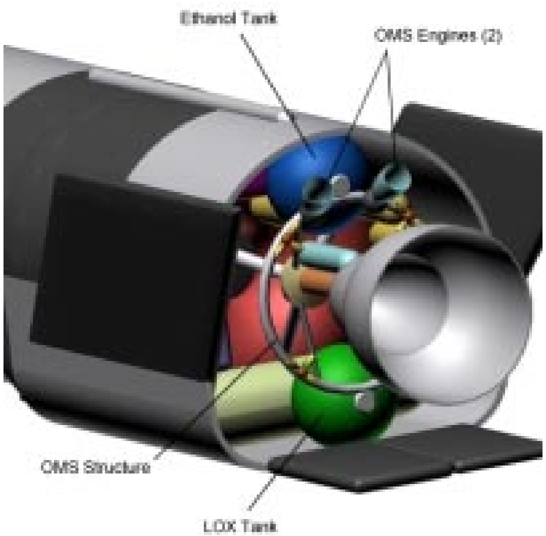

Figure 19: The OMS engine and propellant tanks as they appear on the OV.

Attitude Control System (ACS)

The K2X OV ACS uses the same HAN based monopropellant as the LAP. The ACS has an on-orbit total impulse of 30,000 lbf-s and a reentry total impulse of 30,000 lbf-s. Twelve thrusters are located in 4 clusters of 3 thrusters each at the rear of the vehicle. The catalyst bed ignited engines produce an Isp of 247 s, and a thrust of 150 lbf. The HAN propellant is stored in a titanium tank with a wall thickness of 0.02 inches and a mass of 2.54 kg.

OV Thermal Protection System (TPS)

The OV TPS has three distinct temperature regions. For the sections of the vehicle expected to be exposed to heat-flux no higher than the surface averaged value, DURAFRSI blankets were chosen as the material. The acronym stands for "Durable Advanced Flexible Reusable Surface Insulation", and denotes a flexible blanket material being developed by NASA Ames for use on the X-33 RLV. The material is composed of a hybrid Nextel 440-Incone-Copper outer fabric, Alumina insulation and Nextel 440 inner fabric sewn together with Nextel 440 thread. An Inconel foil (4 mil thickness) is brazed on the surface of the blanket after sewing to provide additional handling ruggedness.[17]

The medium to high temperature regions of the vehicle surface are covered with Composite Flexible Blanket Insulation. CFBI is an advanced TPS developed by NASA Ames that incorporates a multi-layer insulation on the inner surface of a DURAFRSI blanket to improve insulative performance at low pressures.[18]

For those regions of the vehicle seeing the most extreme heat loads during reentry, Advanced Carbon Carbon (ACC) was selected as the material.

K2X Vehicle Performance

Numerical simulations were executed to determine the payload performance of the completed design as a function of launch site, trajectory, final orbit inclination and altitude, and payload mass. Figure 20 shows the results in comparison to the performance of the K-1 RLV.[19]

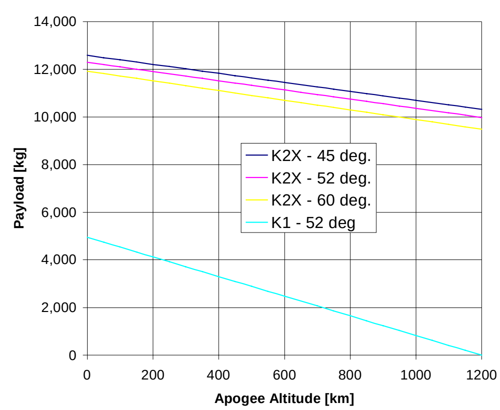

Figure 20: K2X payload performance vs. final altitude and inclination.

Ascent / Return Trajectory

In optimizing an ascent trajectory one normally uses the final mass as the cost function (the quantity that is desired to be maximized or minimized), but since the first stage (LAP) of the K2X must return to the launch site, minimizing its return distance will minimize the jet propellant needed and thus increase the overall vehicle payload mass fraction. Since these are competing quantities (final mass, return distance), a trade is necessary to determine which combination gives both the maximum payload to orbit and at the same time the shortest return distance for the LAP.

Figure 21 shows a side and top view of the resulting trajectory after optimization. Table 10 summarizes the numerical quantities.

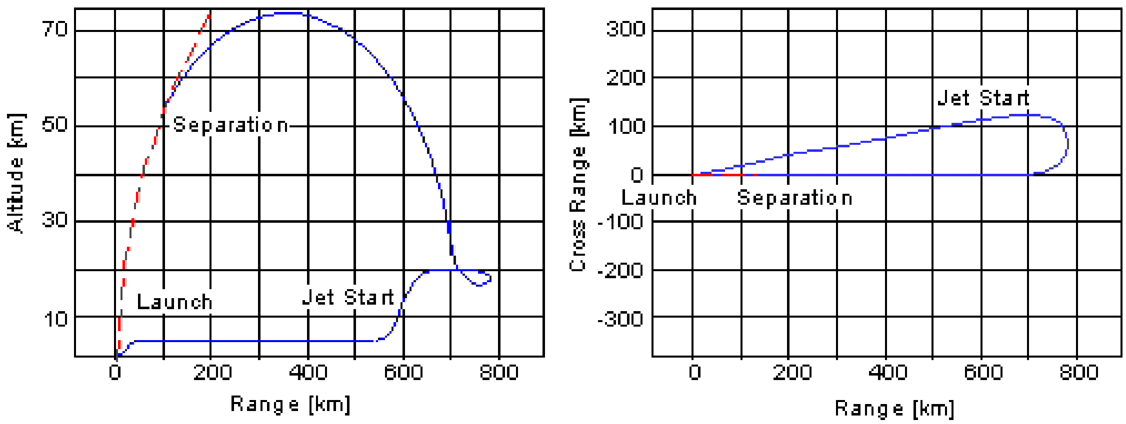

Figure 21: Side and top view of K2X trajectory showing separation, launch site, and jet startup.

Table 10: Optimized K2X ascent trajectory parameters.

Event	*Parameters*	*Time [seconds]*
Lift off	TW=1.4	0
Pitch over	6.3^{o} pitch	6
Max Dynamic Press.	4.7×10^{4} Pa	61
Separation	Velocity = 3.1 km/s Height = 53 km Flight Path Angle = 11.6 deg Downrange = 133 km Mass = 94,180 kg	154
Throttle Back	Minimum throttling = 98%	285
MECO	Velocity = 7.9 km/s Height = 97 km Flight Path Angle = 0 deg Mass = 23,930 kg	289

GEO Performance

The K2X can deliver payloads into geosynchronous (non-zero inclination) and geostationary (zero inclination) transfer orbits using an expendable Orbital Transfer Stage (OTS). The OTS can be either a commercially available upper stage, or specifically designed for the K2X.

Figure 22 shows the payload performance of the K2X when using a custom designed OTS. The OTS makes use of a single LOX/Ethanol engine, identical in performance to the OMS engines of the K2X OV. If the OTS is released in a 200 km LEO parking orbit at an inclination of 45^{o}, the maximum payload delivered to GTO is 4,000 kg and the payload to a geostationary orbit [0°] is 2,200 kg. This particular inclination is the lowest that can currently be achieved by direct injection (no plane change) from the Australia launch facilities, due to heading angle restrictions. If heading angles directly due east become available at a later time (once the vehicle has a proven safety record), the minimum possible inclination for the parking orbit will be 31 degrees instead. For the 31° case the maximum payload to GTO is 4,657 kg and the payload to a geostationary orbit is 3,100 kg.

Figure 22 shows the payload performance for LEO parking orbits at 45 degrees (current launch corridor limit at Woomera, Australia) and 31 degrees (minimum possible for direct injection from the launch facility latitude.).

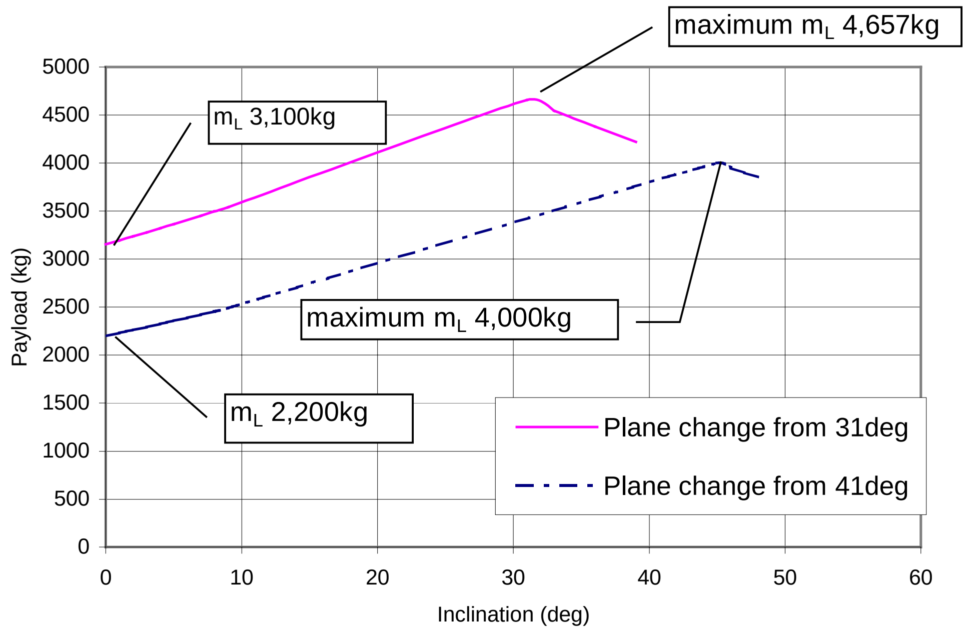

Figure 22: Payload performance of the OTS to GEO from 45° and 31° parking orbits.

Conclusion

The thorough investigation of the two stage to orbit RLV concept revealed that the most sensitive factor for payload performance is the location of the staging point, and the resulting down range distance the first stage has to cover to return to the launch site. In order to address this challenge, the K2X LAP was designed as a winged craft, using lifting surfaces and airbreathing engines, allowing it to cover a substantial part of the return trajectory in a cruise mode at an altitude of 3 km and Mach 0.45. New materials technology was utilized to design a very high temperature Thermal Protection System (TPS), thus allowing the geometry to be optimized for minimum supersonic drag and improved range during reentry.

The second stage (OV) is ignited simultaneously with the LAP at lift-off. Its single engine is fed by propellants from the LAP to provide the OV with a full complement of propellants upon separation. The use of a Double-Bell shaped nozzle in conjunction with the existing NK-43/33 engine core ensures optimum engine performance from sea-level to vacuum operations. The OV shell is a hypersonic lifting body using a system of parachutes and airbags for the final phase of its descent from orbit. The use of aerodynamic control surfaces on the OV improves on stability and increases the cross range of the K2X OV, thus eliminating the need for a phasing burn prior to reentry. The payload bay of the OV is modular for ease of payload processing on the ground and in space. The OV is capable to return as much as 4,550 kg (10,030 lbs) from the International Space Station (ISS) orbit back to the launch site.

Both reusable stages of the K2X vehicle make use of advanced HAN-based monopropellant for their attitude control system (ACS), allowing for lower structural mass fractions and improved handling and maintenance characteristics.

An optional orbital transfer stage (OTS) was investigated to deliver payloads into geostationary and geosynchronous transfer orbits. The OTS is not reusable. The custom design also makes use of advanced, environmentally benign propellant technology to minimize handling and processing hazards on the ground.

While some design details remained to be addressed, the K2X vehicle concept has been shown to provide significant increases in performance over the existing K-1 capabilities. Table 11 summarizes the key parameters of the K2X design.

Table 11: K2X key parameters.

Parameter	*Value*
OV GLOM	0.67 x K1
LAP GLOM	1.35 x K1
K2X GLOM	1.78 x K1
ISS Payload	11,500 kg
LEO Payload	10,400 kg
GTO Payload	4,650 kg

The first three entries compare the Gross Lift Off Mass (GLOM) of the two stages and the combined K2X vehicle, to the values for the K1 (numbers are compared for a mission to the International Space Station). The lower portion of the table summarizes the K2X payload capabilities for the three target missions of the design. It is apparent that the K2X has the capabilities to significantly expand the Kistler customer base, while using existing facilities and technologies proven in the development of the Kistler K-1 RLV.

Acknowledgements

The K2X team would like to acknowledge the following individuals and organizations for the invaluable help and support during the work on this project:

- **Students at the University of Washington**
  Aside from the authors of this report, Gary Lai and Bogdan Udrea also made contributions to this project.
- **Faculty at the University of Washington**
  Professor A. P. Bruckner was the overseeing faculty advisor. Prof. U. Shumlak, freely provided the team with access to his cluster of 15 parallel Alpha computers which were used in all CFD simulations.
- **Kistler Aerospace**
  Special thanks go to Debra Factor Lepore, Chuck Limmerick, Rob Meyerson, David Cochran, and everybody else who patiently answered our endless questions about the Kistler K-1 RLV.
- **Metacomp Technologies**
  Dr. Sukumar Chakravarthy donated the CFD++ code and went far beyond anything we could have hoped for in helping us in our CFD efforts.
- **ICEM CFD**
  ICEM CFD provided us with computational grids based on our CAD drawings.
- **Tools For Systems**
  Ingmar Ogren donated the Tools for Systems (TOFS) software package and helpful material on the science and art of systems engineering.
- **Primex Aerospace**
  Stacy Christofferson provided us with knowledgeable assistance in evaluating the HAN-based monopropellant technology.
- **Federal Aviation Administration**
  Dr. D. Schwartz donated materials to aid the construction of a wind tunnel model for the first stage.
- **Harvard Thermal**
  Dr. David Rosato provided us with a free copy of the Thermal Analysis Software package.

References

[1] The name "Launch Assist Platform (LAP)" originated from the first design of the Kistler K-1 launch vehicle, which used a basic platform with four corner mounted engines to lift the second stage to a higher altitude before ignition.

[2] Larson, W.J., Wertz, J.R., (editors), "Space Mission Analysis and Design", Space

Technology Library, Microcosm, Inc., 2nd Edition, 1992, pp. 640.

[3] Chakroborty, S.P., Limerick, C., Starke, R., "A systematic approach of the development of the propulsion systems for a reusable launch vehicle", 49th International Astronautical Congress, Sep 28-Oct 2, 1998, IAF 98-S.1.08.

[4] Lepsch, R.A., Ware, G.M., "Subsonic Aerodynamic Characteristics of a Circular Body Earth-to-Orbit Vehicle", NASA Technical Memorandum 4726, Langley Research Center, July 1996

[5] Metacomp Technologies, Inc., 650 Hampshire Rd. Suite 200, Westlake Village, CA 91361-2510,(805)-371-8750, info@metacomptech.com

[6] Aerojet Corporation, http://www.aerojet.com.

[7] D.S. Meinhardt and E.J. Wucherer of Primex Aerospace Company, R.S. Jankovsky of NASA Lewis Research Center, E.W. Schmidt, Consultant, "Selection of alternate fuels for HAN-based monopropellants".

[8] Stacy Christofferson, Sr. Design Engineer, Primex Aerospace, personal communications, 4/99 – 9/99.

[9] "Jane's Aero-Engines", McGraw-Hill, 1997, and Pratt & Whitney web page at http://www.pratt-whitney.com/ engines/gallery/v2500.html

[10] E. Clougherty et al, AFML-TR-68-190 Part II Vol. IV and V. From NASA Ames TPSX Database (http://asm.arc.nasa.gov/tpsx/tpsxhome.shtml).

[11] Shirouzu, Masao (National Aerospace Lab.) Inouye, Yasutoshi (National Aerospace Lab.) Takizawa, Minoru (National Aerospace Lab.) Kai, Takashi (National Aerospace Lab.) Yamamoto, Yukimitsu (National Aerospace Lab.) Fujii, Keisuke (National Aerospace Lab.) Takaki, Ryouji (National Aerospace Lab.), Shouji, Hirokazu (National Aerospace Lab.) Ishimoto, Shinji (National Aerospace Lab.) Ito, Takeshi (National Aerospace Lab.), "On the Hypersonic Flight Experiment (HYFLEX) project", National Aerospace Lab. (Tokyo, Japan), Sep 20, 1995

[12] Fallon II, E., Taylor, A., Meyerson, R.; "Landing System Design Summary of the K-1 Reusable Launch Vehicle"; AIAA-99-1720.

[13] Eldred, C. H. , Rehder, J. J., Wilhite, A., "Nozzle selection for optimized single-stage shuttles", IAF PAPER 76-162, Oct 01, 1976.

[14] Horn, M., Fisher, S., "Dual-bell altitude compensating nozzles", Pennsylvania State Univ., NASA Propulsion Engineering Research Center, Volume 2 Page: p 140-147 , Nov 01, 1993.

[15] Goel, Pankaj, Jensen, Robert J.," Numerical Analysis of the Performance of Altitude Compensating Dual Bell Nozzle Flows", 32nd JANNAF Combustion Subcommittee Meeting and Propulsion Engineering Research Center, 7th Annual Symposium , Volume 2 Page: 117-140, Oct 01, 1995.

[16]Judd D.C., May L.R., Boyce W.D., Beaudette B.P., "Development of an orbital manuevering system for the K1 vehicle", IAF-98-S.1.09..

[17] Rasky, I., Kourtides, D., et al., "Durable Advanced Flexible Reusable Surface Insulation," U.S. Patent Application ARC 12081-1, January 1955.

[18] Rasky, D.J., "Thermal Protection Systems for Future Reusable Launch Vehicles," 25th International Conference on Environmental Systems, No. 951618, July, 1995. From NASA Ames TPSX Database (http://asm.arc.nasa.gov/tpsx/tpsxhome.shtml).

[19] Kistler Aerospace Corporation, "K-1 Vehicle Payload User's Guide", May 1999.