DESIGN AND TESTING OF THE K-1 REUSABLE LAUNCH VEHICLE LANDING SYSTEM AIRBAGS

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This paper reports the status of the design, analysis and preliminary testing of the airbag portion of the K-1 Reusable Launch Vehicle landing system. The K-1 consists of two reusable stages that 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 the design and testing of the K-1 airbags are described in this paper.

Nomenclature

AGS - Airbag Gassing System
ACS - Attitude Control System
CG - Center of Gravity
EPDM - Ethylene Propylene Diene Monomer
FEA - Finite Element Analysis
GN2 - Dry Nitrogen
KAC - Kistler Aerospace Corporation
LAP - Launch Assist Platform
OV - Orbital Vehicle

Introduction

The K-1 Reusable Launch Vehicle Landing System consists of parachutes and airbags to land both stages of the Kistler Aerospace Corp., K-1 Launch Vehicle. The K-1 Launch Vehicle is a commercial venture to develop the world's first fully re-usable launch vehicle. The unmanned launcher consists of two stages, the first stage being the Launch Assist Platform (LAP), and the second stage the Orbital Vehicle (OV).

References 1 & 2 provide a description of the recovery sequence.

Following staging, the LAP performs a return to launch site maneuver and is then recovered for a soft earth landing using parachutes and airbags. Recovery of the nearly 45,000 lb. vehicle is accomplished with a drogue and main stage, followed by an airbag attenuated impact. The airbag system requirements include the following:

1. Provide final landing deceleration and impact attenuation.
2. Limit max static accelerations to 4 g's vertical.
3. Prevent rollover.
4. Prevent vehicle skins from touching the ground.
5. Maintain vehicle off ground for recovery.
6. Reusability.

The LAP airbag set consists of four (4) large outer or stroking airbags. Each airbag contains an inner, permanently inflated anti-bottoming airbag. The function of the first is to absorb impact energy while the second prevents ground contact, and maintains ground clearance during recovery operations. The LAP airbags are cylindrical in design, with elliptical endcaps that measure approximately 8.5 ft. in diameter by 12 ft. in length. Figure 1 shows the size of the LAP inner airbag with respect to a man.

Figure 1. LAP Inner Airbag

Following re-entry the 27,000 lb. OV is both decelerated and recovered using its parachute/airbag set. Landing impact is cushioned by four airbag sets as described above. Because of the OV geometry, these airbags have a spherical shape. The outer bag is approximately 10.0 ft. in diameter, while the inner bag is 5.2 ft. in diameter. Figure 2 shows the OV outer airbag size with respect to a 6.0-ft. man.

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Figure 2. OV Outer Airbag

Some of the unique developments and activities to be discussed in this paper include: 1) design of the airbags, 2) design of the airbag gassing system, 3) analysis and simulations required to support the program, and 4) a presentation of test results.

System Description

After parachute recovery, the final phase in the safe return of the K-1 stages is to provide landing deceleration and impact attenuation. The current airbag locations for both the LAP and OV stages are represented in Figures 3 & 4. The mounting locations were selected to provide vehicle stability in the roll axis along with limiting impact accelerations. Stage alignment with the ground relative velocity vector further improves the stability in the roll axis. Alignment is accomplished through the use of onboard GN&C equipment and the stage attitude control system (ACS).

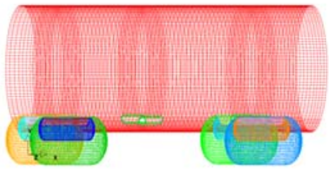

Figure 3. LAP Stage Airbag Location

The Kistler design uses a system of palletized airbags. Each airbag pallet consists of a backboard, attachment

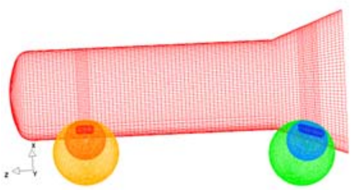

Figure 4. OV Stage Airbag Location

hardware, aspirator interface, gas inflation and sensing lines for inner and outer airbags. Airbags are deployed using a palletized Airbag Gassing System (AGS) that provides a mixture of aspirated ambient air as well as dry nitrogen. Each AGS pallet consists of 2 solenoids (1 latching, 1 non-latching), 2 control valves, 2 vent orifices, a pressure transducer, an aspirator, and sensing and fill lines. An example of the AGS pallet can be seen in Figure 5.

Control of airbag inflation and deflation is accomplished through state of the art digital processes. At a specified altitude, the stage flight control system signals the AGS to begin the airbag inflation process and sequences the airbags through door release, pack release, and inflation of both inner and outer airbags.

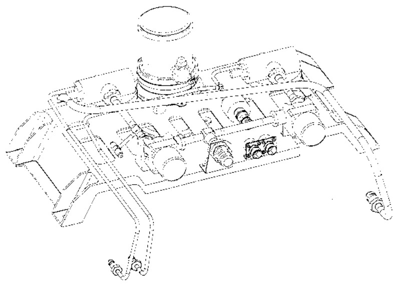

Figure 5. Airbag Gassing System Pallet

At vehicle touchdown, the stage flight control system signals the airbag vents to open when accelerometers located at the vehicle CG measure the preset trigger gee level. The airbags are designed to limit the maximum accelerations to 2 g's (axial) and 4 g's (vertical), as well as, minimize the loads seen by the engines. After vehicle touchdown, the airbags prevent the composite vehicle skins from touching the ground until recovery.

Airbag Design

In an effort to save space and weight, the airbag design has evolved to an inner and outer airbag "set" located at each airbag location. The LAP airbag design, the heavier of the two vehicles, has changed from 8 to 6 to 4 airbag pallets as the concept has matured. The OV airbag concept has remained at 4 airbag pallets throughout the design process in order to maintain stage stability during the impact.

All airbags are constructed of Polyurethane (PU) coated Kevlar (MIL-C-44050 Type I, Class I). The baseline adhesive used to assemble the airbags is a two-part adhesive containing Iso-Cyanides. Although a bit complicated to handle, it has a long track record and bonds well with PU. All joints have a 1-2" overlap to assure good bonding. The PU is flexible, abrasion resistant and prevents leakage while the Kevlar provides thermal capability and strength. Grab testing was completed on all material batches to certify a minimum of 900 lb/in capability in the fabric, while pull tests were performed on various joint overlaps to assure a proper joint. Typical joint strength exceeds that of the parent material. Temperature testing was successfully performed from –65 F to 200 F to validate the material and adhesive limitations under extreme conditions. Figure 6 shows an example of the "hands-on" bonding process.

Figure 6. Bonding of Airbag Seam

To provide the impact attenuation required, the outer airbag design incorporates a deflation orifice that is triggered to open at a specific landing gee level. The trigger gee level was determined to limit gee levels during the landing cycle. Eight (8) flaps and two (2) EDPM 1/6" rubber discs makeup the orifice design. Figure 7 shows details of the flaps, the double Kevlar layer that aids in securing the disks and the actual disks in place. The flaps are held together by Kevlar cord, with cutters in line, to retain the blow out disks until the orifice is trigged to blow. Once triggered by the stage flight control system, the pyrotechnic cutters release the flaps, which in turn allow the disks to blow out, and the airbag is deflated.

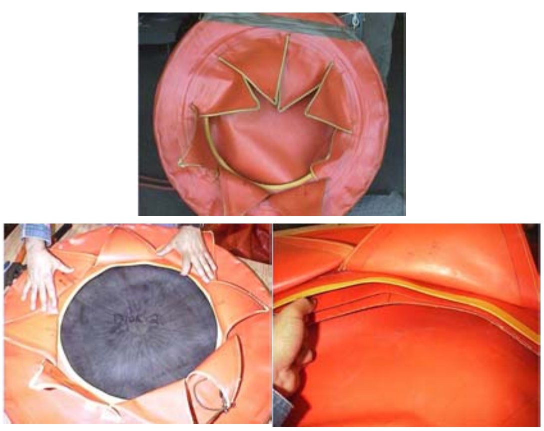

Figure 7. Airbag Orifice Details

Orifice sizing was determined based on the K-1 Reusable Launch Vehicle system requirements using simulations and test results detailed later in the paper.

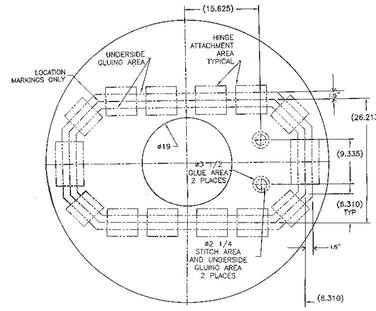

Figure 8. Saddle Area Pattern Details

The most complicated construction area is located at the top of the airbag and is known as the "Saddle" area. In this area, 6 layers of Kevlar are glued and sewn together using 2" overlapped joints and Kevlar stitching.

Figure 9. Saddle Area Construction

Figure 8 shows a pattern of the area while Figure 9 shows the saddle area during actual construction.

The Saddle is an area that unites the inner and outer airbags, contains the hinges that attach the airbag to the vehicle, and provides a flow path from the gassing system to the inner airbag for inflation.

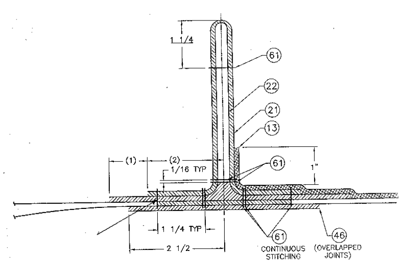

Figure 10. Hinge Flap Drawing

This area must be constructed to withstand the forces that the airbag will see during landing as well as be flexible enough not to prevent proper airbag deployment. Figure 10 shows the detailed hinge flap construction while Figure 11 shows an actual constructed hinge flap. All hinges are standard MS hinges and are each attached to a Kevlar flap. Each airbag compartment has from 10–14 hinges to prevent the airbag from tearing off the vehicle during impact.

Figure 11. Actual Hinge Flap

The airbag is packed and held on to an Aluminum Honeycomb backboard using packing flaps. The backboard provides airbag stiffness during handing and secures the aspirator interface to the gassing system during installation. The flaps are held down using a daisy chain configuration along with two double redundant pyro cutters in line. The cutters provide pack release prior to airbag inflation. Figure 12 shows the daisy chain configuration noted.

Figure 12. Close-up of Packed Airbag

The packed airbag (including backboard, inner/outer airbags, packing flaps, hinges, hoses, mounting hardware, cutters and electrical hardware and blowout patches) weighs approximately 100 lb. Figure 13 shows a packed airbag in a simulated LAP compartment. The LAP compartment measures approximately 58" long by 24" wide by 11" deep.

Figure 13. Packed LAP airbag

Figure 14 is a schematic of a side view of the packed airbag inside the compartment. At the appropriate time in the flight profile the inflation sequence is initiated. As the airbag inflates, the flaps allow the airbag to deploy out of the compartment by rotating on the hinges to a maximum of 60 degrees.

One of the most critical components in the design of the airbag is the inner tunnel. The inner tunnel is part of the inner airbag and provides a flowpath to the outer bag from the AGS. Critical to the tunnel design is the capability to alleviate any backpressure of the aspirator during outer bag inflation. Figure 15 is a top view of an actual constructed inner tunnel.

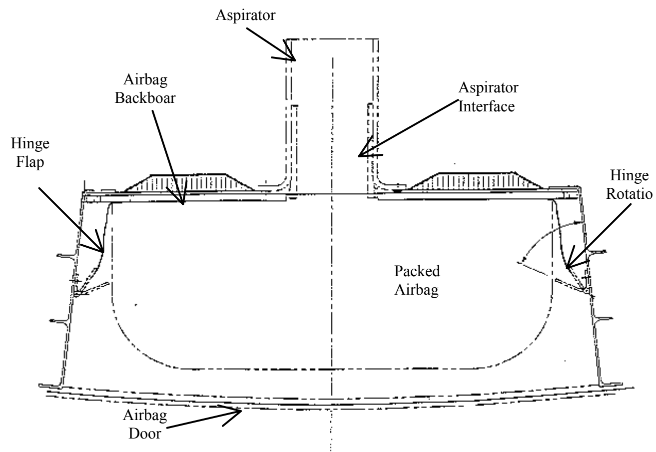

Figure 14. Airbag Deployment Hinge Operation

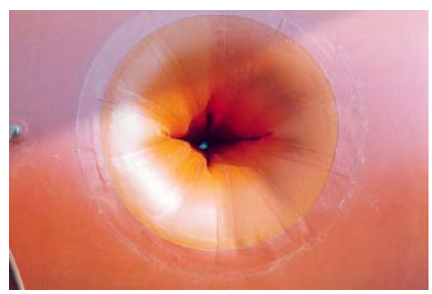

Figure 15. Top view of Inner tunnel

A 5-inch diameter interface fitting on the airbag connects the packed airbag to the AGS by being inserted into the aspirator base. The fitting incorporates 2 multi-seals rather than O-rings to prevent seal rollover and leakage between the AGS and airbag.

Once on the ground, the inner airbags must sustain pressure for at least 30 minutes at full recovered stage weight to allow enough time for ground crews to safely recover the stages from the landing zone. Inflation and maintenance pressurization are provided by the stage mounted nitrogen system, which also provides GN2 for engine purge, tank pressurization, and ACS.

Airbag Gassing System Design

The Airbag Gassing System (AGS) controls the GN_2 that inflates the airbags used in landing each stage of the K-1 Reusable Launch Vehicle. The AGS system requirements have evolved into the following:

1. Provide GN2 to open the airbag door before airbag deployment.
2. Use a maximum of 35 lbs. GN2 by each AGS pallet.
3. Weigh under 25 lbs.
4. Inflate the inner and outer LAP and OV airbags in under 60 seconds.
5. Sustain bag pressure during descent for a maximum of 200 seconds.
6. Maintain airbags at a specified cut-off pressure until touchdown.
7. Sustain inner airbags for 30 minutes before recovery.

An AGS pallet is located above each airbag pallet. The AGS was designed to save on GN_2 usage and thus minimize the stage weight required to inflate the airbags for landing. As the design matured, it was determined that by using a manifold system at a central bottle location, gas blowdown temperatures and weight impact would be more favorable. Dry nitrogen is stored on each stage at 6,000 psi in 13,000 cubic inch bottles with supply lines connected through a regulator to an aspirator system at each bag set. One bottle on the OV and 1-2 bottles on the LAP are assigned for use by the AGS for airbag inflation.

Figure 17 shows a photo of the aspirator, which is the major component of the AGS. The aspirator is activated by Nitrogen that causes a piston and spring to open a flapper valve and entrain ambient air. Airbags located in the Interstage area of the vehicle, use a positive closure add-on to the standard aspirator to seal and protect the airbags from a 6.5 psi pressure during launch.

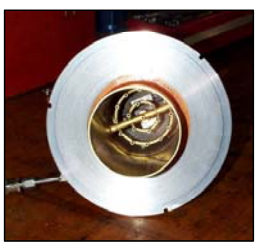

Figure 17. Standard Aspirator

The AGS fills the outer bag with aspirated ambient air until approximately 0.5 psi back pressure, then draws from the GN_2 bottles for completion of outer bag inflation. The inner bags are inflated entirely with GN_2 from the onboard bottles via the AGS.

The inflation time line is 60 seconds to initial inflation, and approximately 200 seconds to thermal equilibrium. To avoid over pressurizing the airbags, various inflation sequence simulations were considered and compared. Proper inflation sequencing assures optimal timeline and stored gas utilization. Figures 18 thru 20 give an example of the data compared for one inflation scenario.

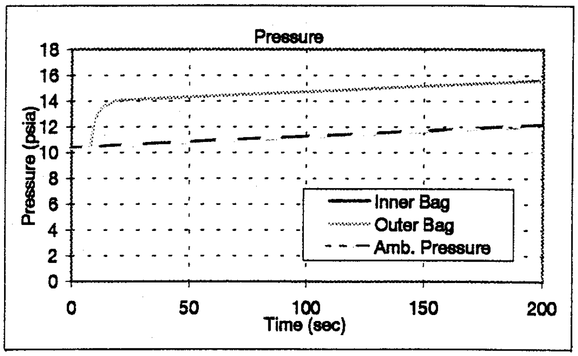

Figure 18. Airbag Pressure vs. Time

The recommended inflation sequence for the OV was determined to be simultaneous inflation of the inner and outer airbags. The LAP was best optimized with a sequential inflation of the outer airbag followed by the inner.

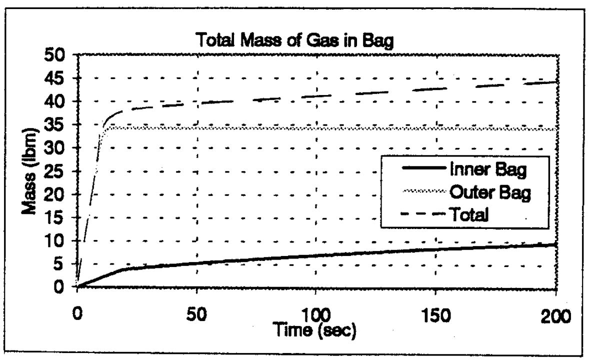

Figure 19. Total Gas Mass vs. Time

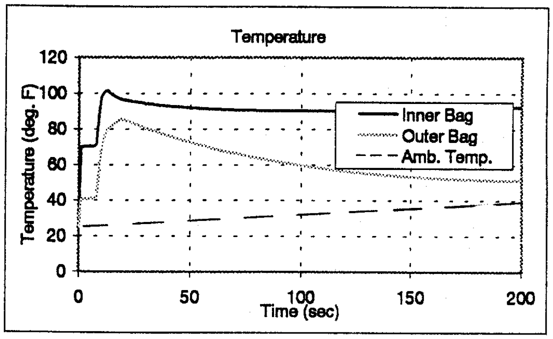

Figure 20. Airbag Temperature vs. Time

<u>Analysis and Testing</u>

One of the primary tasks of airbag testing was simulation model validation. Toward this end, a phased approach to airbag testing was adopted. Test configurations included a ¼ scale model of ½ the LAP length. This model was tested early in the program, with vertical velocity only impacts to provide a level of risk reduction. Figure 21 provides a photograph of the ¼ scale LAP.

Further tests were conducted with a ¼ scale full LAP, and ¼ scale OV. Finally, full scale testing of a LAP stage model is planned for late 1999.

Test results, and comparisons to analysis are presented below.

<u>Analysis and Simulation Tasks</u>

Several tools were used to help in the design and analysis phases of this program. These tools were crucial in guiding Irvin to the best design for K-1 stage recoveries since a limited amount of testing is afforded.

<u>BAGDYN Model</u>

Preliminary sizing analysis was accomplished using BAGDYN, an Irvin in-house tool. This program provides a rigid body simulation of a vehicle landing on airbags. The airbags are simulated as pneumatic springs with proper modeling of the vent mass flow equations and thermodynamics. Options exist for either

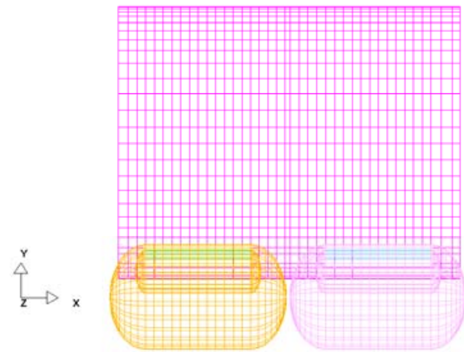

Figure 21. Quarter Scale ½ LAP

analytical or experimental inputs for airbag volume and footprint during deflection. The input deck allows selected theoretical airbag geometries. These are most useful during concept definition and pre-test planning phases.

Figure 22 resents an example of a vehicle/airbag system model during impact, and a summary of the equations that BAGDYN employs during the simulation.

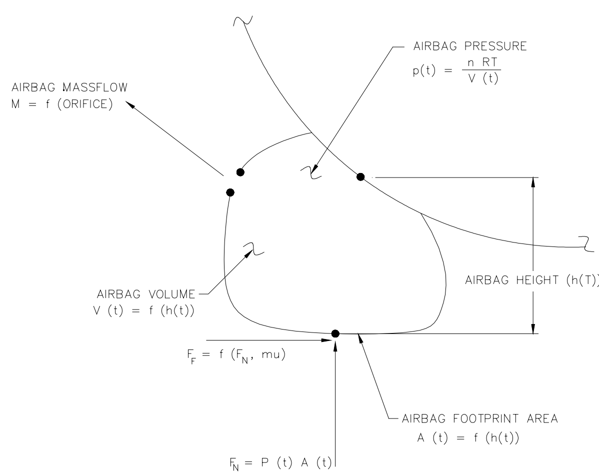

Figure 22. Vehicle/Airbag System Model

Data presented represent a "tuned analysis", that is, the variation of airbag volume (V(h(t)) and footprint area (A(h(t)) are computed and input via a look-up table. Potential sources for these data include:

1. Impact tests with sufficient instrumentation
2. Static Airbag Tests
3. Finite Element Analysis

For the data presented herein, the airbag data was derived from a single impact test, and applied to a wide range of drop tests.

Figures 23 presents test data from one drop test of the ¼ Scale ½ LAP model. Acceleration vs. time is presented for an actual drop test. Over plotted are simulation results using the tuned BAGDYN model.

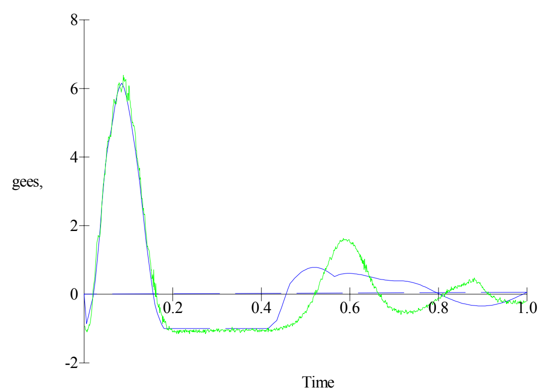

Figure 23. ¼ Scale ½ LAP Data Comparison

Excellent comparison is seen during the first 400 msec. This is the critical portion of the impact. Comparison in the .4 to 1.0 second time frame is less accurate, but adequate. Here the acceleration is due to impact of the inner airbag. BAGDYN modeling of the inner airbag is less critical and therefore is not fully optimized.

DYNA3D

Detailed analysis was also performed using LS DYNA-3D. This explicit Finite Element Analysis (FEA) technique allows large amplitude, time based analysis for impact simulations. It includes material models for fabric, and a model for the thermodynamics of airbag deflation.

This tool was primarily used to analyze airbag fabric stresses, attachment loads, and structural interface loads. Models for both scale model testing, and full-scale projections are presented below. Both DYNA and the BAGDYN tool played key roles in the optimization of test matrices.

The DYNA code was employed for several purposes. Primary among these was the evaluation of airbag characteristics during the landing impact. These include:

1. Internal fabric stresses
2. Accurate prediction of airbag deflection during impact
3. The effects of soil friction and compliance
4. Airbag attachment loads
5. Airbag structure optimization

Of these, items 1, 2 and 4 have been the focus of this work to date. This section presents some of the simulation models built to date. Validation of these models through comparison to test data (1/4 scale) and application of these models to full scale and alternate configurations are presented.

Comparison to Test Results

The primary comparison of DYNA results, to date, has been to the ¼ Scale, ½ LAP test article. Figure 21 presents a Finite Element model of this test article and a photograph of the actual drop test article. Model Scaling laws between ¼ and full scale were per Froud number scaling. The DYNA model was a complete simulation of the ¼ scale model. Figure 24 and 25 present comparisons of DYNA simulations results and dynamic test data. Acceleration comparisons are good,

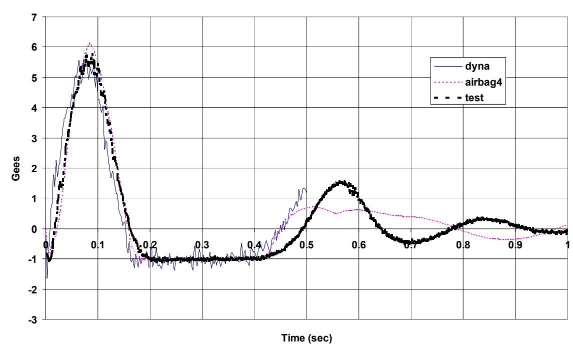

Figure 24. Airbag Acceleration Data

particularly in the critical first 0.2 seconds of the impact (Figure 24). Internal airbag pressures (which were instrumented during the test) provide equally good comparison (Figure 25).

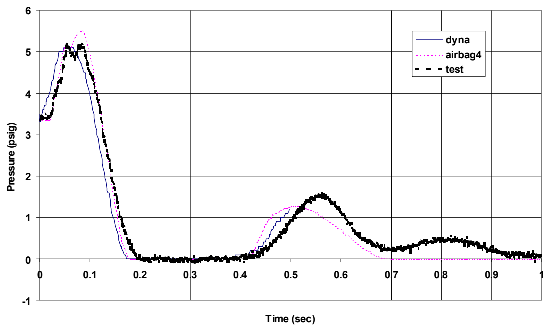

Figure 25. Airbag Pressure Data

BAGDYN simulations for this impact are also presented and show equally good correlation.

<u>Full Scale Models</u>

Several Kistler Full Scale models have been generated either to evaluate the baseline airbag configuration, or to investigate alternate configurations and control sequences. In these, critical parameters such as airbag pressures, orifice area, vent control, and airbag geometry are evaluated.

Figures 26 through 29 present examples of various models that have been evaluated. These include the LAP with 6 airbags (Fig. 26), 4 airbags (Fig. 27), the OV and its 4 airbags (Fig. 28), and the LAP with 4 of the OV airbags (Fig. 29). In the case of Figure 29, the upper surface of the LAP has been eliminated. As the landing stage is modeled as a rigid body (at this point) the upper surface is not required, and elimination in-

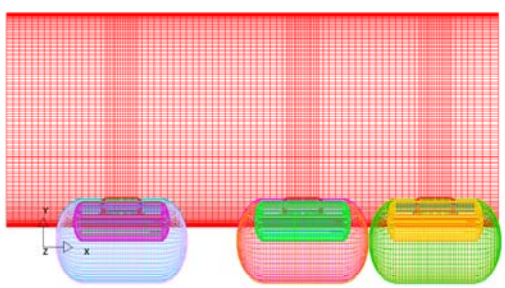

Figure 26. LAP 6 Bag Configuration

creases post-processing efficiency. In general, model construction to execution takes a 10-40 engineering hours, and model execution time is overnight on a modern PC workstation.

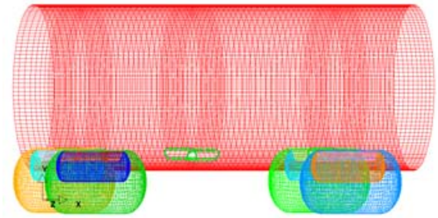

Figure 27. LAP 4 Bag Configuration

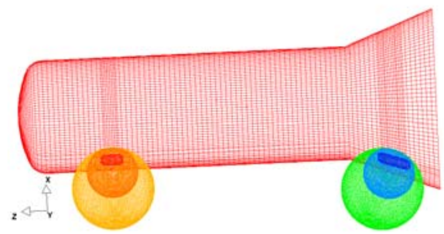

Figure 28. OV Configuration

Figure 29. LAP with OV Airbags

Example results are presented in Figures 30 through 35. Figure 30 presents airbag and vehicle geometry during a sample impact for the LAP. The airbag contours indicate relative airbag stress. In Figure 31 similar data are presented with the LAP omitted for clarity. Here, the peak stress region of the airbag (inside edge in this case) can be seen. Detailed time histories of stress for an element (vs. time) are also possible.

Figure 32 presents airbag pressure time histories for the same simulation vs. time. The airbag pressures are in psia, and are presented for the inner and outer bags. Vehicle rigid body motions data are presented in Figures 33 and 34. Figure 33 presents vertical acceleration (in inches/sec/sec) versus time and Figure 34 presents vertical velocity (in/sec) versus time. Figure 35 presents an example of vertical and horizontal velocities for an impact with initial horizontal velocity and airbag to ground friction. Velocities are in in/sec.

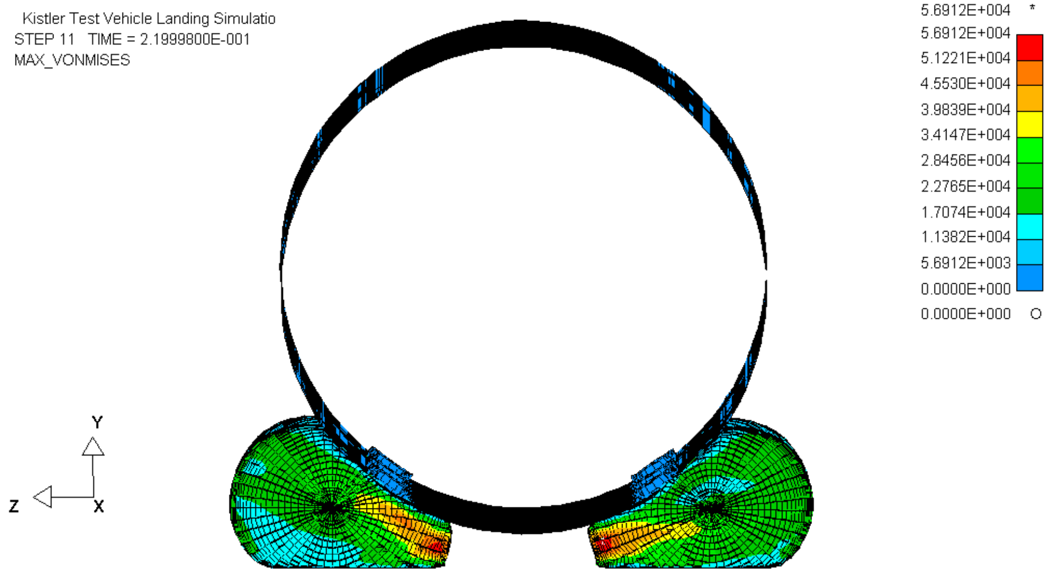

Figure 30. Airbag Shape During Impact

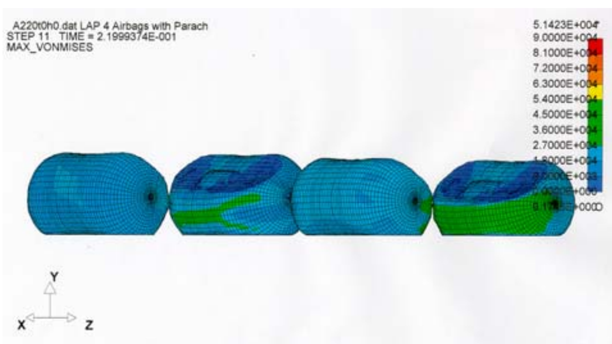

Figure 31. Side View of Airbag Impact

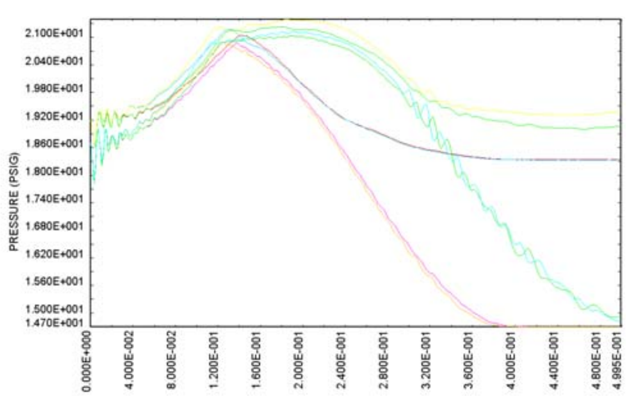

Figure 32. Airbag Pressure Time History

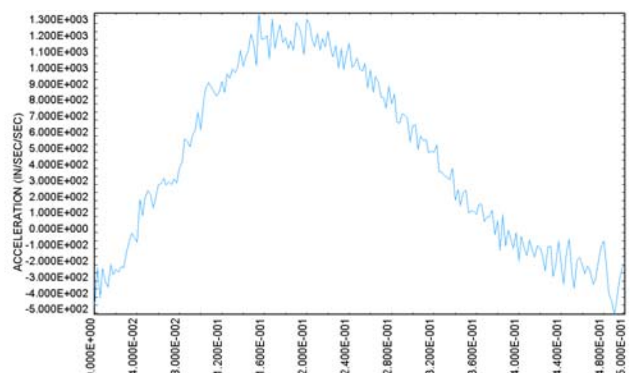

Figure 33. Vehicle Rigid Body Acceleration Time History

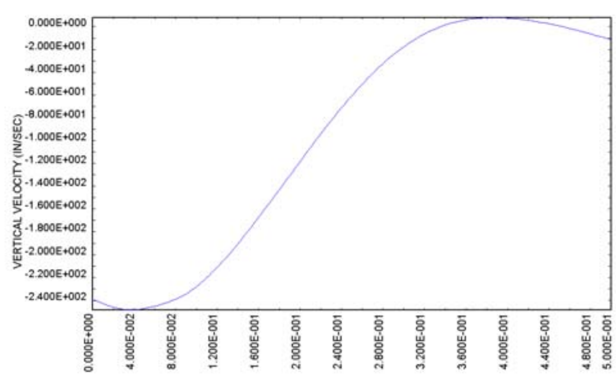

Figure 34. Vehicle Rigid Body Velocity Time History

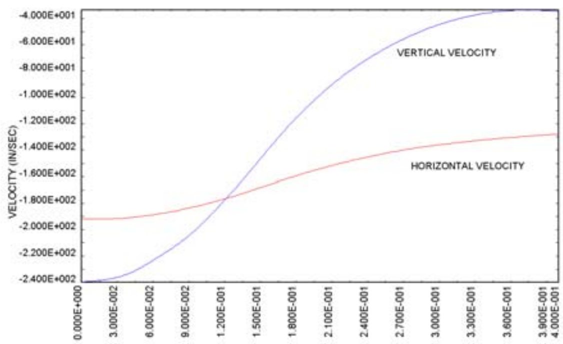

Figure 35. Vehicle Rigid Body Velocity Component

Summary

To date the landing system airbags designed for the K-1 Reusable Launch Vehicle meets all of the design requirements to land the vehicle safely.

Future ¼ scale and full scale testing is planned for mid to late 1999. Objectives include the full-scale validation of the airbag landing dynamics including various dispersions. Airbag and gassing system integration testing will be completed to fine tune inflation sequencing, airbag deployment and optimize gas utilization.

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