AN OVERVIEW OF THE LANDING SYSTEM FOR THE K-1 LAUNCH VEHICLE, PARACHUTES AND AIRBAGS

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This paper reports the status of the design, analysis, and preliminary testing of the landing system for the K-1 launch vehicle. The K-1 consists of two reusable stages which deliver commercial payloads to orbit. Following launch, the vehicles return to their launch site for a soft earth landing achieved with parachutes and airbags. The status of design and development of the parachutes, airbags, and associated controls are described in this paper.

Nomenclature

C_{Do} = parachute drag coefficient
C_{Dv} = vehicle drag coefficient
cg = center of gravity
D_o = constructed parachute diameter, ft.
D_P = parachute projected diameter, ft.
D_V = vehicle base diameter, ft.
d = landing bag stroke, ft.
f = average force , lb.
f_p = average parachute force , lb.
ROD = rate of descent , fps
l_S = length of suspension lines , ft.
S_o = constructed parachute area, ft.^{2}
thedd = pitch acceleration, rad/sec^2

Introduction

The Kistler Aerospace Corp. K-1 Launch vehicle consists of two unique stages, the first stage, or Launch Assist Platform (LAP), delivers the second stage to a pre-selected staging altitude and velocity. Following separation, the LAP performs a "turnaround" and a return to launch site burn, to effect a landing at a pre-determined site close to the launch site.

The second stage, or Orbital Vehicle (OV), continues onto orbit, deploys its payload, and then enters a phasing orbit to prepare for return to launch site 24 hours after initial launch.

In both cases, the vehicles are recovered to a soft landing with parachutes and airbags. The maximum landing acceleration is 4 g's. Recovered vehicle weights are 45,000 lb. for the LAP and 27,000 lb. for the OV.

Irvin Aerospace Inc. was awarded the contract to design, develop, test and deliver the entire landing system for the K-1 Vehicle.

LRU Concept

The K-1 System is configured from five Line Replaceable Units (LRU's), with the term LRU meant to signify the modularity of the design.

These LRU's include the Landing, Propulsion, Structures, Electronics and Launch LRU's. The purpose of each is described below:

Launch

The Launch LRU includes all ground facilities and support equipment required to process and operate the K-1 Vehicle

Landing

The Landing LRU includes the parachutes, airbags and required controls installed on each stage.

Structure

The Structures LRU includes the primary structure for each stage, main propellant tanks, mounting structure for all other LRU components, stage separation system, payload support structure, payload fairing mechanisms, environmental control systems, and purge, vent, and drain systems.

Propulsion

The Propulsion LRU includes the main engines, the engine thrust vector control (TVC) systems, the OV Orbital Maneuvering System (OMS), the fuel and oxidizer feed lines, engine pressurization and purge systems, the Attitude Control System (ACS), and propulsion avionics.

Electronics

The Electronics LRU includes the hardware and software components that control and guide the vehicle.

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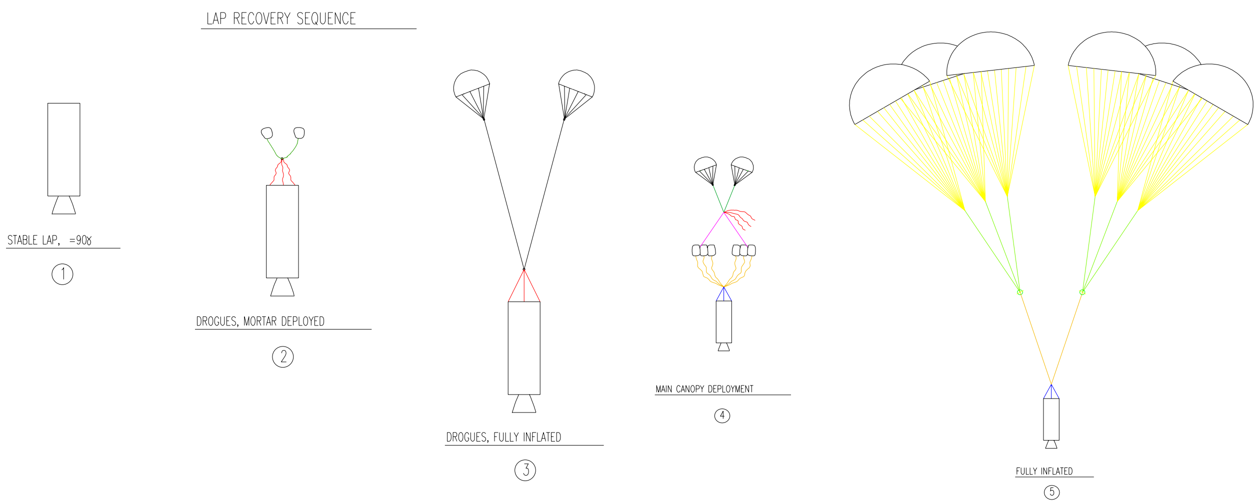


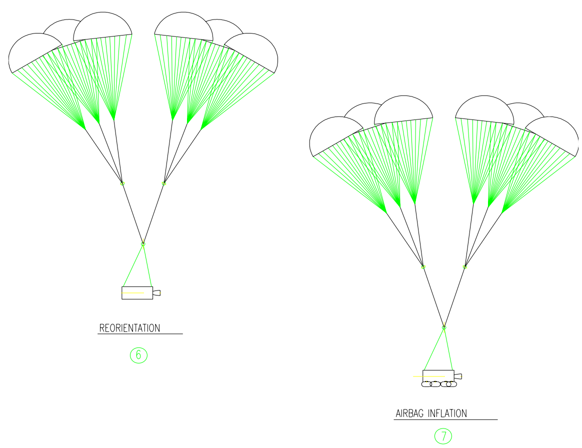


Fig. 1. LAP Recovery Sequence

Parachute System

The parachute system for each vehicle provides deceleration to a final rate of descent. In the case of the OV, an additional parachute provides pitch stabilization for a portion of the flight envelope.

LAP Parachute Sequence

Figure 1 provides a schematic for the parachute recovery sequence. Due to cg location, the LAP re-enters the atmosphere and displays static stability in the engines first attitude. The initial parachute deployment condition is, therefore, the LAP terminal descent rate of approximately 170 psf. At an altitude of approximately 20 kft, the Landing System Controller (LSC), on command from the Electronics LRU, fires two mortars to deploy a cluster of two 40 ft. D_0 conical ribbon drogues.

The drogues are sized and reefed such that either drogue will provide sufficient deceleration for main canopy deployment (at reduced safety factors), thus providing slightly higher reliability than for a single drogue.

Following a fixed time delay, the LSC releases the drogue cluster (through pyro cutters), allowing the drogues to deploy the six main canopies. The mains are rigged in two clusters of three parachutes.

Again, at a pre-selected time, the main harness legs are cut, allowing the vehicle to rotate to the horizontal position for landing. The airbag sequence, discussed in the next section, is then initiated.

OV Parachute

The OV sequence is similar, but necessarily different. The OV sequence begins at Mach = 2.5 and approximately 72 kft. It is at this Mach number, and lower, that the OV displays relaxed static stability in the pitch plane. A Hemisflo stabilization parachute provides stabilization for the OV, with some deceleration. The stabilization parachute is sized for the minimum C_DS_o required to stabilize the OV, thus providing the maximum rate of descent possible.

At the appropriate altitude, controlled by timing, the stabilization parachute is released, deploying a drogue stage, which prepares the vehicle for main canopy deployment. The current drogue design is a conical ribbon with D_0 = 40 ft. This drogue is currently different from the LAP drogues, due to loads, but may be combined with the LAP drogue design.

Drogue release initiates the deployment of a cluster of three main canopies. These being identical to the main canopies of the LAP.

The OV then performs a reorientation maneuver and prepares for airbag landing. Figure 2 provides a depiction of the landing sequence.

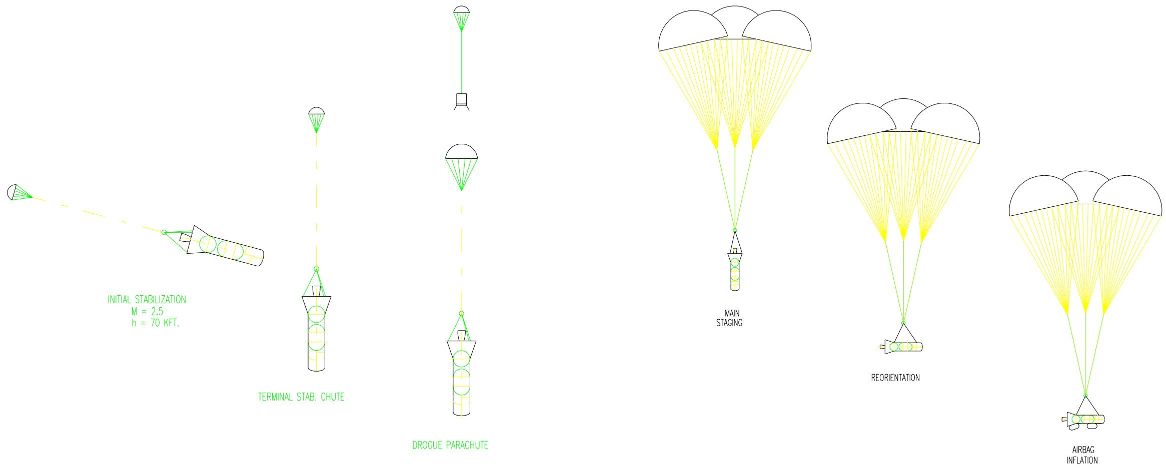


Figure 2. OV Recovery Sequence

Parachute Descriptions

Drogue Parachute

The 20° Conical Ribbon drogue planform is selected. Gore count is 32 for both LAP and OV drogues. A Kevlar-nylon hybrid design for the reusable drogue is based on successful reuse of the Space Shuttle Orbiter parabrake. Using nylon horizontal and vertical ribbons plus a nylon heat tack radial on the drag producing surface will both allow efficient manufacture and reduce material cost. Mini-radial style horizontal ribbon spacing control will be applied versus vertical tapes to assure both drag optimization and a strong geometric porosity gradient toward the skirt region for stability and drag enhancement. The structural grid will include Kevlar outer radials and suspension lines. Radial continuation over-the-vent will provide continuity and weight reduction.

Main Parachute

The main parachute follows the trend in high drag efficiency Ringsail planforms successfully employed on two prior programs. The F-111 Crew Escape Module recovery parachute improvement program was the first to apply the use of (1) mid-range permeability fabric in the central gore height, (2) modified Ringsail planform: quarter spherical with zero fullness at the 60° R/2 tangent point, and (3) linear Ringsail panel leading edge fulness ramp up toward the skirt.

Coupled with an optimum line length ratio at l_s/D_O = 1.15 and the classical C_{D_O} shift with increasing D_O, the EELV recovery main parachute at 136.0 ft. D_O produced a cluster C_{D_V} = 0.97. This was an increase from the 86.7 ft. D_O F-111 Ringsail which produced a 0.92 drag coefficient at higher W_V/S_O than the EELV. At 158.0 ft. D_O, the K-1 design will prove highest in drag efficiency of all canopies in the class.

Hybrid construction is required for the OV because of launch cost economics ($/lb. to orbit) and compartment volume limitations. Since radials of Kevlar are planned, the approach will be to feed in radial fullness to the calculated equivalent nylon elongation level to gain maximum drag production from the fabric rings constituting the drag surface. This approach was successfully employed on the Kevlar-nylon hybrid F-111 main canopy. The post inflation permanent stretch of a nylon radial will be predicted to maintain the nylon construction equivalent drag coefficient.

To save material cost, construction will feature a nylon inner radial and Kevlar structural outer radial. This will allow relaxed and re-rolled material to be underside guided as the operator matches the observable outer Kevlar radial match marks. Drill marks on the full beam width ring panels at mid panel points will be used in joining the drag surface.

A high efficiency, low snag, tubular webbing suspension line material will be applied. Radial wrap around below the skirt band is planned for high efficiency and low skirt bulk. Tape applied reefing ring anchoring is planned. Triple reefing line cutters and dissimilar reefing line materials planned for reliability.

Stabilization Parachute

Because of the 2.5 Mach number at deployment and projected wake loss behind the K-1 OV flared base, a Hemisflo stabilization chute is planned. This design is proven in such applications as the SR-71, F-104, ACES and T-38 escape systems, as well as the Program 227 reentry vehicle drogue. The small ratio of D_P/D_V dictates a very positive inflation stability design. A larger stabilization chute may not be applied for OV stabilization because of landing zone dispersion associated with winds aloft uncertainty. A 50,000 ft stabilization chute descent until drogue chute changeover is typical.

An all Kevlar structural grid is planned. Cut gore construction of the drag productive surface will preclude any planform to inflated shape uncertainties. A 20.0 ft. D_o Hemisflo is presently baselined. Kevlar suspension lines and risers will serve to minimize inflation instability induced by axial pulsation type two-body dynamics, which has induced normal shock ingestion past the skirt plane on certain prior applications, leading to severe breathing. Proper geometric porosity selection will further support solid inflation and minimize lateral instability.

Airbags

The driving performance requirements for the airbag system include minimal weights, 4.0g maximum deceleration load, and no rollover on impact. During conceptual development, the 4.0g and no rollover requirements seamed to provide the greatest challenge.

LAP Airbags

The details of the LAP airbag design are presented in Figures 3. Mounting locations selected are based on providing vehicle stability in the roll axis. Similarly, internal anti-bottoming bags (vs. external to the main bag) were selected to provide roll stability. The cylindrical shape was selected due to its natural integration with the vehicle, and the overall height/diameter dictated by the main bag stroke

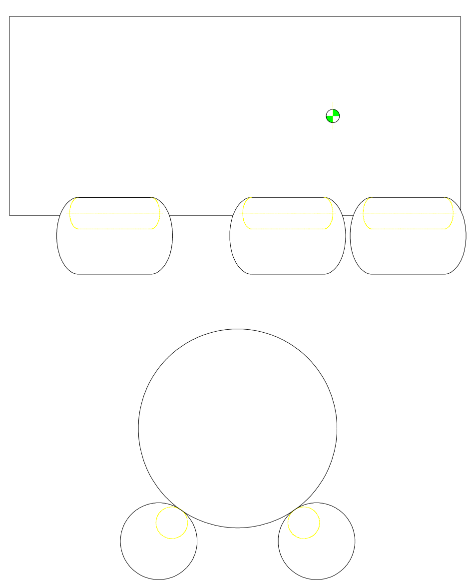


Figure 3. Schematic of LAP Airbag Configuration

requirements, and the inner bag ground clearance requirements.

Bags are constructed of a coated Kevlar material, and have a single, fixed area orifice.

OV Airbags

OV Airbags were driven by a slightly different set of requirements, those include:

(1) Lower weight per airbag
OV - 27000/4 = 6,750 lb./bag
LAP- 45000/6 = 7,500 lb./bag
(2) OV airbag geometry
(3) Additional clearances required for the OV (aft here)
(4) Similar weight goal (per airbag) for the LAP and OV.

The clearance and weight requirements became the driving issues in the OV airbag design. Figure 4 represents the OV configuration and illustrates the clearance issues.

The initial concept was to use similar airbags for both the LAP and OV, but as the OV airbags became taller (diameter) to provide the required clearance, the cylindrical section was also reduced, to provide the target weights. In the limit, as the length of the cylinder approaches zero, the LAP airbag becomes a sphere, exactly the configuration selected for the OV. Figure 4 provides a schematic representation of the OV airbag configuration and illustrates the requirements for additional ground clearance.

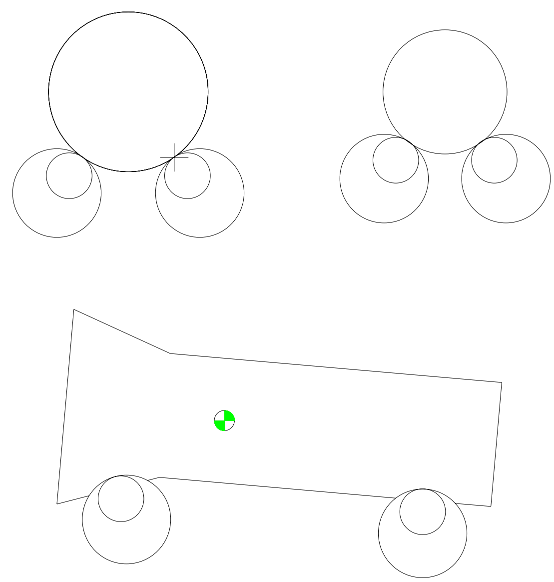


Fig. 4. Schematic Representation of OV Airbag System

Rate of Descent - Weight Optimization

A trade completed early in the conceptual definition involved the system rate of descent (ROD). High ROD allows smaller parachutes, but larger airbags and vice versa. At what ROD does the system reach an optimal weight? Figure 5 provides a comparison of relative system weight vs. ROD. Weight growth to the left of the minimum is due to a minimum size for airbags, based on vehicle geometry. To the right, increasing airbag size (volume) is growing faster than the parachutes are shrinking (somewhat due to selected airbag geometry).

In the end, ROD = 22 fps was selected as near optimal, and slightly conservative in the airbag design.

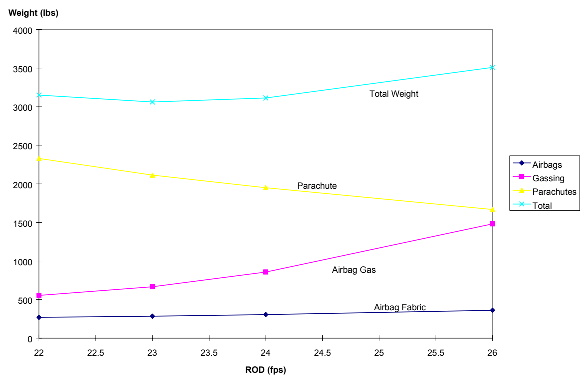


Fig. 5 System Weight vs. Rate of Descent

Airbag Performance

Early simulations, and sanity checks, revealed that the 4.0 g requirement was obtainable with relatively simple airbags. The resulting design was an airbag with a single orifice. The orifice, being released based on sensed gees on the vehicle. Figures 7 and 8 provide time histories from a representative simulation for the LAP, orifice release is commanded at 2.6 g's vertical acceleration, with the nominal cg acceleration never exceeding 4 g's. Additional control can be obtained through the delay/scheduling of various airbag orifices.

As a sanity check, the following calculation neglecting the parachute force vector work ($f_p d$) and assuming ideal airbag efficiency was performed to compare required airbag stroke, to proposed geometries. The chosen rate of descent was discussed in detail above.

or

$$\tfrac{1}{2}mv^2 + wd - f_p d = fd \qquad \text{equation (1)}$$

solving for required stoke,

$$d = \frac{.5(45000/32.2)(22.0)^2}{[4.0(45000) - 45000]}$$

$$d = 2.5 \text{ ft.}$$

This stroke of 2.5 ft. compares favorably with the resulting designs which are discussed later. Figure 6 provides a comparison of the theoretical f-d impulse used in equation (1), and simulation results for the selected configuration. These results demonstrate that the theoretical analysis and these simulations are in the same "ballpark", and that the required stroke compares with the airbag configuration selected (required < vertical bag dimension). Terms such as the parachute force are, however, neglected in equation (1)., but included in the simulation, which limits the level of correlation possible.

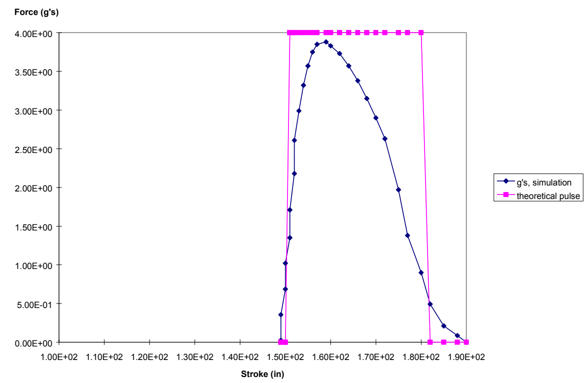


Fig. 6. Comparison of Simulation and Ideal Airbag

Rollover Performance

The tendency of the vehicles to roll during impact was also an early conceptual concern. This was of particular concern, as the vehicle heading, relative to the wind vector, and therefore, the vehicle's velocity, relative to the ground, was a random event. Ground impact, with broadside velocities to 20 knots is possible.

For this reason, airbags were placed sufficiently outboard, to provide a stable configuration, based on assumed friction coefficients. Additionally, airbag control was maintained as an option to provide restoring moments, if required.

As the design matured, the capability to align the vehicle with the wind drift vector became a real option. This is accomplished through the use of the onboard attitude control system, and INS/GPS as velocity sensors.

Some minor adjustments to parachute bridling serve to assist in the solution.

This change was adopted to reduce the landing system risk, and clearly, aligning the long axis of the vehicle with the ground velocity vector eases the job of the airbag system.

Figure 7 provides a time history for a typical LAP landing case. The figure presents cg acceleration (gees), local rigid body acceleration at the engine location (geng), and the vehicle vertical velocity (vvt) in fps. The local acceleration at the engine location has become a design criteria due to the relative sensitivity of the engine. Figure 8 presents pitch acceleration (thedd) in rad/s^2, during a typical landing case, the pitch accelerations induced at landing serve to increase the local accelerations at the engine location.

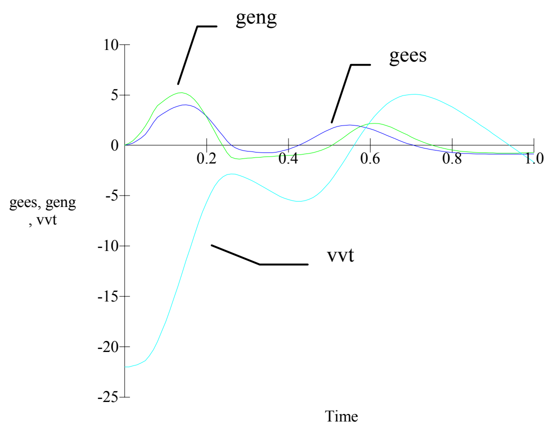


Fig. 7 LAP Airbag Nominal Landing

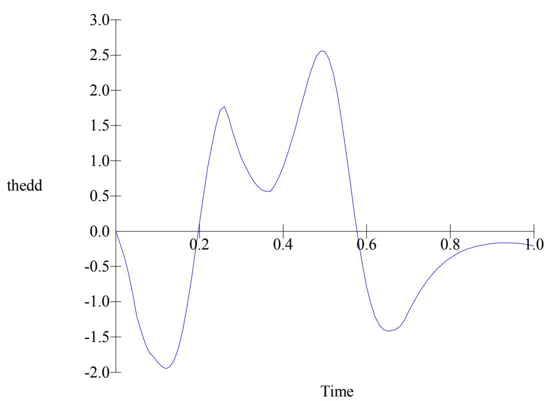


Fig. 8 Pitch Acceleration: LAP Nominal Landing

Figure 9 presents a typical OV airbag impact time history. Acceleration at the cg, the engine (gst984) and vertical velocity are presented.

Initial concerns for this configuration centered on higher airbag pressures, as compared to the LAP. Analysis revealed that the combination of longer stroke, and reduced airbag loading resulted in similar maximum pressures for both the main (pg2) and anti-bottoming bags (pg4) as compared to the LAP (Figure 10). Maximum airbag pressures for the LAP are 9 psig for the main bag and 15 psig for the anti-bottoming. This was a criteria for vehicle skin design.

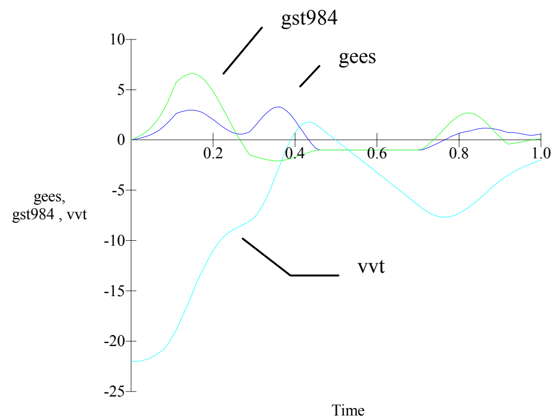


Fig. 9. OV Airbag Nominal Landing

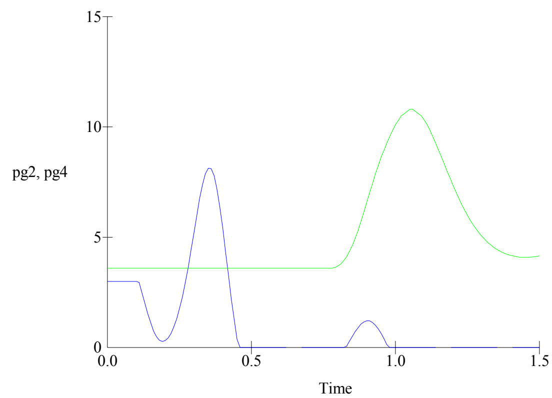


Fig. 10. OV Airbag Pressures

<u>Airbag Footprint Tests</u>

Some of the analysis and tests for this program are described below. With the exception of airbag footprint data, at the time of this writing, no test data are available. These will be the subject of a future paper.

An initial survey of LAP airbag footprint area, and airbag volume has been completed using a 1/12 scale model of the airbag and LAP. The purpose of this analysis is to develop detailed information on airbag ground contact footprint, and airbag volume, during the landing stroke. These tests are conducted quasi statically, and will be compared with dynamic testing and simulation as the program advances. Additional footprint tests at ¼ scale, are underway, and full scale testing is possible.

These data are critical to the detailed performance of the airbag model, within the airbag/vehicle simulation. Figures 11 and 12 present comparisons of the 1/12 scale data, with theoretical footprints and volumes used in simulations during concept definition. As illustrated in these figure, there is close comparison between the 1/12, and theoretical data. The result, conceptual simulations receive some level of validation.

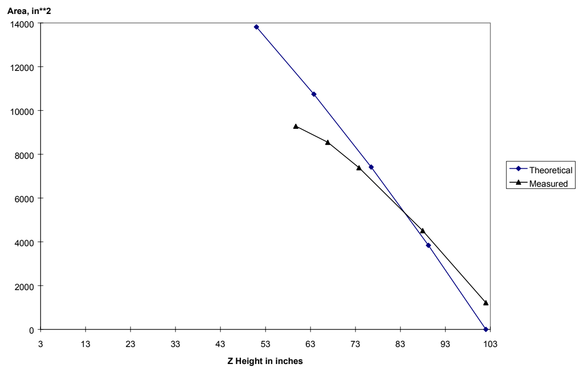


Fig. 11. Theoretical vs. Measured Airbag Footprint Area

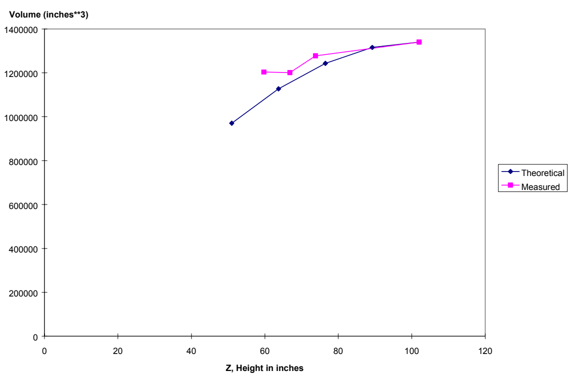


Fig. 12. Theoretical vs. Measured Airbag Volume

Simulations Tasks

In addition to rigid body simulations of the Vehicle/Landing Bag Suite, various other tools are being developed, created, or investigated. These include:

1) Quasi -static FEA of the airbags
2) Non-linear, dynamic FEA simulations of the airbags
3) Flexible vehicle simulations of airbag landing

These are discussed briefly below.

Quasi Static FEA

At conception, it was concluded that an FEA tool would be required to model the airbags, primarily due to the difficulty with testing these large devices. The tool selected by Irvin was the ANSYS Mechanical Package. At the time of writing, analysis are under way, but not completed, related to airbag deflected shape, footprint, stresses, and geometry variations.

It should be notes that these analysis, are being conducted by the author, on a high end notebook computer.

Dynamic FEA Simulations

Dynamic FEA simulations are also required to support analysis in areas such as soil compliance/compaction, inertial effects on airbag shape and stresses, and inertial effect on gasses inside the airbag. For these purposes, the ANSYS LS-Dyna tool has been selected. Simulations are planned for the summer of 1997.

Flexible Vehicle Analysis

To date, a preliminary analysis of the vehicle dynamics, including flexible effect has been completed by SDRC. These loads inputs to the analysis were based on Irvin simulation, and included individual loads at each airbag station. Preliminary results indicate that the LAP and OV vehicles are fairly rigid, and that only minor load amplification occurs due to vehicle flexibility.

It is, however, realized, that detailed structural analysis will be required to support the ongoing engineering design effort. Part of this analysis, may include further refinement of the airbag simulations. Towards that end, plans are underway to provide a detailed airbag simulation to the vehicle structures analysts. With this tool they will perform detailed structural dynamics analysis, including airbag landing loads at the individual locations.

Parachute and Airbag Testing

The Kistler Philosophy towards testing is to provide a balance between cost and risk, as with any commercial venture. Towards that end, the Parachute and Airbag testing are limited to that required to provide a balance risk. The test programs are discussed below.

Parachute Testing

The parachute test program is largely defined, with the exception being the stabilization parachute. Only recently added to the program, the stab. Chute, is still being defined.

Drogue and main canopy testing will be performed at Yuma Proving Ground (YPG) during the summer and fall of 1997. Testing will include single canopy testing to validate the reefing and load capability of each canopy, and full cluster tests for all parachute clusters. Drop weights will be limited to 42,000 lb, as opposed to the max. of 45,000 to assure the economy of C-130 aircraft.

Airbag Testing

Airbag testing will commence in two phases. The first, is scaled testing. The K-1 scaled airbag testing will be conducted at ¼ scale. Testing will be conducted at a drop gantry constructed at the Irvin Canada facility in Fort Erie, Canada. Figure 13, below, depicts LAP scaled airbags.

Scaled airbag testing was chosen to reduce the cost and time required to conduct developmental tests. The facility picture can produce the scaled equivalents of 24 fps vertical and 36 fps horizontal velocity.

The scaled airbag test program consists of several phases:

1) ½ LAP Testing
2) Full LAP Testing
3) OV Testing

The ½ LAP configuration, as shown in the photo above, was included to provide a simple model for early testing, and to reduce the test to a simple 3-DOF problem.

Full LAP testing will address pitch plane dispersions and the complexity of all six (6) airbag assemblies.

OV testing, is not reduced to fewer degrees of freedom, primarily due to the assumption that the previous LAP testing will provide sufficient knowledge about airbag performance and modeling.

The primary purpose of scaled testing is to provide validation and fine tuning of airbag simulations. If the simulation works for ¼ scale bags, then the full scale results are valid.

Additional work to support the scaled testing include calibration of the orifices in the airbags, and determination of the time delays within the system, relative to orifice cutting command vs. event.

Fig. 13. Scaled Airbags Being Prepared for Testing

Full Scale Airbag Tests

A required number of Full Scale tests will be conducted at the NASA Langley Research Center (LaRC). Plans include development testing, with a minimum of five test per vehicle, and a qualification series for the LAP. The OV qualification will be conducted as described in the System Level Test section, below.

For these tests, boilerplate test vehicles, which have the proper mass properties, and the correct lower vehicle Outer Mold Line (OML) will be conducted.

System Level Test

One system level test, of the OV is envisioned. In this test, the boilerplate OV is launch from a helicopter, and the maximum number of parachute stages possible, are exercised to recover the vehicle. Airbags are used to provide the final landing attenuation.

No such test for the LAP is envisioned, due to the large size (22.0 ft dia), and large weight (45,000 lb) required to test a LAP boilerplate.

Control System

In addition to the fabric components, Irvin will provide the controls and controller necessary to perform the landing sequence. Controls are based on a fault tolerant architecture, and an integrated health management system.

The Irvin provided Landing System Controller (LSC) will control the entire landing sequence following initiation from the ELRU, which houses the vehicle management function.

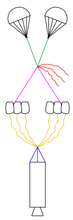
Parachute scheduling will be based upon the final sequence for optimal parachute deployment.

Airbag sequencing will include the precision scheduling of airbag orifices based on sensed acceleration during the landing sequence. Detailed control could include the addition of bag to bag time delays, based on vehicle attitude and velocities at touch down.

Health monitoring will include BIT test to assure the proper functionality of all circuits, and systems prior to launch.

Summary

Irvin Aerospace will provide a compete Landing System for the K-1 Launch vehicle. The Landing System is applied to two stage vehicles, each with unique requirements. Each landing system includes parachutes, deployment devices, airbags, and all the necessary controls to effect a soft landing of the K-1 stages.



MAIN CANOPY DEPLOYMENT

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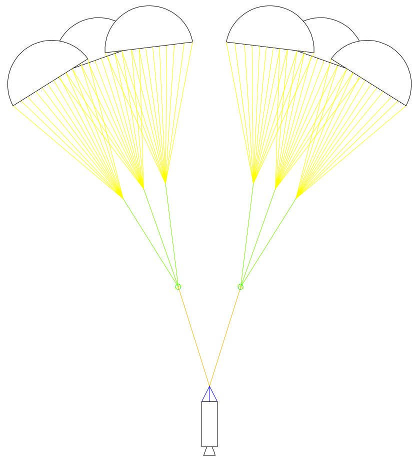

FULLY INFLATED

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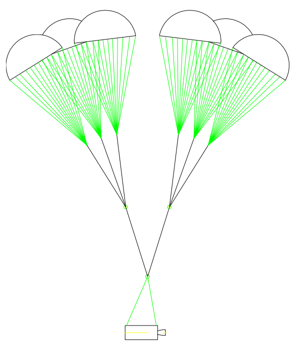

REORIENTATION

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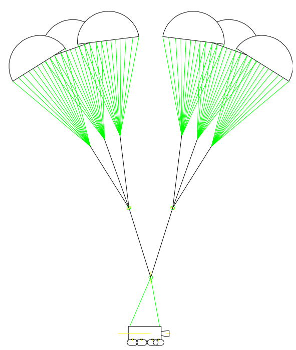

AIRBAG INFLATION

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