A Summary of the Development of a Nominal Land Landing Airbag Impact Attenuation System for the Orion Crew Module

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Airborne Systems North America (formally Irvin Aerospace Inc) has developed an Airbag Landing System for the Orion Crew Module of the Crew Exploration Vehicle. This work is in support of the NASA Langley Research Center Landing System Advanced Development Project. Orion is part of the Constellation Program to send human explorers back to the moon, and then onwards to Mars and other destinations in the Solar System. A component of the Vision for Space Exploration, Orion is being developed to also enable access to space following the retirement of the Space Shuttle in the next decade. This paper documents the development of a conceptual design, fabrication of prototype assemblies, component level testing and two generations of airbag landing system testing. The airbag system has been designed and analyzed using the transient dynamic finite element code LS-DYNA®. The landing system consists of six airbag assemblies; each assembly comprising a primary impact venting airbag and a non-venting anti-bottoming airbag. The anti-bottoming airbag provides ground clearance following the initial impact attenuation sequence. Incorporated into each primary impact airbag is an active vent that allows the entrapped gas to exit the control volume. The size of the vent is tailored to control the flow-rate of the exiting gas. An internal shaping structure is utilized to control the shape of the primary or main airbags prior to ground impact; this significantly improves stroke efficiency and performance.

Nomenclature

σ = sigma, standard deviation

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I. Introduction

In January of 2004, US President George W. Bush announced a new Vision for Space Exploration[1] setting the long-term goals and objectives for the Nation's space exploration efforts. Among these goals and objectives was the development and deployment of a new spacecraft capable of transporting humans to the International Space Station (ISS), the Moon, and eventually Mars. The subsequent Exploration Systems Architecture Study (ESAS) [1] identified an exploration framework that would enable NASA to achieve this goal of extending a human presence throughout the Solar System. The Constellation Program encompasses NASA’s initial efforts to implement the framework developed during the ESAS. The Constellation Program currently consists of: a Crew Launch Vehicle (Ares I), and a Cargo Launch Vehicle (Ares V), the Orion Crew Exploration Vehicle (CEV), the Earth Departure Stage (EDS), and the Altair Lunar Lander. Figure 1 illustrates these primary components.

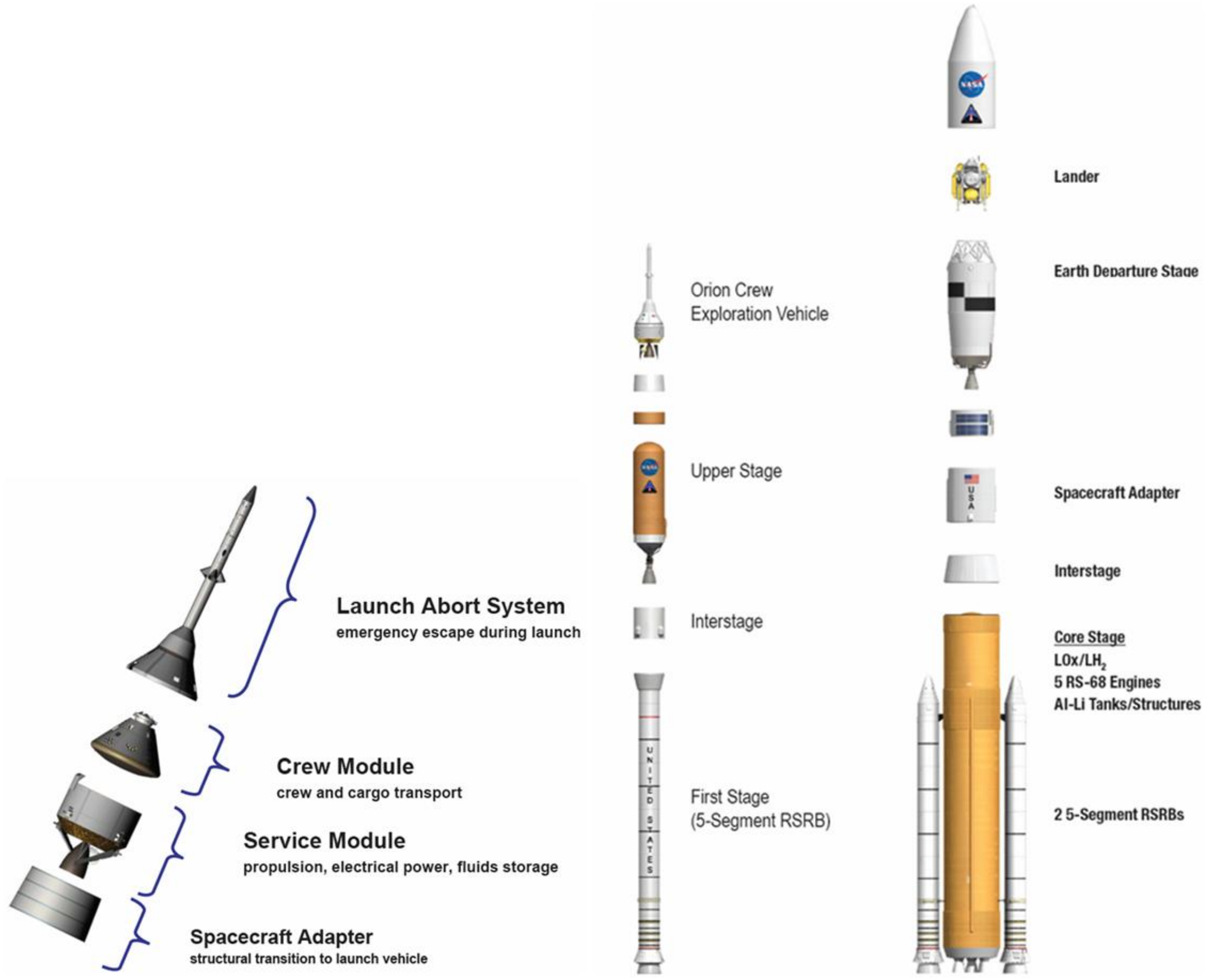


Figure 1: Primary Constellation Program Components

The ESAS also recommended a primary land landing mode for the Orion Crew Module (CM) when returning to Earth. This recommendation was made for ease and minimal cost of recovery, post-landing safety, and reusability of the spacecraft. The desire for a land landing capability lead NASA to task the Langley Research Center to investigate potential systems under the Landing System Advanced Development Program. As part of this program Airborne Systems has been under contract since February 2006 to demonstrate the application of airbags to land the Orion CM. This paper discusses the design, development and analysis of a nominal land landing airbag landing system (ALS) for the Orion CM.

II. Airbag Landing System Development Overview

The ALS has undertaken the following development path:

- Concept Development to Generation 1 (Gen1) Flight System Design
- Generation 1 Prototype Drop Testing
- Generation 1 Prototype Inflation Testing
- Generation 2 (Gen2) Flight System Design
- Generation 2 Drop Testing

This section will briefly discuss the Gen 1 activities, and the following section will describe in more detail the Gen 2 ALS design and testing results.

The objective of the Gen 1 conceptual design and testing phase was to demonstrate the capacity of an airbag landing system to perform the role of landing the Orion CM safely back on Earth. In addition to establishing the technical credentials of an airbag landing system, it was crucial to demonstrate a capability to accurately predict and simulate the dynamic landing event. Clearly, not all potential landing scenarios could be tested so a high level of confidence would be required in the method selected to predict system performance over the entire landing envelope. The transient dynamic finite element code LS-DYNA[2] was selected to simulate system performance throughout this program. LS-DYNA has an impressive series of features that enable both fabrics and dynamic impact events to be accurately modeled.

During the Gen 1 phase LaRC was also considering several alternative technologies for the CM landing system; a propulsive (retro-rocket) system, a deployable crushable panel system, and a deployable landing gear system were all potential solutions. The conceptual design resulting from the Gen 1 development and analysis cycle is depicted in Figure 2. The conceptual design configuration comprised six individual airbag assemblies with each assembly containing four core components:

- A primary impact, main venting airbag
- A non-venting, anti-bottoming airbag
- A main venting airbag internal shaping structure, patent pending
- A fast acting, low leak rate active vent, patent pending

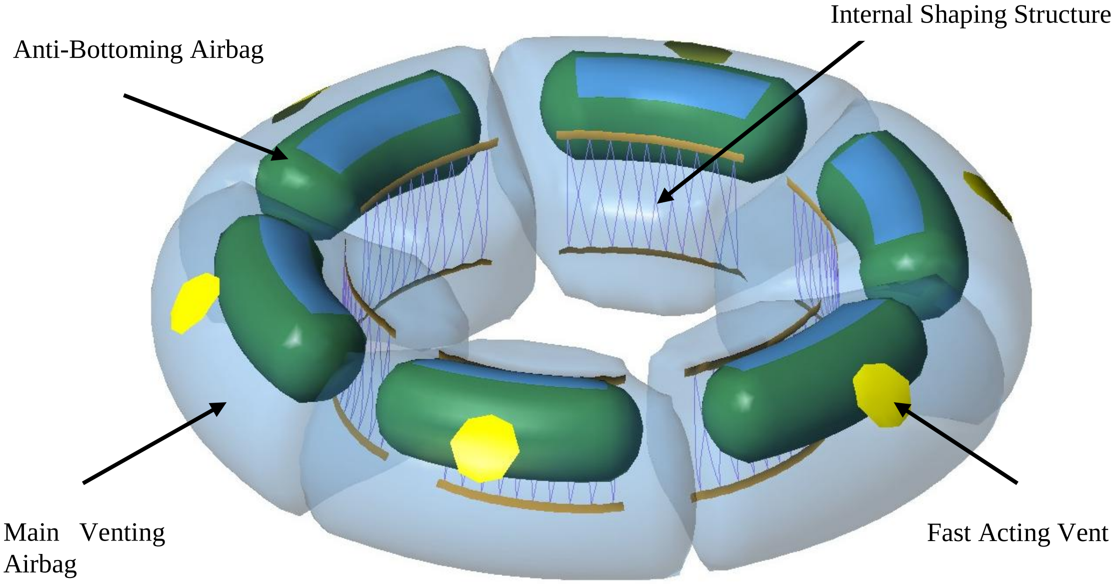


Figure 2: Gen 1 Conceptual ALS Design

Gen 1 airbag system testing included a series of 8 drop tests, and an extensive series of packing and inflation tests.

The Gen 1 drop testing was conducted at the Landing and Impact Research (LandIR) Facility at NASA LaRC, Figure 3. At the time of testing the facility was not certified to test the full-scale CM weight. To maintain schedule, a full-scale, half mass flat-bottomed Airbag Research Plate (ARP), also referred to as Boilerplate 3 (BP3), was used as the test vehicle.

The conceptual airbag design was modified to integrate with the test vehicle; airbags were shaped to conform to the flat-bottomed BP3 shape, two airbag assemblies were located at the front and a single assembly at the rear of the test vehicle, and the orifice in each of the venting airbags was standardized (BP3 did not have an off-center CG, unlike the CM). Additionally, the airbags were fabricated from inventory material; polyurethane coated Kevlar.

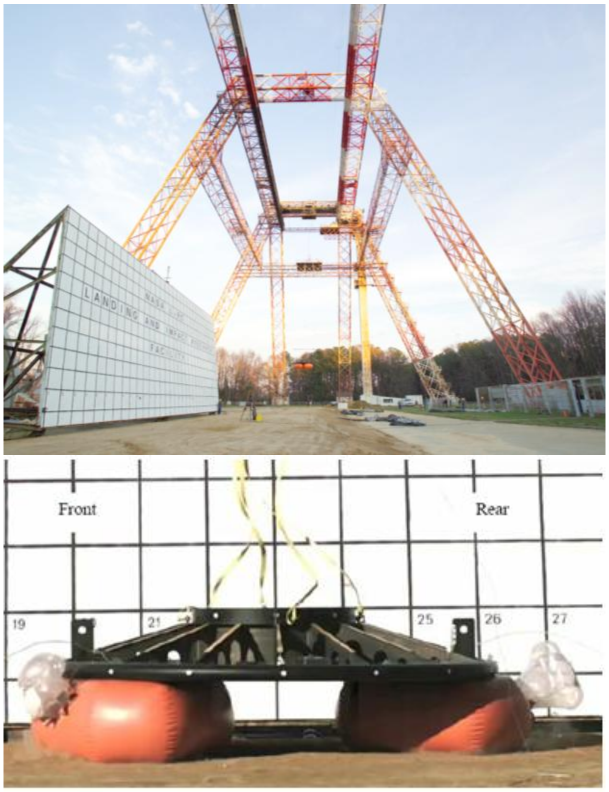


Figure 3: NASA LaRC LandIR Facility, and ARP

Gen1 drop testing started in December 2006 and finished in June 2007. Table 1 documents the drop testing undertaken for Gen 1. The testing provided invaluable data concerning system performance for a broad range of landing scenarios; 3-parachute cluster landings in no wind and in high speed winds, 2-parachute cluster rate of descent (simulating a parachute failure), and both toe-in and heel-in CM pitch orientation (simulating oscillation under the parachutes). All 8 drop tests resulted in a crew and CM survivable landing; CM accelerations were as expected and no roll-overs. Airbag damage was observed in several attachment locations during the high horizontal velocity landing scenarios, this will be discussed further in the Gen 2 section of the paper.

Drop Test #	Test Article / Surface	Facility / Date	Vertical Velocity (ft/s)	Horizontal Velocity (ft/s)	Pitch Angle	Roll Angle	Yaw Angle
1	BP3 Soil	LandIR Dec 5, 2006	25	0	0	0	0
2	BP3 Soil	LandIR Dec 7, 2006	25	20	0	0	0
3	BP3 Soil	LandIR Dec 12, 2006	25	40	0	0	0
4	BP3 Soil	LandIR Dec 15, 2006	25	40	0	0	0
5	BP3 Soil	LandIR May 24, 2007	32	0	0	0	0
6	BP3 Soil	LandIR May 31, 2007	25	0	10 Toe-in	0	0
7	BP3 Soil	LandIR June 7, 2007	25	20	10 Toe-in	0	0
8	BP3 Soil	LandIR June 11, 2007	25	40	10 Heel-in	0	0

Table 1: Gen 1 Drop Testing Matrix

In addition to drop testing, a series of stowage and deployment tests were conducted. The objective of these tests was to demonstrate the method used to pack and retain the airbag assemblies in the stowed condition, the volume and shape of the stowed airbag, and demonstrate functionality after deployment. During pad abort scenarios the airbag system could be required to deploy, inflate, and attenuate ground impact within 30 seconds.

A single airbag assembly (the prototype developed prior to drop testing) was used to demonstrate the requirements for this task. A simple inflation system was developed to replicate the system proposed during the conceptual design phase.

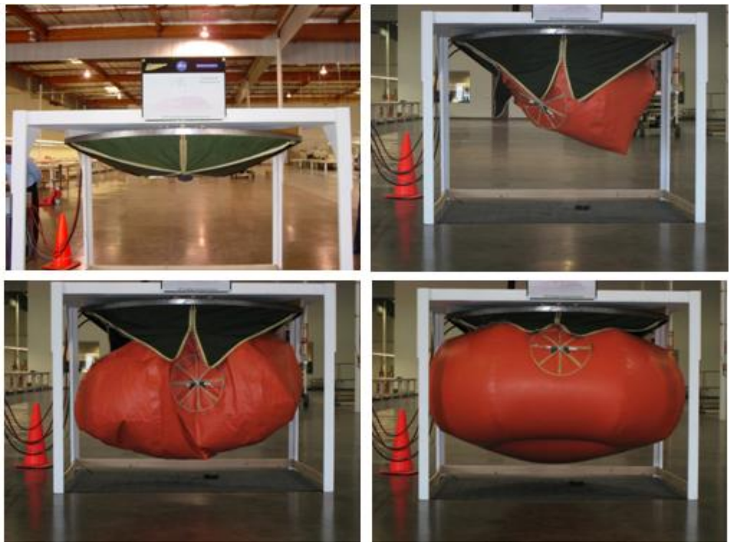


Figure 4: Rapid Inflation Testing

The inflation system comprised a combination of an aspirator fed by pressurized nitrogen, and just high pressure nitrogen. This class of inflation system was shown to be the most mass efficient during the conceptual design phase. The aspirator enables ambient air to be used to inflate the large volume airbags, and reduces the mass of gas required onboard the CM. Aspirator efficiency drops rapidly at pressures above 2 psig, at which point the aspirator is isolated and high pressure nitrogen is used to top-off the airbags to the required pressure.

Figure 4 illustrates four frames from the video of a rapid inflation test. It was demonstrated that the airbag assembly (main and anti-bottoming airbags) could be deployed and inflated within 20 seconds. The presence of a safety pressure regulator in the inflation system did not allow a faster inflation time. Post-test analysis indicated the inflation time could have been dropped to 10 seconds if the regulator had been removed or resized.

Throughout the test electrical connectivity was monitored in a representative pyrotechnically actuated cutter attached to the main airbag vent. The continuous connectivity observed in the wire harness demonstrated that the airbag was still functional following the stowage and deployment process.

Subsequent to the rapid inflation testing conducted at the Airborne Systems facility in Santa Ana California, the airbag assembly and inflation system was used to demonstrate similar performance in the vertical wind tunnel at NASA LaRC. The wind tunnel testing validated system deployment and inflation at a freestream dynamic pressure representative of a single parachute failure rate of descent.

Following the successful drop testing and rapid inflation testing the airbag landing system design was progressed into a Gen 2 phase.

III. Generation 2 Airbag Landing System Development

The Gen 2 ALS design was largely based upon the successful Gen 1 design. The 6 airbag assembly configuration, illustrated in Figure 5, retains the 4 core components from the Gen 1 system; a main venting airbag, a non-venting anti-bottoming airbag, a main airbag internal shaping structure, and the fast acting, low leak rate active vent.

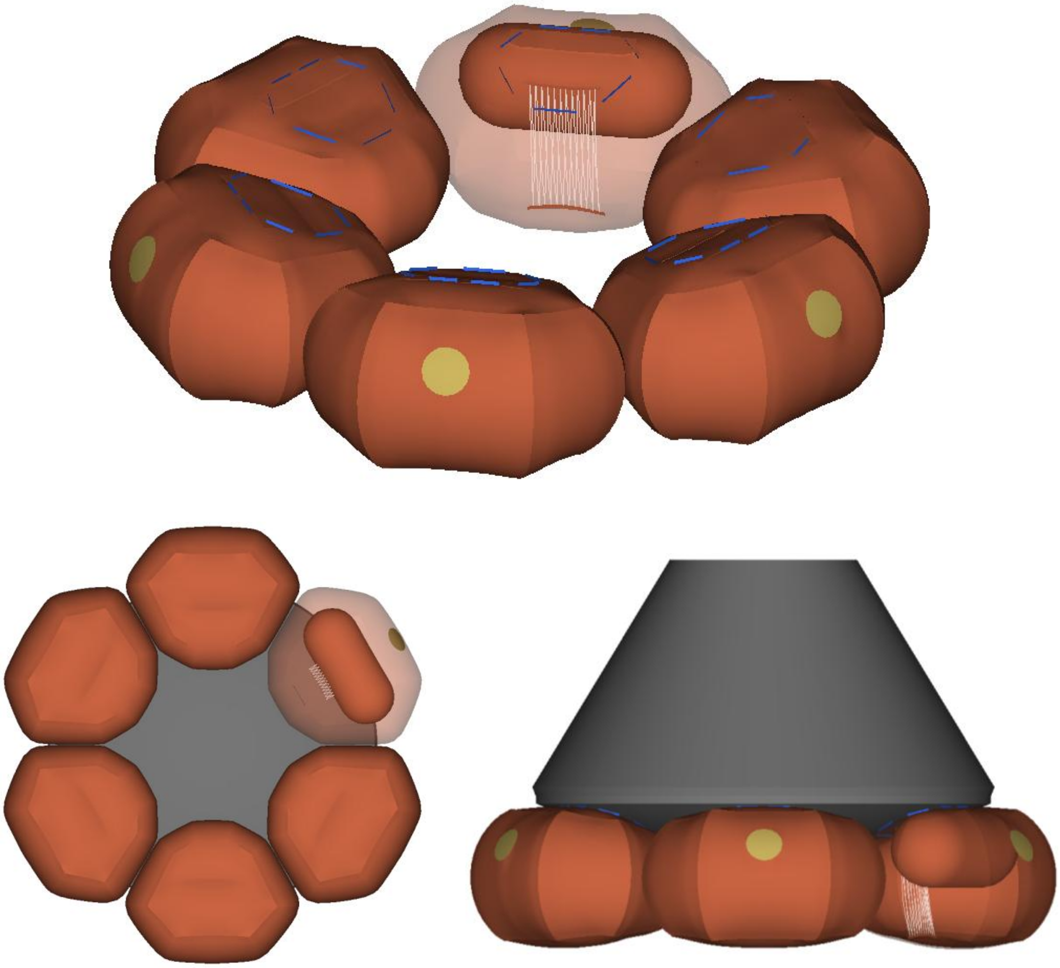


Figure 5: Gen 2 Airbag Configuration

The primary role of the main-venting airbags is to decelerate the CM. The main airbags are sized to provide sufficient stroke to decelerate the CM and maximize the contact area with the CM structure. The height of the airbag is predominantly based upon providing sufficient stroke for the parachute failure vertical velocities and minimizing rebound velocity for a nominal landing scenario. Maximizing the airbag/CM contact area minimizes the pressure applied to the base of the CM during the primary impact stroke. These features, in combination with the vent size and vent trigger pressure, are tailored to ensure deceleration levels are within the specified limits.

The main airbags extend beyond the outer mold line (OML) of the CM to improve pitch and yaw stability during the primary landing stroke. This feature is particularly important when the CM exhibits pitch and yaw departures in a high crosswind landing environment. As the vehicle contacts the ground during these scenarios, the capsule begins to pitch/yaw and the portion of the airbag that extends beyond the CM conforms to the OML and provides a restoring moment.

Another key feature of the main airbags is that they were designed to conform to the curved shape of the aft bulkhead. This attribute was incorporated into the design for two reasons-

- Shaping the airbags to conform to the CM generates a more efficient deceleration stroke. Alternative airbag shapes must first deform to the shape of the CM before they can provide a decelerating force. By shaping the airbags we ensure that the entire airbag stroke is used to decelerate the CM. This approach ensures that the shortest possible stroke is realized. A shorter airbag stroke correlates to a smaller moment arm between the ground and CG during the impact sequence, which is highly beneficial during crosswind landing scenarios.
- The second benefit of the shaped airbags is that they enable improved positioning of the airbag under the aft bulkhead. This design produces a large airbag surface area which is in close proximity to the aft bulkhead structure. This enables the attachment locations to be spread out over a broader area and can therefore provide a tight and stable connection between the airbag and bulkhead.

The role of the non-venting anti-bottoming airbags (AB airbags) is to protect the aft bulkhead from ground impact, and prevent the CM from rolling over. The airbag size originates from the requirement to maintain a minimum dynamic ground clearance of 8 in during the nominal landing scenarios. The particular cases within this group that drive the airbag diameter are those incorporating a 3 sigma high vertical velocity. The size was then marginally increased to account for the main airbag failure landing scenarios where the primary impact is taken by the AB airbag inside the failed main airbag.

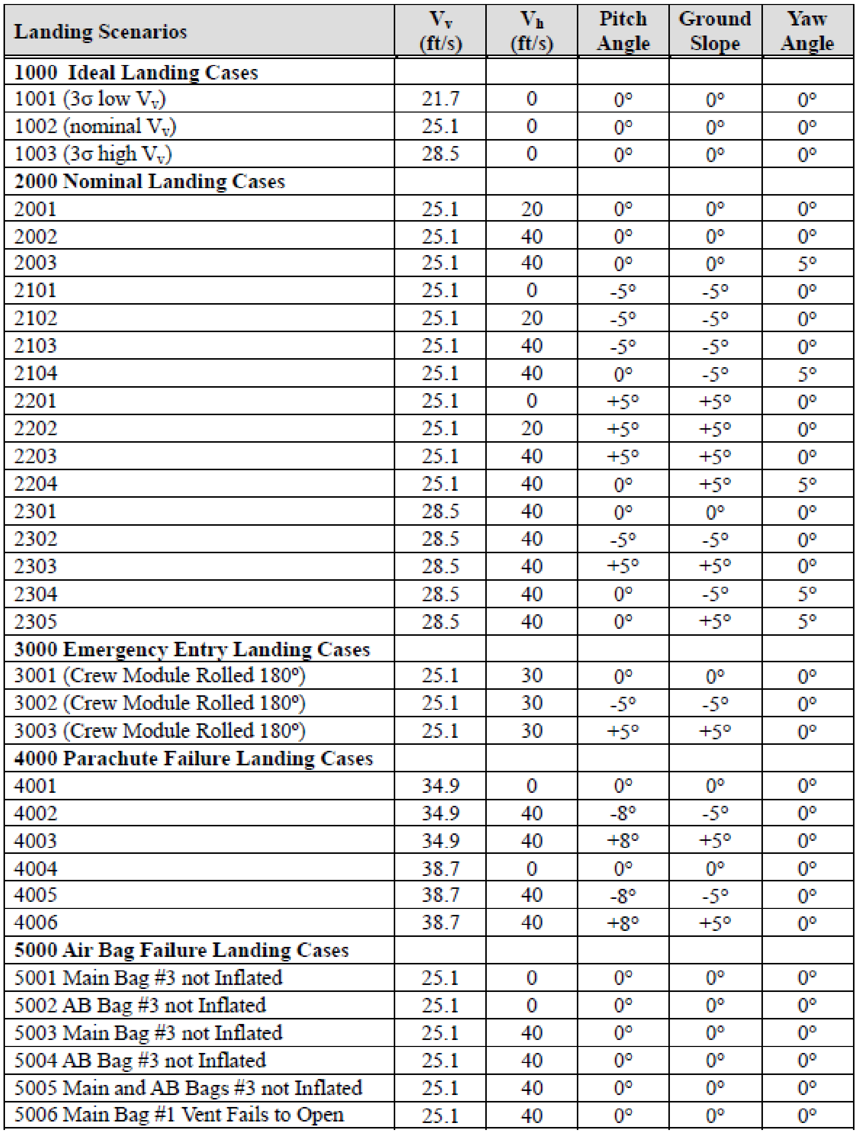
Perhaps the primary consideration in the design of the AB airbags was an efficient pressure vessel shape; the AB airbags have to withstand peak pressures in excess of 30 psig for the more exotic parachute failure landing cases. An inefficient shape would require heavier material to withstand the same fabric stresses. Another key design feature was integration into the main airbag, more specifically: the AB airbag had to perform without detracting from the performance of the main airbag. In addition, the requirement for a successful landing if a single AB airbag failed dictated that adjacent airbags are capable of providing sufficient redundant protection. The resulting AB airbag shape was a cylindrical body with hemispherical endcaps. The location of the airbags, at the perimeter of the CM, is driven by the requirement to protect the aft bulkhead during the landing sequence. Locating the airbags as far outboard as possible enables protection of the entire bulkhead during maximum pitch orientations and crosswind scenarios. This placement of the AB airbags also establishes a flat bottomed system with as wide and stable a base as possible.

The internal shaping structure is integrated into the main airbag to maximize stroke efficiency by pre-deforming the airbag. This design feature results in two key performance enhancements:

- The reduction in airbag height also reduces the propensity for CM roll-over during high crosswind velocities by effectively reducing the system CG location
- The shaping structure also enables more control over the positioning of each airbag assembly by producing a more stable airbag assembly shape. This results in a more repeatable airbag positioning post deployment and inflation.

Venting of the main airbags is achieved through an active pressure-based vent. The venting sequence is as follows:

- Following deployment and full inflation, pressure transducers, connected to each of the main venting airbags, continually monitor control volume pressure.
- When the pressure in a single main venting airbag exceeds 3.5 psig for a cumulative time of 2 ms (to eliminate spurious data) an electrical signal is sent to the dual pyrotechnically-actuated cutters located at the vent assembly of that specific airbag.
- The two cutters (only one required for successful operation) sever the retaining loop, allowing the vent to open and discharge the entrapped gas.



Landing Scenarios	V_v (ft/s)	V_h (ft/s)	Pitch Angle	Ground Slope	Yaw Angle
1000 Ideal Landing Cases					
1001 (3σ low V_v)	21.7	0	0°	0°	0°
1002 (nominal V_v)	25.1	0	0°	0°	0°
1003 (3σ high V_v)	28.5	0	0°	0°	0°
2000 Nominal Landing Cases					
2001	25.1	20	0°	0°	0°
2002	25.1	40	0°	0°	0°
2003	25.1	40	0°	0°	5°
2101	25.1	0	-5°	-5°	0°
2102	25.1	20	-5°	-5°	0°
2103	25.1	40	-5°	-5°	0°
2104	25.1	40	0°	-5°	5°
2201	25.1	0	+5°	+5°	0°
2202	25.1	20	+5°	+5°	0°
2203	25.1	40	+5°	+5°	0°
2204	25.1	40	0°	+5°	5°
2301	28.5	40	0°	0°	0°
2302	28.5	40	-5°	-5°	0°
2303	28.5	40	+5°	+5°	0°
2304	28.5	40	0°	-5°	5°
2305	28.5	40	0°	+5°	5°
3000 Emergency Entry Landing Cases					
3001 (Crew Module Rolled 180°)	25.1	30	0°	0°	0°
3002 (Crew Module Rolled 180°)	25.1	30	-5°	-5°	0°
3003 (Crew Module Rolled 180°)	25.1	30	+5°	+5°	0°
4000 Parachute Failure Landing Cases					
4001	34.9	0	0°	0°	0°
4002	34.9	40	-8°	-5°	0°
4003	34.9	40	+8°	+5°	0°
4004	38.7	0	0°	0°	0°
4005	38.7	40	-8°	-5°	0°
4006	38.7	40	+8°	+5°	0°
5000 Air Bag Failure Landing Cases					
5001 Main Bag #3 not Inflated	25.1	0	0°	0°	0°
5002 AB Bag #3 not Inflated	25.1	0	0°	0°	0°
5003 Main Bag #3 not Inflated	25.1	40	0°	0°	0°
5004 AB Bag #3 not Inflated	25.1	40	0°	0°	0°
5005 Main and AB Bags #3 not Inflated	25.1	40	0°	0°	0°
5006 Main Bag #1 Vent Fails to Open	25.1	40	0°	0°	0°

Table 2: Gen 2 ALS Landing Scenario Matrix

The design and analysis of the airbag system was a continual closed loop process, with LS-DYNA being used to both design and then analyze system performance. Fabric running loads and attachment strength requirements were also derived from the LS-DYNA models.

An initial design was assessed and enhanced based upon the results of a landing matrix of 60 scenarios. This matrix included nominal landings, emergency entry landings, parachute failure, and airbag deployment or inflation failure, as shown in Table 2. The airbag system is required to operate successfully throughout all the possible landing scenarios without modification or prior knowledge of that landing scenario.

The Gen2 CM landing conditions were biased to have a predominantly leading CG location. This reflects a feet first landing for the astronauts and is achieved by utilizing roll control motors. This preferred landing orientation in turn lead to a small biasing of the main airbag design. The biasing is only minimal because the landing system is also required to successfully protect the CM and crew during emergency landing scenarios when directional control is not available.

Several options were available to the designer to bias the design of the main airbags to account for the preferred landing orientation: airbag shape, airbag pressure, venting pressure, and vent area. In addition, it is highly likely that any of these techniques would result in a stronger heavier fabric being required for the leading airbags compared to the trailing airbags.

It should be noted that the biasing built into the main airbag design had to fulfill two tasks-

- The first being to nullify the influence of the offset CG location; this alone is the most prominent task at zero and low horizontal velocity landing scenarios. For such landings the influence of the preferred landing orientation is minimal.
- The second task is to eliminate ground impact and rollover during high horizontal velocity landing cases. the leading CG location makes this more challenging. These scenarios require the leading airbags (#3 and

#4) to provide an increased resistance to rollover, and the trailing airbags (#1 and #6) to impart minimal pro-rollover moment.

The method used to achieve these two goals was to have differing vent areas in the main airbags. This decision enabled the shape of all six airbags to remain the same. It also ensured that all six airbags utilize the same initial pressure. The value of the initial pressure, 2 psig, is the result of an exhaustive study during Gen 1 that evaluated the onset rate of the ground impact as a function of initial airbag pressure, and also considered the efficiency of the aspirator class of inflation system. The other possible variable, venting pressure, was discarded due to the sensitivity of this variable to time delays in the venting process. This effect is most evident during high horizontal velocity landing cases which involve large relative angles between the CM and ground plane. In these scenarios the leading or trailing airbags, depending on the direction of the relative angle, reach and then exceed the venting pressure rapidly. The pressure in the airbags will continue to rise during the venting process as the volume changes more quickly than the gas can escape. In these scenarios a small delay in venting pressure can result in large dynamic effects for the CM.

Figure 6 illustrates the airbag numbering scheme, the horizontal velocity vector for the nominal, parachute failure and airbag failure landing scenarios, and the relative location of the CM CG.

Table 3 details the nominal inflation pressure of both the main and anti-bottoming airbags, the main airbag venting pressures, and the vent areas used to achieve the biased behavior.

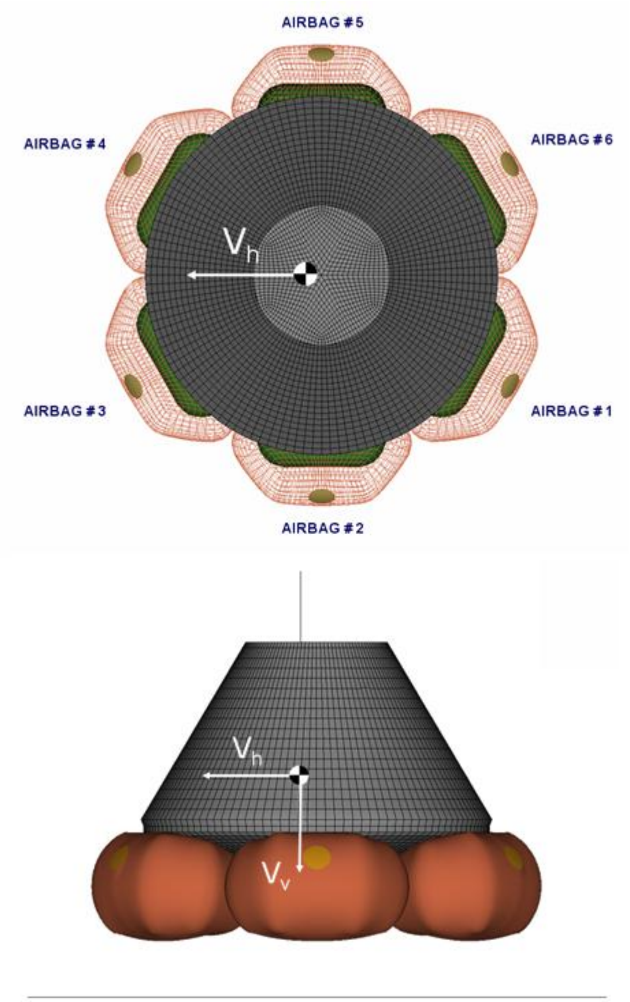


Figure 6: Gen 2 Airbag Numbering and System Definition

Airbag Location	Main Airbag Inflation Pressure (psig)	Anti-Bottoming Airbag Inflation Pressure (psig)	Main Airbag Venting Pressure (psig)	Main Airbag Vent Diameter (in)
1	2	7	3.5	14.4
2	2	7	3.5	13.6
3	2	9	3.5	13.2
4	2	9	3.5	13.2
5	2	7	3.5	13.6
6	2	7	3.5	14.4

Table 3: Gen 2 Airbag Pressure and Vent Description

Figure 7: ALS Operational Sequence

Figure 7 details the operational sequence of the nominal land landing airbag landing systems. The CM would be under a cluster of 3 fully open parachutes at an altitude of 5,000 ft AMSL, at between 2,000 and 1,000 ft the heatshield would be jettisoned, and this function would initiate airbag system deployment and inflation.

The projected mass of the ALS has remained fairly constant throughout both the Gen 1 and Gen 2 design phases. The total Gen 2 system mass was projected to be 136 lbm. This mass does not include the inflation system, heatshield jettison device, any additional CM structure, or additional fuel needed to be carried to extend flight path over land. It should be noted that the Gen 2 phase did not include provisions for developing an inflation system, the mass of the conceptual inflation system defined under Gen 1 was projected to be 96 lbm.

IV. Gen 2 Airbag Fabrication and Drop Test Set-up

Once the airbag landing system design had matured and stabilized the LS-DYNA model was used to generate the airbag patterns. This technique ensured the fabricated airbag was as close to the analyzed geometry as possible. An iterative step was included that took the final flat patterns and reconstructed the airbags to further ensure the appropriate geometry was being fabricated. Figure 8 displays a Gen2 main airbag flat pattern.

The Gen 2 airbags were fabricated from a polyurethane coated Vectran® fabric and assembled using radio-frequency welding.

The flat patterns was used to develop the most appropriate fabric usage, minimizing the number of seams and welds, and ensuring the location of the seams were in the most efficient location and direction. Perhaps the most challenging aspect of the airbag fabrication was identifying a suitable means of testing the attachment configurations. An attachment is defined as either the attachment between the airbag assembly and the CM/BP or between the main and anti-bottoming airbags. Both of these attachments would be highly loaded during the impact sequence and would be required to transfer and dissipate energy between the rigid CM and the ground. A dynamic means of testing these attachment techniques was not available prior to the drop testing so the design drew heavily from past systems and some limited static testing.

Both attachments utilized a grommet and lacing technique to distribute landing loads into the airbag fabric. Nylon cord was laced between grommets on fabric strips attached to the BP and the airbag assembly. Nylon was chosen for the lacing cord due to its elongation characteristics. Seven independent fabric strips were used to attach each assembly to the BP, this offered several layers of redundancy, and also simplified the test integration processes.

Prior to the commencement of the Gen 2 drop testing a dual pendulum control configuration was incorporated into the LandIR facility at NASA LaRC. The dual pendulum configuration improved the repeatability and control of the landing scenarios.

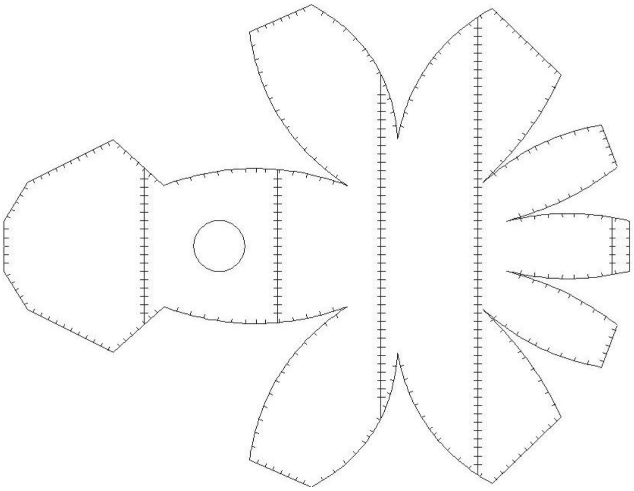


Figure 8: Gen 2 Airbag Flat Pattern

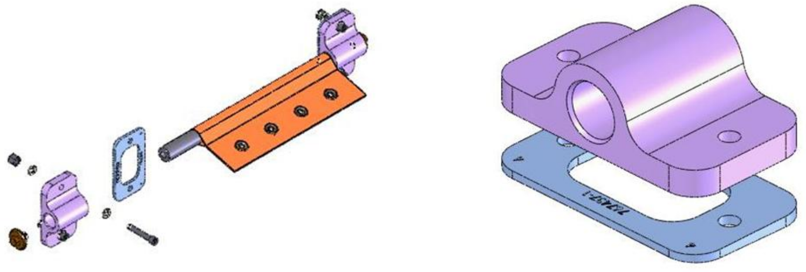
The drop test configuration and landing scenario of the Gen 2 ALS varied from the proposed flight system in a number of ways-

The airbag fabric proposed for the Gen 2 system was a polyurethane coated Vectran® whose strength and weight was dependent on the location of the airbag on the CM. It was also a single use fabric; its design did not include a factor for reuse. The material selected to fabricate all six main and AB airbags for this series of drop tests was a polyurethane coated Vectran® rated at 1660 pounds per linear inch (pli) in the warp direction, and 1440 pli in the fill direction. This fabric was selected and procured prior to the Gen 2 design process based on preliminary analysis and experience from Gen 1. This decision facilitated the landing system development schedule.

The attachment hardware fabricated for testing was based upon the design that successfully completed Gen 1 testing, Figure 9. In addition to this test heritage, the design was chosen for the following reasons-

- Integration with the test fixture
- Cost and schedule
- Ease of assembly and disassembly during test series

The attachment hardware was not indicative of attachment hardware used for a flight system. Flight system attachment hardware will depend heavily on the structure of the interface between the airbags and the CM. This interface was not sufficiently defined during the airbag design phase to identify flight system capable attachment hardware.



Gen 2 Test Hardware

Gen 2 Clevis and Spacer (Test)

Figure 9: Drop Test Specific Attachment Hardware

During operational performance the CM would be returning to Earth under at least two main parachutes. These parachutes would ensure that the entire system had reached a steady descent rate prior to impacting the ground. The drop testing conditions did not permit the use of a parachute or equivalent structure to generate a steady descent rate prior to impact. All drop tests were therefore conducted with the CM accelerating into the ground. The initial conditions were specified so that the velocities at impact matched those expected during operational performance. It should also be noted that for those drops incorporating a horizontal velocity the vertical acceleration of the CM was less than 1g due to the action of the pendulum cables.

The flight system was developed and designed based on landing on a rigid landing surface. At the time, many options were still available for the landing site and no material models had been developed to described the nature of the landing media. Following the ALS design phase, NASA defined a series of LS-DYNA MAT5 material models for a variety of potential landing surfaces. Subsequently, ASNA conducted LS-DYNA simulations to assess the performance of the proposed flight system for those potential landing surfaces. However, the ALS design fabricated for testing was developed based on a rigid landing surface.

V. Gen 2 Airbag Landing System Drop Testing

Gen 2 ALS drop testing was conducted at the LandIR Facility between February and October of 2008. Table 4 details the 7 tests conducted. BP4 was used throughout this test series. The mass of BP4 with instrumentation and airbags was 15,990 lbm, this represented the full-scale mass of the CM at ground impact. A single airbag ship set was used for Drop Tests 1 through 6, and a second set was used for Drop Test #7. Instrumentation, control systems and attachment hardware were reused for each test. Prior to each drop test system checks were performed to verify electrical connectivity and data synchronization, and to monitor airbag leak rates.

Drop Test #	Test Article / Surface	Facility / Date	Vertical Velocity (ft/s)	Horizontal Velocity (ft/s)	Pitch Angle	Roll Angle	Yaw Angle
1	BP4 Soil	LandIR Feb 7, 2008	25	0	0	0	0
2	BP4 Soil	LandIR Feb 29, 2008	25	0	10 Toe-in	0	0
3	BP4 Soil	LandIR Apr 18, 2008	25	20	0	0	0
4	BP4 Soil	LandIR May 6, 2008	25	20	0	0	0
5	BP4 Soil	LandIR May 15, 2008	25	20	0	0	0
6	BP4 Soil	LandIR June 4, 2008	25	40	0	0	0
7	BP4 Soil	LandIR Oct 15, 2008	22	35	0	0	0

Table 4: Gen 2 Drop Testing Matrix

Gen 2 drop testing generated copious volumes of test data; pressure transducers recorded airbag pressures, tri-axial accelerometers were placed in several locations throughout the BP, rate sensors were positioned at the CG to monitor rotational velocities, and 5 high speed video cameras were used for photogrammetry purposes. This data provided a wealth of knowledge and enabled the airbag system performance to be investigated on numerous levels.

Figure 10 provides the airbag numbering sequence, coordinate system definition, and horizontal velocity direction.

This paper is intended as a top level summary of the overall program, and as such will not go into detail for every test. However, an example of the analysis undertaken for each test, and comparisons of model prediction and test data have been included.

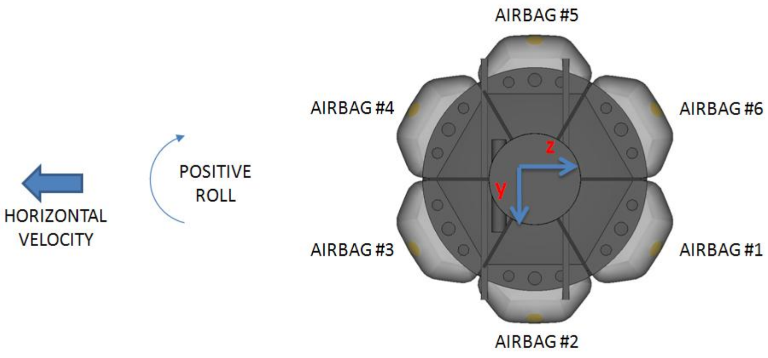


Figure 10: Gen 2 Test Configuration Definition

Figure 11 presents the BP accelerations recorded at the CG for Drop Test #1. The key events are annotated in the figure. Maximum acceleration was in the CM x-axis, as expected, and reached a peak of almost 8.0 g. This was also the maximum acceleration recorded in any single direction throughout the entire drop test series.

Raw accelerations were filtered using an SAE J211 filter at 30 Hz. The filtering frequency was selected following a Fast Fourier Transform (FFT) analysis of the raw accelerations. The pyrotechnic process used to release the BP from the pendulum cables induced significant noise into the system, as seen in Figure 11.

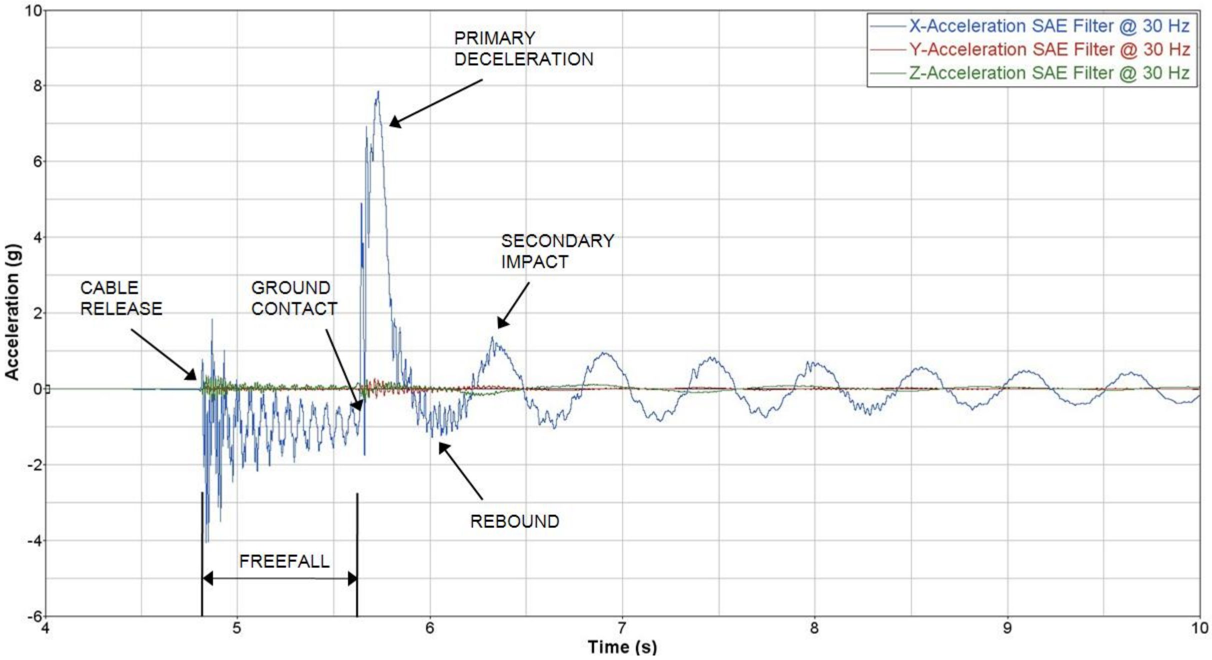


Figure 11: Drop Test #1, BP CG Translational Accelerations

Figure 12 presents the airbag pressure time history data for both the main and anti-bottoming airbags for Drop Test #1. As discussed above, no parachute force was present in the drop testing set-up, this caused the BP to accelerate into the ground during the drop test sequence. This represented a departure from operational use as the parachutes would remain attached to the CM during the impact sequence until they are jettisoned post-landing.

It was therefore expected that the main airbags would not dissipate all the kinetic energy during the drop tests, and that the BP would retain some energy when impacting the anti-bottoming airbags. This characteristic can be seen in the pressure traces shown in Figure 12.

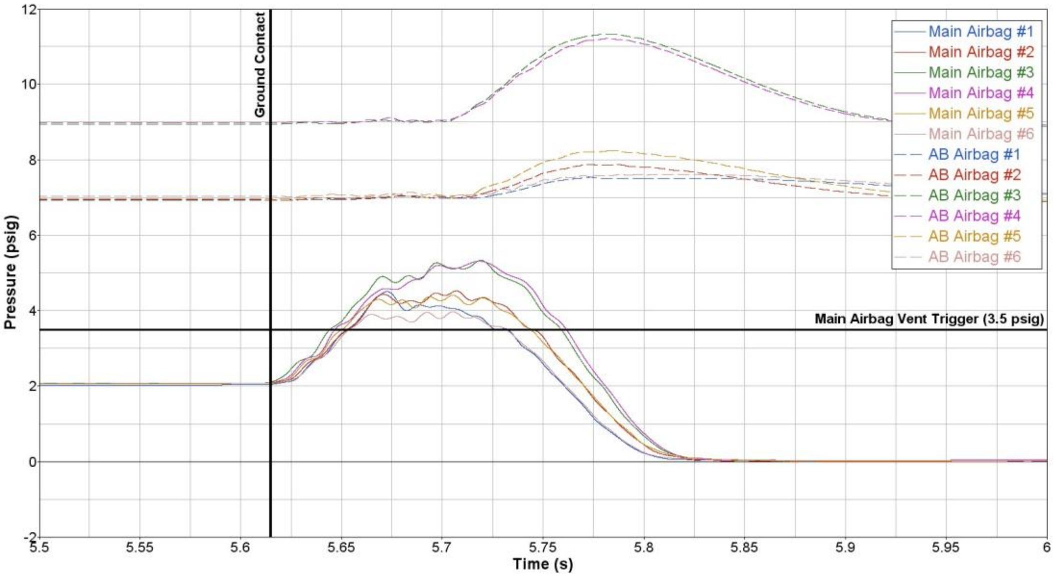


Figure 13: Drop Test #1, Airbag Pressures

Figure 13 displays the LS-DYNA model of the boilerplate and ALS. This model was used in conjunction with a MAT5 LS-DYNA soil material model, developed by NASA to simulate the soil conditions at the LandIR Facility, to provide simulation predictions of the drop test scenarios.

Figure 14 presents a comparison of CG x-axis acceleration from the test and the LS-DYNA model. The data compares well in both the magnitude and period of the acceleration.

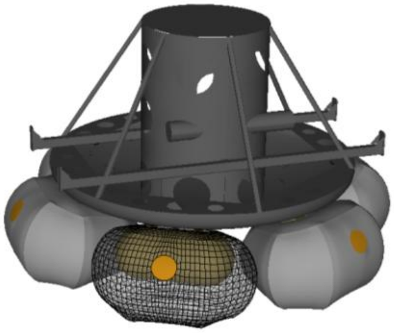


Figure 12: LS-DYNA Drop Test Model

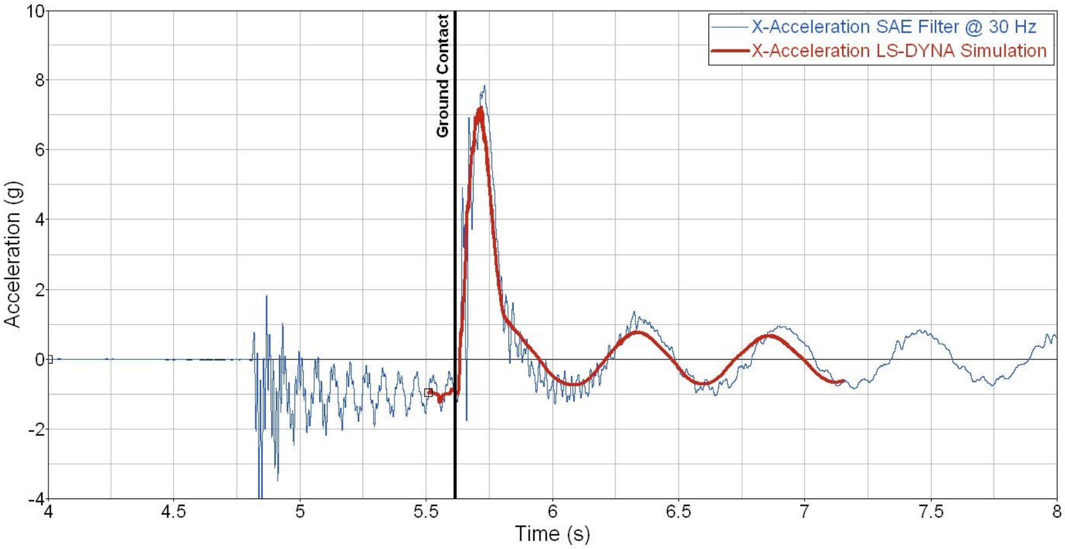


Figure 14: Drop Test #1, Test Data and LS-DYNA Model Correlation

Figure 15 depicts 3 frames from the high speed video during Drop Test #2. This test simulated a relative impact angle of 10 degrees. The figure highlights the independent timing of the venting of each airbag as the BP pitches backwards during the impact sequence.

Figure 15: Drop Test #2, Landing Sequence

Figure 16 presents the x-axis acceleration data correlation between the drop test and the LS-DYNA model.

Drop Tests #1 and #2 were the least challenging of the landing scenarios and involved only vertical velocities.

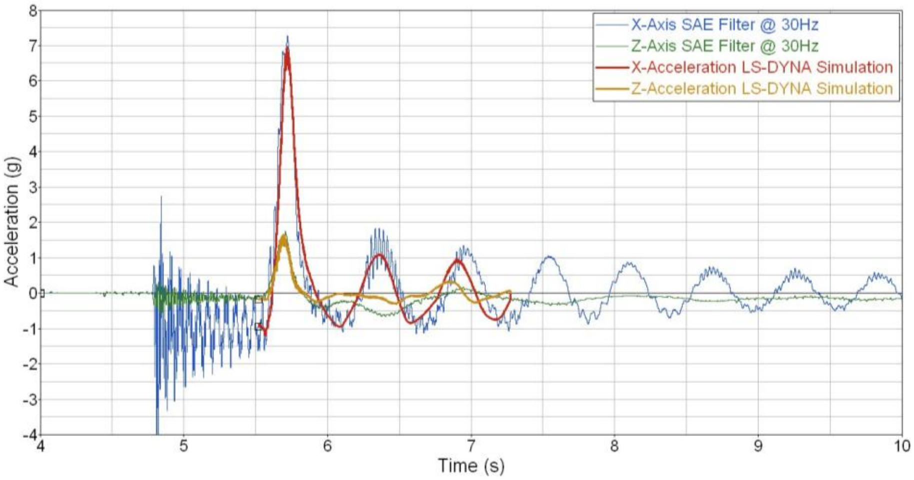


Figure 16: Drop Test #2, Test Data and LS-DYNA Model Correlation

Drop Test #3 was the first test to utilize the new dual pendulum configuration at the test facility. During this test the pyrotechnic cutter arming lanyard did not successfully activate the cutters attached to the vents on each main airbag. This caused the secondary vent initiation technique to become the means of venting. The strength of the vent closure cord was purposely selected to be the weak link in the airbag structure, this ensured that if problems occurred with the test specific electrical system the airbags would vent without compromising the structural integrity of the airbag assemblies.

Drop Test #4 was a repeat of Drop Test #3. Premature venting of main airbag #1 during Drop Test #4 caused the 20 ft/s landing scenario to be repeated again for Drop Test #5. The cause of the premature venting was later identified (following Drop Test #6) as a loose optocoupler in the vent sequencing computer, which lost connection during the impact event. Drop Test #5 was completed without any problems and the ALS produced another safe landing.

Drop Test #6 replicated prevailing wind conditions of 40 ft/s; the most challenging landing scenario. This landing scenario develops extrememly high loads in the airbag attachment fixtures. The airbag assemblies effectively shear out from underneath the BP, being squeezed between the ground and the test vehicle, with only the attachments to distribute this load.

Drop Test #6 produced another crew and CM survivable landing but some damage did occur to the airbag system. Main airbag #6 failed to vent at the appropriate pressure, this generated a moment that pitched the BP further forward than designed. This in turn caused the attachments on the leading edge that connect the front of airbag assemblies #3 and #4 to the BP to become overloaded. As the load in these atachments exceeded their rated strength the leading airbag assemblies were able to roll under the BP. This eventually pulled the airbag hosing out of the anti-bottoming airbags, which caused them to lose pressure. Figure 17 displays main airbag pressure, anti-bottoming airbag pressure and CG accelerations as a function of time, combined with a frame from the high speed video taken at 7.25 seconds.

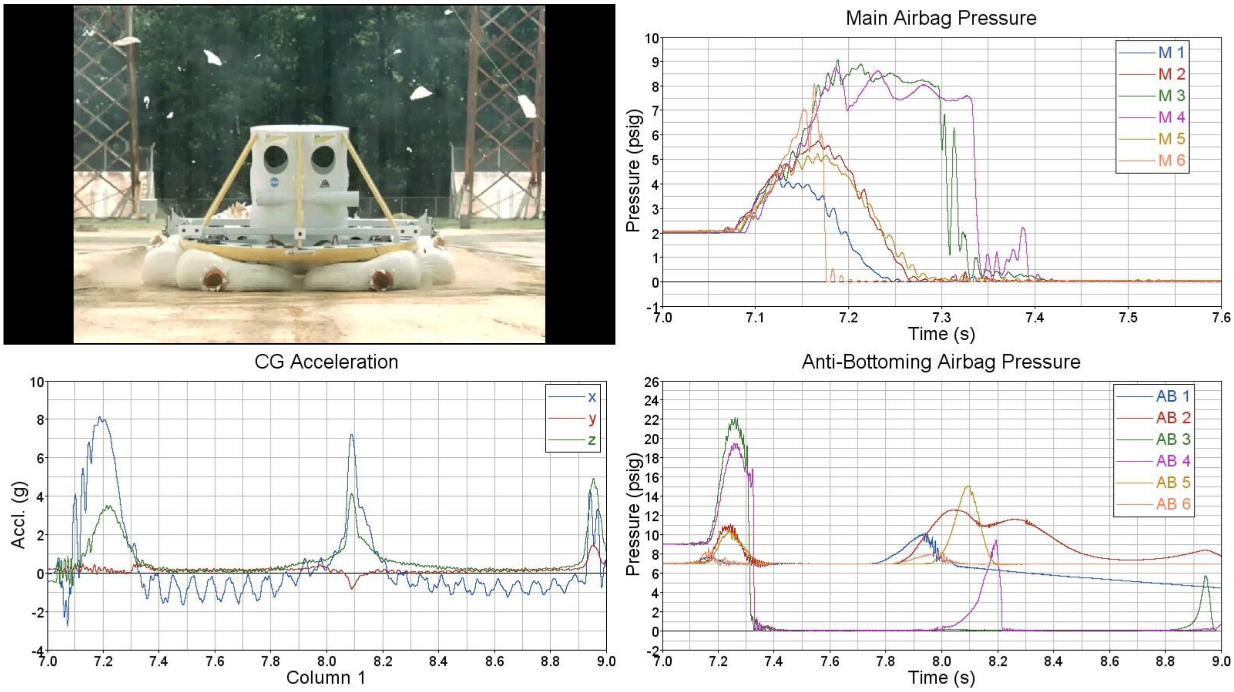


Figure 17: Drop Test #6, Data Synchronization

Modifications were made to the attachments on the second airbag ship set to mitigate similar damage for the final drop test. The second ship set had already been manufactured and delivered to LaRC so only non-intrusive modifications could be made to the airbag assemblies. Cost and schedule, as well as technical requirements did not justify a more complete modification.

Impact velocities for Drop Test #7 were reduced to account for the absence of the parachute force. Once again the ALS produced another crew and CM survivable landing with translational and rotational accelerations well within the requirements. However, more damage was observed in the main airbags. This damage was focused around the vents on main airbags #3 and #4 and was likely caused by a combination of the landing scenario and an artifact of using the new airbag ship set.

During the swing sequence and the post cable release event the BP attained significant pitch, yaw, and roll rotational velocities. The BP impacted the ground with a pitched up orientation and over 5 degree roll and yaw angles. This generated a landing event that was not expected and for which the ALS test configuration had not been designed.

In addition, the second ship set had not previously been used, this meant that the main airbag orifice had not been reinforced (through several orifice assembly applications) like the previous ship set. A consequence of the BP landing orientation was that the leading main airbags became overloaded around the orifice, which initiated a tear across the front the airbag.

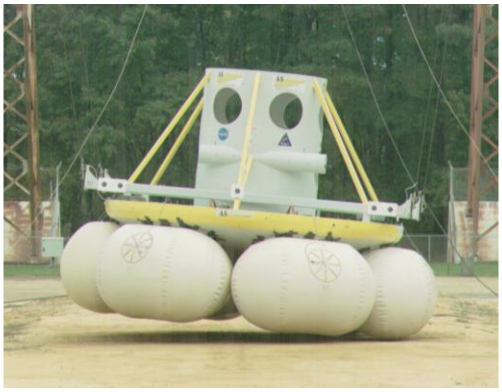


Figure 18: Drop Test #7, BP Impact Orientation

VI. Conclusions

This paper has summarized the successful development and testing of the Airborne Systems Airbag Landing System for the Orion Crew Module. Two series of drop tests comprising a total of 15 tests were conducted at NASA LaRC between December 2006 and October 2008.

All drop tests demonstrated a safe and survivable landing for both the crew and the Crew Module structure. The testing highlighted the robustness of the airbag technology to electrical malfunctions, test set-up issues, airbag damage, and soil conditions.

The drop tests reinforced the airbag landing system primary design driver as being the airbag to Crew Module attachment interface. The baseline attachment configuration was demonstrated to be sufficient for the majority of landings, however it was susceptible to point loading when subjected to the more extreme horizontal velocities (40 ft/s). This point loading resulted in structural damage to the leading edge airbag assemblies during the drop tests, although it did not influence the primary impact attenuation purpose of the airbag. This interface was modified between the penultimate and last drop tests, resulting in an improved load transfer technique between the airbags and the Crew Module. The modifications eliminated the airbag attachment structural damage observed in the penultimate drop test.

The drop test series also identified several areas that did, or could, impact system performance that had previously not been considered as primary design parameters:

- The attachment of the anti-bottoming airbag to the main airbag.

This attachment was considered to be an important component within the overall design although no detailed LS-DYNA analysis was performed to accurately assess the loading environment prior to the drop tests. Knowledge gained from past programs was utilized for the design of this component. It also became apparent that the attachment technique permitted the AB airbag to rotate within the main airbag. This can lead to the location of the AB relative to the main airbag being subject to the pre-impact dynamics of the Crew Module.

- Main airbag vent blockage caused by the internal AB airbag

This issue was considered to be a concern during the initial design process, in part because no analysis technique was available to accurately capture the influence of this blockage on system performance. As a result, the design of the system was purposely guided to minimize the propensity of this blockage to occur. In general the airbag, system performed as expected in this manner and the only blockage of this fashion was observed during Drop Test #7. The boilerplate was subjected to considerable post release rotational velocities during Drop Test #7 causing one AB airbag to rotate outboard and generate significant vent blockage.

In addition to demonstrating a successful landing system for the Orion Crew Module this drop test series generated a wealth of data for model validation purposes. Throughout the design, fabrication, and analysis phases of this program the LS-DYNA models have proven invaluable. In the majority of cases the results and predictions generated by the models have been validated with test data and in some cases have identified inaccuracies or inconsistencies in the test data itself.

The progression of the credibility of the model results and the resulting confidence in the predictions has been almost immeasurable. The evolution in the perception of the modeling results from uncertainty at the beginning of the program to almost taken for granted at the conclusion has been a valuable accomplishment. The modeling techniques conceived, developed, and validated throughout this program will prove beneficial for follow-on work as well as other programs where inflatable impact attenuation systems are applicable.

Acknowledgments

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