LANDING SYSTEM DESIGN SUMMARY OF THE K-1 REUSABLE LAUNCH VEHICLE

Edward J. Fallon II*, Anthony P. Taylor†
Irvin Aerospace Inc, Santa Ana, CA

Robert E. Meyerson‡
Kistler Aerospace Corporation, Kirkland, WA

Abstract

This paper presents a design summary of the Landing System used in the recovery of the Kistler Aerospace K-1 Reusable Launch Vehicle. A brief history of Reusable Launch Vehicle (RLV) recovery is provided along with a summary comparison of the K-1 and the Space Shuttle Solid Rocket Booster (SRB) and their related applications to RLV recovery technology. Finally, major elements of the K-1 Landing System are presented with the view towards today's RLV technology and in particular the advances in recovery systems technology.

Introduction

The endeavor for a fully reusable launch vehicle began shortly after the beginning of the space race. Commercial expendable launch vehicles originally derived from military ICBM's, such as the Atlas and Titan, were converted for commercial use as the need arose. As the market demand for commercial space access increased and became more competitive, the goal for low cost launch operations was evident in order to become profitable. NASA initiated the Space Shuttle Program with the recognition that fully reusable launch vehicles will reduce the cost of space access and increase the flight integrity and reliability of the vehicle through re-use. The program began in 1969 with the objective of developing a fully reusable Space Transportation System for transfer of humans and cargo to and from low earth orbit (LEO). The Phase A design activity included participation from most of the major aerospace companies of the day: Lockheed, General Dynamics, Martin Marietta, McDonnell Douglas, North American Rockwell[1]. One common theme that was proposed in the majority of the early design studies was the concept of "return to launch site" (RTLS), in which both the booster and orbital stages fly back and land at the launch site. This concept was carried as the baseline mission profile until late in Phase B, when development, cost, and schedule concerns dictated the need for the current partially reusable approach. While the Space Shuttle is a triumph of engineering, its high operations costs are due, in part, to the design compromises that were made (i.e., downrange water landing of the boosters, etc.). Presently, the benefits of full reusability are evident in the proposals to develop a "Liquid Fly Back Booster" (LFBB) to reduce Space Shuttle operations costs as well as in the many commercial RLV companies in the world today.

As the Space Shuttle begins its third decade of operations, Kistler Aerospace Corporation expects to begin commercial operations of the next generation RLV—The K-1, Reusable Launch Vehicle. The K-1 developed entirely through private financing, will be the world's first fully reusable launch vehicle. It is designed to lower the cost of access to space, increase launch reliability, and reduce lead-time requirements to launch. The following sections presented in this paper will provide an overview comparison of the recovery systems of both the K-1 and the Space Shuttle Solid Rocket Booster (SRB), illustrating the evolution of RLV technology and related advances in recovery systems.

* Engineering Manager (CA), Senior Member AIAA
† Manager, Technical Development, Member AIAA
‡ Manager, Landing and Thermal Protection Systems, Senior Member AIAA

Description of K-1 Reusable Launch Vehicle

The K-1 is a fully reusable two stage launch system designed to place 10,000 lbs. (4536 kg) of payload into orbit. The K-1 offers two different Payload Modules, a Standard Payload Module (SPM) and an Extended Payload Module (EPM), which can accommodate a wide range of

the LAP is reoriented and its center engine is restarted to loft the LAP back to the

The second stage, or Orbital Vehicle (OV), uses one (1) NK-43 engine which is a 395,000 lbf (1.76 MN) vacuum thrust version of the NK-33. After stage separation, the OV main engine ignites to place the vehicle in an elliptical orbit.

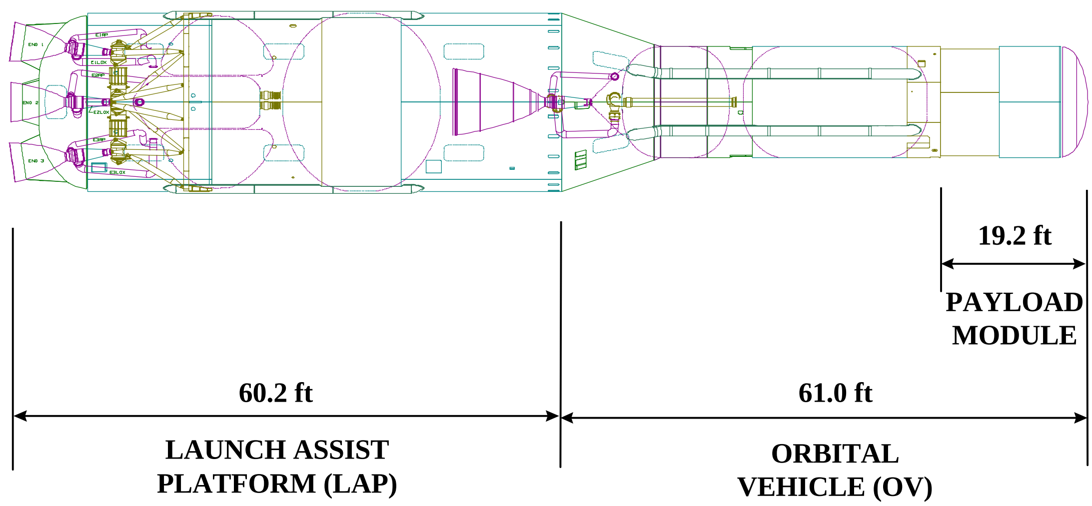

Figure 1 - Kistler K-1 Vehicle Profile

payloads. With the EPM, the K-1 is 121 feet (36.9 m) long, 22 feet (6.7 m) in diameter and weighs 840,000 lbf (381,000 kg) at liftoff. Each stage is fully reusable, carries its own suite of avionics, and operates autonomously. Three (3) NK-33 liquid oxygen (LOX) kerosene engines built for the Russian moon program power the first stage, or Launch Assist Platform (LAP). Together, these engines provide 1,020,000 lbf (4.54 MN) thrust at liftoff. The first stage lifts the vehicle to an altitude of approximately 135,000 feet (41.2 km) at 130 seconds after liftoff where Main Engine Cut-Off (MECO) and stage separation occurs. Following separation, launch site. It returns to the launch site autonomously and lands using parachutes and airbags.

In short, the K-1 design incorporates primarily existing technologies that were adapted from other successful aerospace programs and applications. Table 1 presents the Kistler K-1 Contractor Team along with their relevant responsibilities in the production of the K-1 Aerospace Launch Vehicle as well as their applicable design experience as incorporated into the K-1 program.

Following coast to apogee, the Orbital Maneuvering System (OMS) LOX/ethanol engines fire to circularize the orbit. Then the OV attitude is adjusted, the payload fairing is opened, and the payload deployed. After waiting sufficient time to preclude any plume interaction with the satellite, the OMS engines fire again to place the OV into a phasing orbit with the correct period for re-entry. Following a second coast phase of up to 22 hours, the vehicle reorients itself, performs a de-orbit burn with the OMS engines, and reenters the Earth's atmosphere. The OV returns to the launch site autonomously and (again) lands using parachutes and airbags.

Comparison of the K-1 Reusable Launch Vehicle to the Space Shuttle SRB

In the truest sense, a system to system comparison of the K-1 and the Space Shuttle SRB is a match of dissimilarities as the operational environments of both vehicles are quite different. However, when viewed from the relevance of recovery system technology for RLVs, a comparison of both vehicles provides a vista of the evolution, range, and demonstrable use of recovery system technology for

Organization	K-1 Responsibilities	Relevant Technology Experience
Kistler Aerospace Corporation	Customer services, systems engineering and integration, launch system development, launch operations	Redstone, Mercury, Gemini, Saturn, Apollo, Skylab, U.S. Space Shuttle, International Space Station
Lockheed Martin	Liquid oxygen tanks, LAP fuel tank, ablator thermal protection	U.S. Space Shuttle external tank, X-33 RLV demonstrator
Northrop Grumman	LAP and OV structural components, OV fuel tank, payload module, TCS	B-2 bomber, Boeing 777 components, F/A-18E/F structures
GenCorp Aerojet	Modifications and testing of AJ26 engines, OMS, ACS, pressurization system, feedlines, gas bottles	Delta II, Titan IV
Draper Laboratory	GNC system, flight vehicle software development and testing (IV&V, HWIL)	U.S. Space Shuttle, Apollo, DOD programs
AlliedSignal	Avionics hardware, software and vehicle management system	X-33, Iridium, Space Telescope, Skylab, Galileo
Irvin Aerospace	Parachutes, landing airbags, activation and control systems	U.S. Space Shuttle, F-111, CL-289, NATO drone, EELV, DOD satellite recovery systems
Oceaneering Thermal Systems	Thermal protection system (tiles and blankets) on both stages	U.S. Space Shuttle

Table 1 – K-1 Contractor Team Responsibilities and Relevant Experience

potentially all vehicles of the RLV class. A summary of the differences between the K-1 and the SRB is provided in Table 2. In the sections to follow, obvious advantages and disadvantages will be noted as well as differences due to operational environments, etc. From this, evidential inferences will be drawn and presented in the concluding remarks. For brevity and simplicity, system comparisons relate only to the K-1 LAP and the Space Shuttle SRB though major recovery system elements of the K-1 OV will be mentioned.

Characteristic	Vehicle	
	SRB	K-1
Flight Profile	Landing Down Range	Return to Launch Site
Deceleration	Parachutes	Parachutes
Landing Medium	Water	Land
Impact Attenuation	Water Impact	Airbags
Materials	Nylon	Kevlar, Nylon, Spectra, Vectran

Table 2. K-1 and SRB Characteristics

Flight Profile

K-1 Aerospace Launch Vehicle

The flight profile of the K-1 is as described in the prior section (see Description of K-1 Reusable Launch Vehicle). The following provides a detailed narrative of the recovery flight profile.

Figure 2 – LAP Recovery Sequence

Figure 3 - OV Recovery Sequence

Following the second main engine burn, the LAP returns to the launch site on a ballistic trajectory. At approximately 25,000 feet (7.62 km), two (2) Variable Porosity Conical Ribbon Drogue parachutes (40.2 feet (12.25 m) in diameter) are mortar deployed, stabilizing and decelerating the LAP in preparation for main parachute deployment. The Drogue parachutes have two (2) stages of reefing for structural loads management. At approximately 15,000 feet (4.57 km), pyrotechnic cutters fire to release the Drogue harness and in turn deploy the cluster of six (6) Quarter-Spherical Ringsail Main Parachutes (156 feet (47.55m) in diameter). The main parachutes have two (2) stages of reefing for structural loads management. While under the first reefed stage, pyrotechnic cutters fire to reorient the LAP from a vertical to horizontal suspension position in preparation for landing. At approximately 10,000 feet (3.04 km), the main parachutes are fully opened. Minutes prior to landing, four (4) cylindrical airbags (approximately 8.5 feet (2.59 m) in diameter and 12 feet (3.66 m) in length) are deployed. Upon landing, the airbags attenuate landing energy to acceptable structural levels of approximately 4.0 gees acceleration. Pyrotechnic cutters fire to release the main parachutes and the LAP rests on smaller airbags (internal to the outer primary airbags mentioned above), keeping it above the Earth's surface for safe recovery.

Following on-orbit operations, the OV reorients itself, performs a de-orbit burn with the OMS engines, and reenters the Earth's atmosphere returning toward the launch site. At approximately 80,000 feet (24.38 km) and Mach 2.5, a Supersonic Hemisflo Stabilization Parachute (23 feet (7.01 m) in diameter) is mortar deployed stabilizing and decelerating the OV. At approximately 27,000 feet (8.23 km), pyrotechnic cutters fire to release the stabilization parachute harness and in turn deploy a single Drogue parachute. The Drogue parachute on the OV is the same design and flight configuration as the LAP Drogue parachutes with the exception that it has a single stage of reefing for loads management. While under the fully opened Drogue chute, pyrotechnic cutters fire to reorient the OV from a vertical to horizontal suspension position for proper landing attitude. At approximately 15,000 feet (4.57 km), pyrotechnic cutters fire to release the Drogue harness and in turn deploy three (3) Quarter-Spherical Ringsail Main Parachutes. The OV main parachutes are the same design and flight configuration as the LAP main parachutes (including the reefed staging). At approximately 11,000 feet (3.35 km), the main parachutes are fully deployed. Minutes prior to landing four (4) spherical airbags (approximately 10 feet (3.05 m) in diameter) are deployed. Upon landing, the airbags attenuate the landing energy to acceptable structural levels. Pyrotechnic cutters fire to release the main parachutes and the OV rests on smaller airbags (internal to the outer primary airbags), keeping it above the Earth's surface for safe recovery.

Space Shuttle SRB

The Space Shuttle is launched at the Kennedy Space Center from a vertical position and fires simultaneously, the main Orbiter engines and the SRBs, whose thrust is programmed by internal design. Booster burn-out and subsequent separation occur after 122 seconds at an altitude of approximately 140,000 feet (42.67 km) with separation aided through the use of separation rockets. The empty SRBs reach an apogee of 200,000 feet (60.96 km) and reenter broadside, decelerating to subsonic speeds.

Prior to booster separation, a command from the Orbiter arms the recovery system and accompanying avionics. After separation, the booster follows a ballistic trajectory to the recovery site and descends into the lower atmosphere in a nearly horizontal position. At approximately 16,000 feet (4.88 km), pyrotechnic thrusters eject the small nose cap of the booster. Separation of the nose cap deploys a

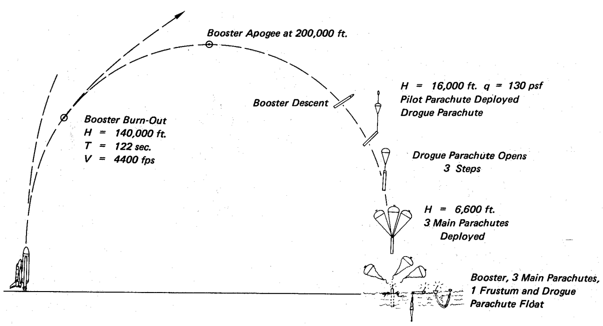

Figure 4 – SRB Recovery Sequence

Conical Ribbon Pilot Parachute (11.2 feet (3.41 m) in diameter) stored below the nose cap. The pilot parachute then deploys a Conical Ribbon Drogue Parachute (54 feet (16.46 m) in diameter). The Drogue has two (2) stages of reefing for loads management. At a nominal altitude of 6600 feet (2.01 km), the nose frustum separates from the booster body by means of a linear shaped charge. The Drogue pulls the frustum away from the booster and deploys three (3) Conical Ribbon Main Parachutes (136 feet (41.45 m) in diameter). The main parachutes incorporate two (2) stages of reefing for loads management. The main parachutes decelerate the booster to a terminal velocity acceptable for structural levels due to water impact. At water impact, six (6) attachment fittings that connect the three (3) main parachutes to the booster are disconnected. Each main parachute and Drogue are attached to their own floats and remain in the water along with the booster until recovered for refurbishment.

Flight Profile Comparison

Figure 5 shows a flight profile comparison of the K-1 LAP and the Space Shuttle SRB. The obvious advantages depicted by both vehicles are that they are *recoverable* and hence reusable. Further, the flight profile comparison also shows that a wide range of landing conditions (i.e., ground & water landings) can be satisfied for the recovery of launch vehicles with *present recovery system technology*. However, there are differences presented in Figure 5 that should be considered.

The K-1 vehicle has a steeper flight trajectory than the SRB, though stage separation occurs at nearly the same altitudes for both vehicles. The reason for this steeper flight trajectory is that the K-1 mission profile optimizes both payload performance as well as *return to launch site* execution. The SRB flight profile is optimized for payload performance. As a result, SRB water recovery occurs approximately 122 n.m (225 km) down range from the launch site, whereas *K-1 recovery occurs back at the launch site*.

Precise GN&C, navigation sensors, and engine control algorithms allow the LAP to land within a 1.0 n.m (1.83 km) diameter landing zone. For comparison purposes, the landing zone dispersion ellipse for the Space Shuttle SRB is approximately 7.8 n.m. (14.44 km) by 5.2 n.m. (9.63 km).

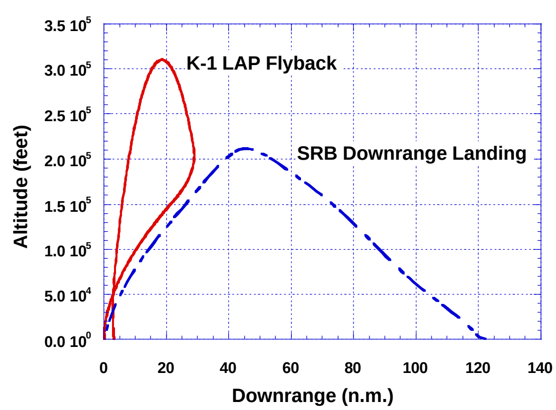

Figure 5 – K-1 LAP and Space Shuttle SRB Flight Profile Comparison

Recovery Site

The obvious advantage of using the launch site as the recovery site is the significant simplification and hence reduction in costs of vehicle recovery. With the refurbishment facilities at the launch site, recovering and refurbishing the K-1 is a matter of transporting the vehicle (and associated recovery system elements) from one point to another *within the same facility site.* Down range recovery not only requires the transport of the vehicle (and associated system elements) over potentially large distances, but also the transport of large equipment to enable recovery of the same. Labor and other logistics issues increase with down range recovery as well. The fact that recovery of a launch vehicle enables *reusability* should not be overlooked; however, launching and recovering at the same facility site offers greater operational efficiency with reduced costs.

Another consideration of the recovery site is water versus ground landing. For water landings, in addition to favorable wind conditions, favorable sea-states must also prevail to effect a safe recovery. In addition, floatation devices must be used for the recovery system elements and salt-water environments must be considered for the integrity of the vehicle structure and other subsystems. Further, the experience with the Space Shuttle SRB in using water impact for landing energy attentuation has been an evolution in reducing booster damage[2]. The reduction in booster damage being largely brought about by an increase in the parachute size (i.e., lower terminal velocity) and structural enhancements to the booster. Though effective, the use of water landing to attenuate landing energy varies with predictability based on the experience of the Space Shuttle SRB program.

For ground landings, in addition to favorable wind conditions, there must be favorable ground terrain (i.e., accommodating elevation, grade, minimal natural obstructions, etc.) to effect a safe recovery. With ground landings, generally some form of landing energy attenuation is used (i.e., airbags, retro-rockets, crushable structures, etc.). On the K-1, airbags are employed for landing energy attentuation. With the use of airbags, a controlled and predictable level of landing energy attenuation is obtained. At vehicle touchdown, the stage flight control system signals the airbag vents to open when accelerometers located at the vehicle Center of Gravity (CG) measure the preset trigger gee level. Also with ground landings (though not exclusive with water landings), vehicle attitude may also be a consideration depending on the vehicle structure and type of landing energy attenuation device employed. Generally, the K-1 vehicle's landing attitude is controlled by the stage Attitude Control System (ACS) aided by an on-board Inertial Navigation System (INS), Global Positioning System (GPS), and a stage flight computer.

Refurbishment

K-1 Aerospace Launch Vehicle

The K-1 recovery crew will total less than ten (10) people and will use a Straddle-Lifter and a Transporter Vehicle (e.g., a modified tractor-trailer designed to operate "off-road" on prepared surfaces) to complete the recovery process.

Before approaching the vehicle, the K-1 vehicle provides confirmation that it is in a safe condition. The LAP is then approached, grounded, and external power applied. To prevent contamination by sand and dust, protective caps are installed on the main engines, the ACS, the OMS engines, and the vehicle vents. The LAP is then lifted using the Straddle Lift Vehicle (SLV) and the airbags removed. The vehicle is then moved and lowered onto the LAP horizontal pallet on the Transporter Vehicle where it will be transferred to the K-1 Vehicle Processing Facility (VPF). The parachutes and airbags will be recovered by the ground crew and transported to the parachute refurbishment facility using separate vehicles. A similar recovery process is conducted on the OV. Figure 6 shows the K-1 post-landing recovery sequence.

Once at the process facility, the parachutes and airbags will be de-fouled, spread-out, and disassembled. During the de-fouling process, a "quick look" post flight inspection will take place to verify proper operation and to identify major element damage or anomalies that may require special attention. The canopies, suspension lines and other refurbishable components will be untangled (as applicable), hung, and shaken out as to rid the said items of dirt, sand, or other local contaminates. Once

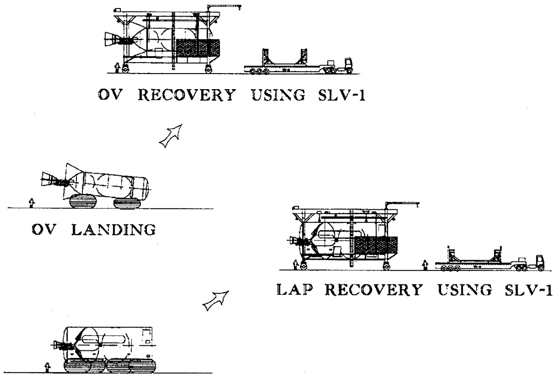

Figure 6 – LAP and OV Post-Landing Recovery Sequence

sufficiently rid of the contaminants, the recovery system components will be inspected in detail and (where appropriate) repaired. When all the required repairs are completed and accepted, refurbishment (e.g., replacement of consumables) and packing of the recovery system components will commence.

Space Shuttle SRB

The recovery crew consists of two (2) unique ships. Each ship is 176 feet (53.6 m) in length and can carry up to 24 people: a ten (10) person ship crew, a nine (9) person SRB recovery crew, and up to five (5) observers. These ships include forward and aft maneuvering thrusters, four (4) reels to recover the parachutes, advanced navigation equipment, and a deck crane.

Once the booster with main parachutes and the frustum with the attached Drogue enter the water, the recovery crew, waiting outside the dispersion ellipse, locates the booster floating upright in the water and closes the rocket nozzle with a plug. The water inside the booster is replaced with compressed air, which causes the booster to change to a horizontal floating position. Each floating booster is then towed to Port Canaveral near Kennedy Space Center (KSC). Once the ships approach the Hangar at Port Canaveral, both boosters are lifted out of the water using a Straddle-Lifter and placed on rail cars to begin the disassembly and refurbishment process.

The main parachutes, floating vertically in the water, are wound on retrieval reels. The reels with the main parachutes and the nose frustum with the attached Drogue are taken aboard ship and brought back to KSC. Throughout their transport to the Parachute Refurbishment Facility (PRF) at KSC, the parachutes are kept damp to prevent salt crystallization. Once the parachutes have arrived at the PRF, they are transferred to the cleaning area for de-fouling, washing, and drying. Each parachute is individually spread out and disassembled. During the de-fouling process a “quick look” inspection is conducted to verify proper operation, and to identify major element damage or anomalies that may require special attention. The canopy, suspension lines, deployment bags, and other refurbishable components are untangled and suspended in an orderly manner from racks supported by an overhead monorail system and then transferred into the washing tank. The washing tank is filled with potable water, totally immersing the parachute components, which is circulated until an acceptable salinity level is established. The parachute (or associated component) is then transferred to the adjacent dryer where warm air at approximately 140°F (60°C) is circulated throughout the item until the fabric is dry. The dried components are transferred to the inspection and repair area via the overhead monorail system where they are inspected in detail and repaired. When all the required repairs are completed and inspected, parachute refurbishment and packing can commence.

Refurbishment Comparison

The refurbishment processes of the K-1 and the Space Shuttle SRB can be summed by one major difference: The recovery of a wet parachute versus the recovery of a dry parachute. As shown with the K-1 vehicle refurbishment, a dry parachute recovery does not necessarily require the equipment or processes for washing and machine drying of the parachute and its associated components. By virtue of sea recovery, the parachute and related components by necessity must undergo de-salinization through a washing process. The washing process, in turn, necessitates a controlled and timely drying process. One complication of the washing process is that the parachutes (and other related textile components) shrink. For parachutes (and other related items) which require a repair that necessitates the partial rebuilding of the item, this creates a problem, as the shrunken parachute cannot match any of the re-built portions of the canopy to be incorporated for repair (e.g., the re-built portions are made to the original patterns). The solution to this dilemma (as determined on the SRB program) is to pre-shrink the re-built parts by washing and drying them prior to joining them to the shrunken canopy. Another complication discovered on the SRB program was that washing the parachutes washed out a chemical agent in the parachute fabric that helps provide lubricating properties to the nylon monofilament, which aided the weaving process of the fabric. With this chemical agent removed, the fabric lubricity was significantly lower and resulted in higher abrasion and more burn damage (due to friction) as a result of normal deployment. The end result being a diminished service life of the parachute. The problem was deemed significant enough by the SRB program that a recommendation was made to add lubricant to the parachutes prior to every launch.[3] Hanging and shaking out "dry" parachutes is common practice and has a long history of useful service. Ground landings that provide "dry" recovery offer greater simplification and less cost for recovery system refurbishment as long as the recovery site meets acceptable criteria (as previously mentioned).

Major Recovery System Elements

For brevity's sake, a very brief description of the major recovery elements of the K-1 vehicle is only provided. A more detailed description of the recovery system elements of both the K-1 and the Space Shuttle SRB may be found in References 1 through 4.

K-1 Aerospace Launch Vehicle

The parachute elements for the K-1 vehicle consist of a Stabilization Parachute, a Variable Porosity Conical Ribbon (VPCR) Drogue Parachute, and a Quarter-Spherical Ringsail Main Parachute. Only the OV requires the use of the Stabilization Parachute for supersonic deceleration. The design and construction of the VPCR Drogue and Ringsail main parachute is the same for both the LAP and OV stages with the exception of minor reefing changes. The OV parachute system consists of one (1) Stabilization Parachute, one (1) VPCR Drogue, and three (3) Ringsail main parachutes. The LAP parachute system consists of two (2) VPCR Drogues and six (6) Ringsail main parachutes.

A Supersonic Stabilization Parachute was required on the OV to maintain a low angle-of-attack during transonic flight. The Hemisflo Parachute was chosen due to its extensive flight history as a supersonic stabilization parachute. The size and porosity (23 feet (7.01 m) in diameter, 15.5 % λ_G) was chosen based on the analysis of aerodynamics, vehicle rigid-body flight dynamics, and computational fluid dynamics of the OV wake. The parachute uses a continuous ribbon construction and is built entirely from high temperature materials (e.g., Kevlar and Nomex) to preclude concerns due to stagnation temperature effects as a result of supersonic deceleration.

The VPCR Drogue design is based on the successful Space Shuttle Orbiter Drag Chute. In fact, the porosity of this design (16.1 % λ_G) is derived from the Orbiter Drag Chute test program, which proved to be extremely stable. The size of the Drogue (40.3 feet (12.28 m) in diameter) was established to provide commonality and dual flight mode operations for both the LAP and OV stages. The Drogue uses cut gore ribbon construction and is built from a hybrid of nylon and Kevlar materials.

The Irvin Quarter-Spherical Ringsail design was chosen due to its excellent stability characteristics, reefed performance, and high drag coefficient. The Ringsail main parachute is made up of five (5) rings and ten (10) sails. The size of the main parachute (156 feet (47.55 m) in diameter) was established as a result of system analysis, which determined the system rate of descent that provided the minimum landing system weight. The main parachute is constructed of a Kevlar structural grid and a nylon drag-producing surface and incorporates a feature allowing rapid removal and replacement of suspension lines (when necessary) for reusability enhancement.

The LAP and OV airbag set consists of four (4) large outer stroking airbags. Each airbag contains an inner, anti-bottoming airbag which is permanently inflated after deployment. The function of the outer airbag is to absorb the landing impact energy while the inner airbag prevents ground contact, and maintains ground clearance during recovery operations. The design of an outer and inner airbag was derived in an effort to minimize space and weight on the vehicle. The LAP airbags are cylindrical in design with elliptical endcaps. The LAP outer airbags measure 8.5 feet (2.59 m) in diameter and 12.8 feet (3.90 m) in length with the inner airbags measuring approximately 4.0 feet (1.22 m) in diameter and 10.0 feet (3.05 m) in length. Because of the OV geometry, these airbags are spherical in design. The OV outer airbag is approximately 10.0 feet (3.05 m) in diameter, while the inner airbag is 5.2 feet (1.58 m) in diameter. All airbags are fabricated with industry standard stitching/bonding adhesive processes and are built from a polyether polyurethane coated (both sides) Kevlar fabric.

Major Recovery System Element Comparison

Table 3 provides a short comparison of the recovery system major elements of both the K-1 Aerospace Launch Vehicle and the Space Shuttle SRB.

As previously noted, the dissimilar operating environments of both the K-1 Aerospace Launch Vehicle and the Space Shuttle SRB dilutes somewhat a direct component to component comparison. Nonetheless, a direct component to component comparison of the major recovery system elements does offer a view of the evolution of recovery systems technology for RLVs as well as the broad range of applications which recovery systems technology can serve.

Evolution

A major consideration in the design of a recovery system is its mass and available storage volume. As shown in Table 3, design improvements incorporated into the Space Shuttle (as well as the K-1 present design) reveal a drastic reduction in recovery system mass. This is vital for RLV performance in that every pound reduced on the recovery system can be an additional pound of fuel or increased payload capacity. The reduction in recovery system mass is largely due to the advancement in materials technology. Materials such as Kevlar, Vectran, Spectra, Technora, et al offer substantial mass savings while maintaining strength margins whether used alone or in combination with other materials. In fact, the K-1 main and drogue parachutes are a nylon/Kevlar hybrid construction with the design objective of maintaining aerodynamic performance while minimizing mass. Other gains in material technology are the advances in the manufacturing processes where special woven fabric designs, hybrid woven tapes, large braided cords of advanced/hybrid polymers, etc. all provide for optimal strength to mass performance or any other special intended purpose. The K-1 main parachute harnesses will consist of a large braided cord construction made of Vectran. Future system improvements for the K-1 main parachutes that will be investigated include the incorporation of Technora (or Spectra hybrid) in the main suspension/radial members as well as a special woven triple selvedge canopy fabric to replace lateral reinforcement tapes.

Advancements in polyether polyurethane coating compounds (in combination with the advanced materials above) have been a boon for airbags and other inflatable devices. Polyether coating compounds exhibit excellent resistance to hydrolysis and fungus. In addition, They perform well in low temperatures (down to -65°F (-54°C)) as well as in high temperatures (approx. +250°F (121°C)) when used in combination with anti-oxidants. Black polyether polyurethane coated fabrics (the color black used to absorb UV) have experienced environmental exposure of up to 15 years of service with good performance. In addition to the polyether compounds, silicon has also been used as a coating compound. Silicon, though soft, exhibits excellent environmental resistance within a wide range of operating temperatures (as high as +500°F (260°C)) as well as equivalent low temperature performance of the polyether compounds. Also, films such as Tedlar, Teflon, etc. are available and are in common use in other industries. These films also exhibit excellent resistance to hydrolysis and fungus and can perform under a wide range of temperature environments. In addition to the above performance improvements, the above coating compounds require significantly less coating applications and hence add significantly less

	SRB				K-1			
Parameter	**Drogue**	**Small Main[1]**	**Large Main[2]**	**Light weight Main[3]**	**Stab**	**Drogue**	**Main**	**Airbags**
Number of Parachutes	1	3	3	3	1[4]	1[4], 2[5]	3[4], 6[5]	4[4], 4[5]
Type	Conical Ribbon	Conical Ribbon	Conical Ribbon	Continuous Ribbon Hybrid	Hemisflo	Variable Porosity Conical Ribbon	Quarter Spherical Ringsail	Spherical[4] Elliptical[5]
Diameter D_O, feet	54.0	115.0	136.0	123.5	23	40.3	156	10.0[4] 8.5 X 12.8[5]
Number of Gores	60	96	160	128	40	40	112	N/A
Effective Suspension Line Length Ratio (D_O/S_{LE})	1.94	1.49	1.49	1.49	2.0	1.2	1.15	N/A
Deployment Q, psf	190	--	--	--	~256	77[4], 167[5]	30.2[4], 28.8[5]	N/A
Terminal Velocity, fps	--	~90	~75	~75	--	--	~20	N/A
Weight of Assembly, lbf (each)	1224	1656	~2142	760	~183[6]	~179[6]	330	~100[4,7], ~100[5,7]

Notes:
1 First SRB Flight Version
2 Present SRB Flight Version (baseline)
3 Developed, but not flying
4 OV Only
5 LAP Only
6 Includes Mortar Assembly
7 Includes Gassing System

Table 3 - Major Recovery System Elements

mass to the coated fabric as was required in prior coated fabric technology.[4] K-1 airbag system improvements that will be investigated include a single surface coating (presently a two surface coating on a Kevlar fabric base) with a modified polyether coating (with anti-oxidants) on a Kevlar or Technora fabric base. Use of this material modification will reduce the constructed airbag weight *without changing any of the manufacturing processes*.

Conclusions

The Space Shuttle program was no doubt, the *pathfinder* for reusable launch vehicle technology and provided the foundational technology and confidence upon which next generation RLVs would endeavor. As presented in this paper, the evolution of RLV technology and particular recovery systems technology continues to improve. As established from both the Space Shuttle SRB and K-1 Reusable Launch Vehicle programs, the use of very large parachutes in clusters are not only economically beneficial, but also well demonstrated technology spanning over twenty (20) years. With the K-1's introduction of very large airbags for system recovery, a broad range of vehicle class and site recovery becomes available for the further expansion of RLV technology and applications. In comparison to other primary recovery technologies, whether they be landing rockets, winged structures, rotors, et al, none can out-perform parachute and associated recovery systems with regards to costs, demonstrated flight performance, and an ever increasing evolution of significant system mass reductions.

Endnotes

[1] Jenkins, Dennis, R.; "Space Shuttle: The History of Developing The National Space Transportation System"; Motorbooks International; Osceola, WI, 1993.
[2] Wailes, W. K., Carlson, E.R.; "Repair and Refurbishment of Space Shuttle Solid Rocket Booster Decelerator Subsystem Components"; AIAA 9th Aerodynamic Decelerator and Balloon Technology Conference; Albuquerque, N.M.; October 1986.
[3] Ibid.
[4] Fallon II, E.J.; "Supersonic Stabilization and Deceleration—Ballutes Revisited"; AIAA 13th Aerodynamic Decelerator and Balloon Technology Conference; Clearwater, FL; April 1995.

References

1. Taylor, A.P., Sinclair, R.J., Allamby, R.D.; "Design and Testing of the Kistler Landing System Parachutes"; AIAA-99-1707; CEAS/AIAA 15th Aerodynamic Decelerator and Balloon Technology Conference; Toulouse, France; June 1999.
2. Gardinier, D.J., Taylor, A.P.; "Design and Testing of the K-1 Reusable Launch Vehicle Landing System Airbags"; AIAA-99-1757; CEAS/AIAA 15th Aerodynamic Decelerator and Balloon Technology Conference; Toulouse, France; June 1999.
3. Woodis, W.R.; "Space Shuttle Solid Rocket Booster (SRB) Decelerator Subsystem"; AIAA-81-1911; AIAA 7th Aerodynamic Decelerator and Balloon Technology Conference; October 1981.
4. Rodier, R.W., Moog, R.D., Kross, D.A.; "136-foot Main Parachute for Recovery of Space Shuttle Solid Rocket Boosters"; AIAA 8th Aerodynamic Decelerator and Balloon Technology Conference; Hyannis, MA; April 1984.
5. Jenkins, Dennis, R.; "Space Shuttle: The History of Developing The National Space Transportation System"; Motorbooks International; Osceola, WI, 1993.
6. Wailes, W. K., Carlson, E.R.; "Repair and Refurbishment of Space Shuttle Solid Rocket Booster Decelerator Subsystem Components"; AIAA 9th Aerodynamic Decelerator and Balloon Technology Conference; Albuquerque, N.M.; October 1986.
7. Fallon II, E.J.; "Supersonic Stabilization and Deceleration—Ballutes Revisited"; AIAA 13th Aerodynamic Decelerator and Balloon Technology Conference; Clearwater, FL; April 1995.
8. Fagan, D., Edson, B., et al; "Kistler Reusable Vehicle Design and Operational Approach"; IAF-98-V.5.05; 49th International Astronautical Congress; Melbourne, Australia; Sept.-Oct., 1998.
9. Mueller, G.E., Brandenstein, et al; "The K-1 Commercial Reusable Aerospace Vehicle"; IAF-98-V.1.01; 49th International Astronautical Congress; Melbourne, Australia; Sept.-Oct., 1998.
10. Telecon with Mr. Ken Heindel, May 11, 1999.
11. Ewing, E.G., et al; "Recovery System Design Guide", AFFDL-TR-78-151; Air Force Flight Dynamics Laboratory; Wright-Patterson AFB, OH; December 1978