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Status of the Development of an Airbag Landing System for the Orion Crew Module

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This paper documents the status of the development of an airbag landing system for the Orion Crew Module. This work was in support of the NASA Langley Research Center LaRC Landing System Advanced Development Project. Airborne Systems (formally Irvin Aerospace Inc) and ILC Dover, originally as competitors and now as partners have developed and tested nominal land landing and contingency land landing airbag systems. 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 provides a brief overview of the work undertaken by Airborne Systems, ILC Dover, and NASA LaRC to develop a nominal land landing airbag system for the Orion Crew Module. The overview will discuss two generations of airbag system design, analysis, and testing; highlighting the evolution of the design and the enhancements made to analysis techniques. It also describes the transition from a nominal land landing system to a contingency land landing airbag system, along with a discussion on the technical and programmatic reasons for this transition. The inclusion of component-level as well as system-level testing in the early design cycles is discussed. The importance of such a process when designing an innovative and unique technology is conveyed as well as the reliance on advances in dynamic finite element analysis. The airbag systems were designed and analyzed using the commercially available transient dynamic finite element code LS-DYNA®.

Nomenclature

2C	=	2 parachute cluster
3C	=	3 parachute cluster
V_v	=	Velocity in the vertical direction
V_h	=	Velocity in the horizontal direction
SS3	=	Sea State 3
SS5	=	Sea State 5
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.

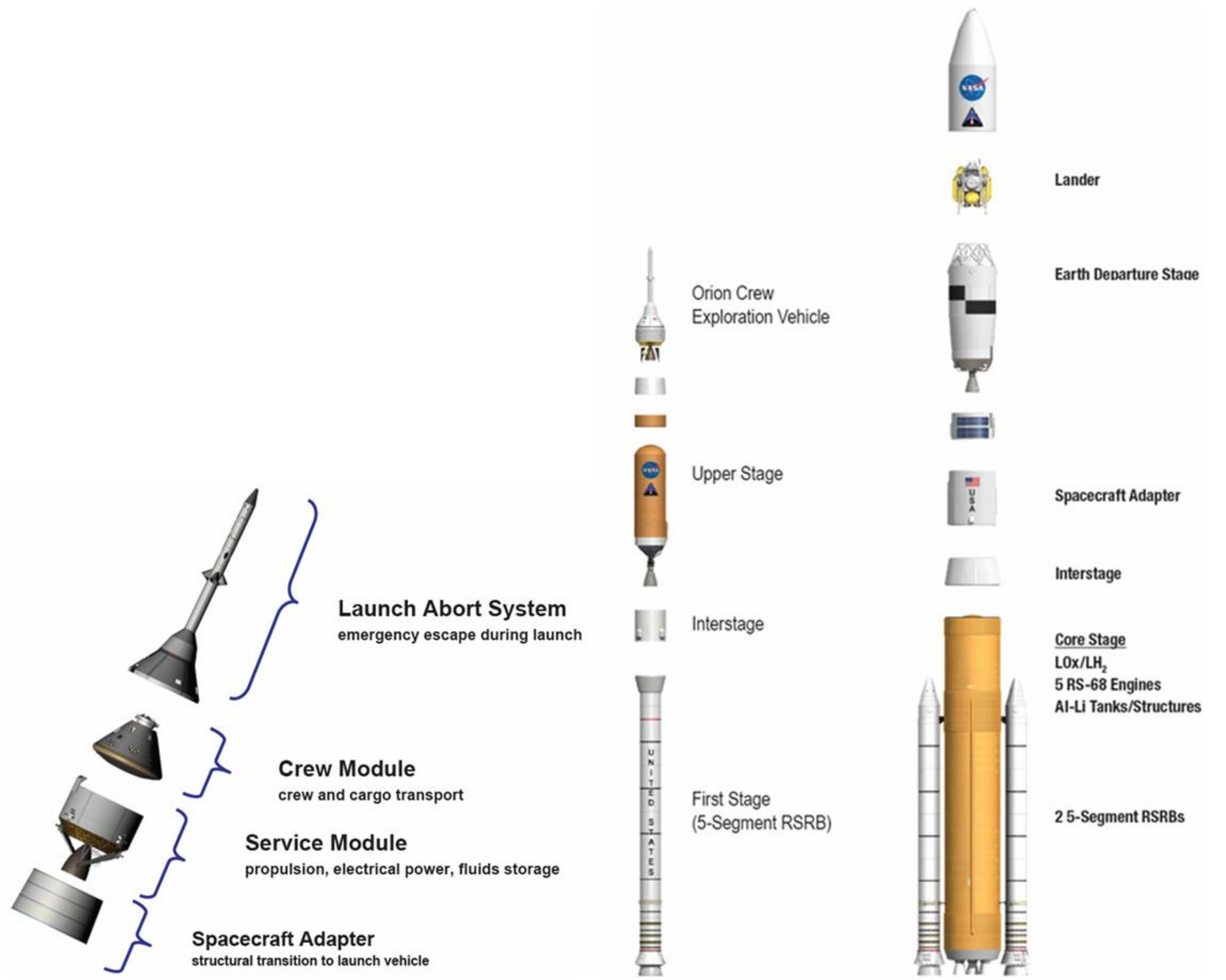

Figure 1: Primary Constellation Program Components

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 Project. As part of this project Airborne Systems and ILC Dover have been under contract since February 2006 to demonstrate the application of airbags to land the Orion CM.

II. Airbag Landing System Development Overview

The Orion Crew Module has followed a variety of paths to find a suitable landing system. This paper will attempt to provide an overview of the phases of this process that relate to airbag system technology.

In 2006, NASA LaRC was tasked to investigate potential landing technologies under the Landing System Advanced Development Project. This evaluation phase considered airbag systems and a variety of potential alternative CM landing technologies; a propulsive (retro-rocket) system, a deployable crushable panel system, and a deployable landing gear system were all potential solutions. Under this task both Airborne Systems North America (ASNA) and ILC Dover (ILC) were awarded Generation 1 (Gen 1) contracts to develop a conceptual Airbag Landing System (ALS) design. Similar contracts were awarded for the alternative technologies. The objective of this initial Gen 1 conceptual design phase was to conceptualize a landing system capable of safely landing the Orion CM on land. The development of such a system would minimize the recurring costs and simplify the associated recovery process and ultimately provide a means of producing a fully reusable spacecraft. The Mercury, Gemini, and Apollo astronauts all returned to Earth via water landings. Each landing required significant naval resources and eliminated the re-use of the capsule.

The ALS has undertaken the following development path:

Nominal Land Landing System

- 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

Contingency Land Landing System

- Airbag Singular Landing Architecture Study
- Prototype Inflation Testing
- Design Optimization, Investigation of Nominal Land Landing Capability
- Fabrication of Drop Test Systems

III. Gen 1 System Development

Throughout the Gen 1 phase of the ALS program ILC and ASNA were effectively in competition. NASA had selected both companies to develop a conceptual design and would evaluate both designs against system requirements. Although both companies developed similar conceptual designs, several key differences did exist between the two approaches. Figure 2 presents the two Gen 1 conceptual designs.

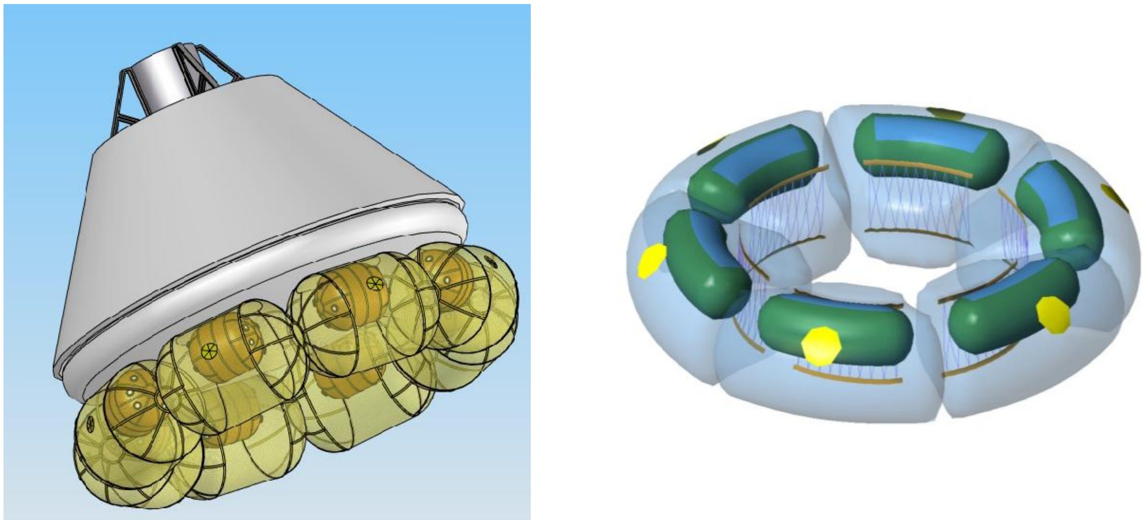

Figure 2: ALS Conceptual Design, ILC left, ASNA right

Both designs incorporated independent airbag assemblies which each comprised a main venting airbag and a permanently inflated internal airbag. This compartmentalization is an inherently redundant design approach which ensures a single component failure will not render the complete system inoperative. The main airbag provides the primary deceleration stroke and the internal airbag ensures ground clearance is maintained. ASNA contended that a six assembly configuration was optimal based on CM integration, total system mass, and fault tolerance. Whereas ILC believed an eight assembly approach was more robust due to the additional fault tolerance.

Both companies proposed an active pressure-based main airbag venting scheme. This venting approach utilizes onboard pressure transducers and a venting sequencer to monitor the pressure in each main airbag and then send an electrical signal to a pyrotechnically actuated cutter located on the appropriate airbag vent. The cutter then severs a retention cord which allows the vent to open and discharge the entrapped gas.

The most significant difference between the two concepts was the initial geometry of the main airbags. Both companies conducted similar trade studies but eventually selected different shapes. ILC selected a ring of horizontal cylinders for the main airbag shape. Horizontal cylinders provide a gradual deceleration onset rate, interface well with the underside of the CM, and build on the heritage of past ILC programs. ASNA selected wedge shaped main airbags that utilized an internal shaping structure. Pre-deformed wedge shaped airbags can improve stroke efficiency over cylindrical airbags, at the expense of generating a faster deceleration onset rate. ASNA believed that the primary system design drivers: mass and performance in high wind conditions, could both be improved with the use of wedge shaped airbags. Both companies utilized the transient dynamic finite element code LS-DYNA[2] to analyze system performance and guide design decisions.

Following the conceptual design phase both companies were awarded contracts to fabricate and test a representative Gen 1 ALS. Gen 1 airbag system testing included a series of 8 drop tests, and an extensive series of packing and inflation tests for each contractor.

The Gen 1 drop testing was conducted at the Landing and Impact Research (LandIR) Facility at NASA LaRC, Figure 3. The ASNA system is shown at center and the ILC system is shown at the foot of 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) was used as the test vehicle, therefore, only half of the airbags for each configuration were assembled onto the ARP.

Gen1 drop testing started in December 2006 and finished in June 2007. 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 drop tests resulted in a crew and CM survivable landing; CM accelerations were as expected and no roll-overs occurred. Airbag damage was observed in several attachment locations during the high horizontal velocity landing scenarios, which needed to be addressed in the follow-on Gen 2 development phase.

Figure 3: NASA LaRC LandIR Facility, and ARP

IV. Gen 2 System Development

The successful Gen 1 development programs resulted in additional contract awards for both ASNA and ILC to further develop their respective ALS. The Second Generation (Gen 2) airbag systems were intended to be the next step in an incremental development program. The objectives of the Gen 2 programs were to improve the contractor's designs based on the results of the Gen 1 testing, and to provide relevant airbag landing dynamics demonstrations through the use of a full-scale representative CM drop test article.

In the case of both contractor's airbag systems, the Gen 2 ALS design was largely based upon the successful Gen 1 system. It was specified by NASA that the airbag system should comprise six assemblies to more efficiently interface with the CM structure; this required the ILC configuration to be modified from an 8-bag to a 6-bag configuration.

The ASNA six airbag assembly configuration, illustrated in Figure 4 retained the four core components from the Gen 1 system; a main venting airbag, a internal non-venting anti-bottoming airbag, a main airbag internal shaping structure, and the fast acting, low leak rate active vent.

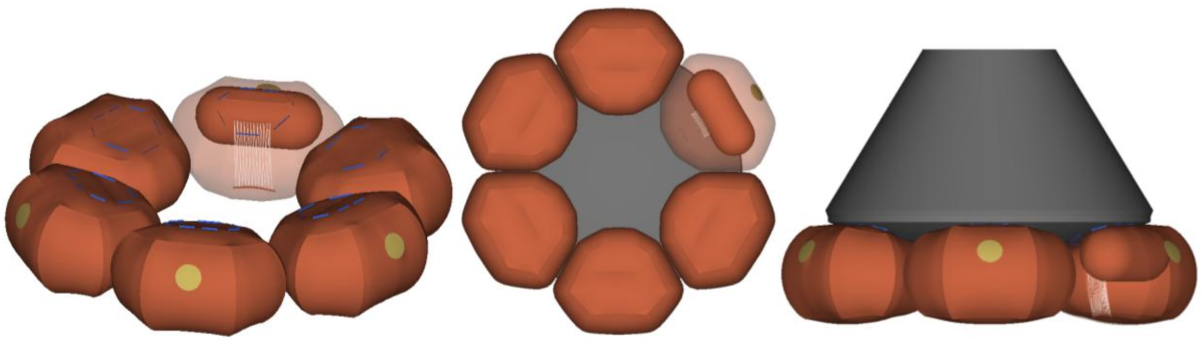

Figure 4: ASNA Gen 2 Airbag Configuration

The Gen 2 CM landing conditions were biased to have a predominantly leading CG location. This reflected a feet first landing for the astronauts and is achieved by utilizing roll control motors. This scenario required 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. This preferred landing orientation in turn lead to a small biasing of the main airbag design. The biasing was only minimal because the landing system was also required to successfully protect the CM and crew during emergency landing scenarios when directional control would not be available. The operational airbag pressures and the main airbag vent diameters of the ASNA Gen 2 ALS are shown in Figure 5.

Airbag Location	Main Airbag Inflation Pressure (psig)	Internal Airbag Inflation Pressure (psig)	Venting Pressure (psig)	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

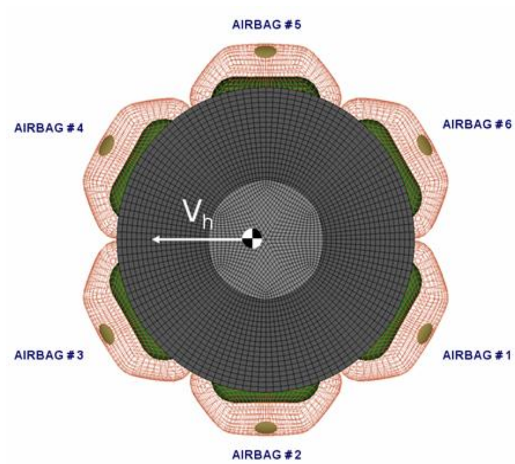

Figure 5: ASNA Gen 2 System Definition

The ILC Gen 2 configuration, shown in Figure 6, was adapted to the six-bag arrangement and retained a similar cylindrical geometry as its Gen 1 configuration. To better follow the CM curvature with fewer bags, each bag was shaped as shown using two miter seams. It also retained the cylindrical non-vented anti-bottoming airbag in each actively vented main airbag. Two vents in each main airbag, located as shown, reduced the likelihood of vent blockage by the internal bag during landing.

The most significant ILC Gen 2 change was the adoption of a webbing net that enclosed each airbag and attached it to the CM. These high strength webbings restrained airbag membrane loads and transferred landing loads between the ground and the vehicle. A similar webbing net enclosed each anti-bottoming bag, passed through the main bag and also connected to the CM. This approach addressed difficulties with the ILC Gen 1 continuous attachment method that resulted from the concentrated and directional nature of the landing loads.

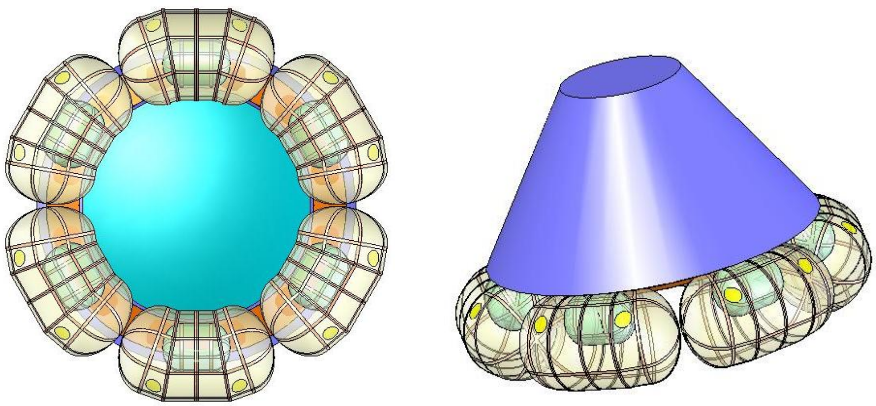

Figure 6: ILC Gen 2 Airbag Configuration

The ILC Gen 2 airbag inflation and vent pressures were also biased, as shown in Figure 7, to improve resistance to rollover by taking advantage of directional knowledge provided by the CM roll control capability.

Airbag Location	Main Airbag Inflation Pressure (psig)	Internal Airbag Inflation Pressure (psig)	Venting Pressure (psig)	Vent Diameter (in)
1	5	11	7	8.8
2	6	11	8	8.8
3	7	11	10	8.8
4	7	11	10	8.8
5	6	11	8	8.8
6	5	11	7	8.8

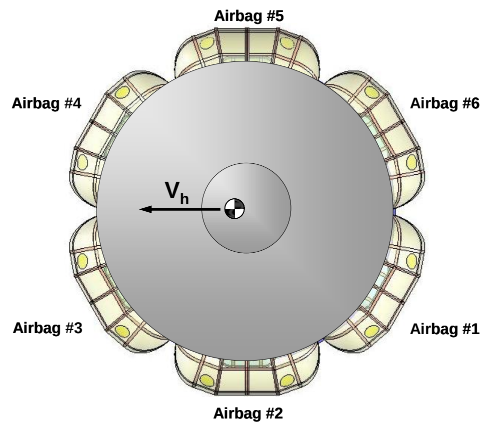

Figure 7: ILC Gen 2 System Definition

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 180º)	25.1	30	0°	0°	0°
3002 (Crew Module Rolled 180º)	25.1	30	-5°	-5°	0°
3003 (Crew Module Rolled 180º)	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 1: Gen 2 ALS Landing Scenario Matrix

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

The airbag landing system was required to operate successfully throughout all the possible landing scenarios without modification or prior knowledge of that landing scenario. The Gen 2 landing matrix included nominal landings, emergency entry landings, parachute failure, and airbag deployment or inflation failure, as shown in Table 1.

Figure 8 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 above ground level (AGL), at between 2,000 and 1,000 ft (AGL) the heatshield would be jettisoned, and this function would initiate airbag system deployment and inflation.

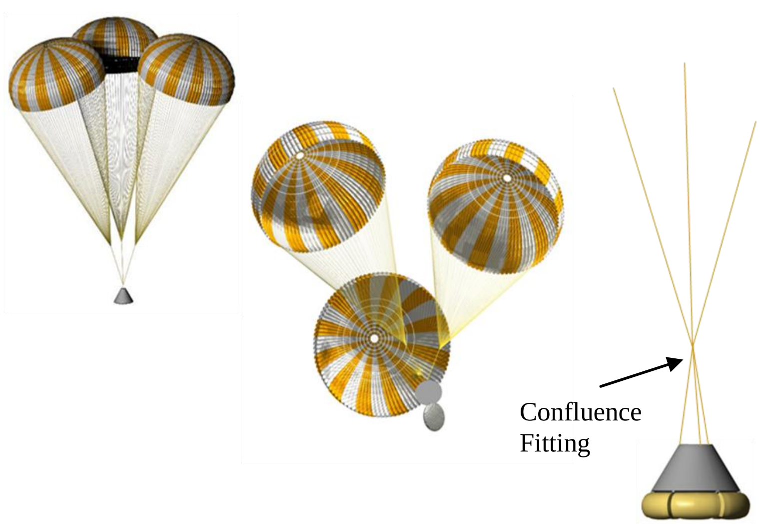

Figure 8: ALS Operational Sequence

V. Gen 2 ALS Drop Testing

Gen 2 ALS drop testing was conducted at the LandIR Facility between February and October of 2008. Table 2 and Table 3 detail the 14 tests conducted between the two airbag contractors. The mass of test article with instrumentation and airbags was 15,990 lbm, this represented the full-scale mass of the CM at ground impact. 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 2/7/2008	25	0	0	0	0
2	BP4 Soil	LandIR 2/29/2008	25	0	10 Toe-in	0	0
3	BP4 Soil	LandIR 4/18/2008	25	20	0	0	0
4	BP4 Soil	LandIR 5/6/2008	25	20	0	0	0
5	BP4 Soil	LandIR 5/15/2008	25	20	0	0	0
6	BP4 Soil	LandIR 6/4/2008	25	40	0	0	0
7	BP4 Soil	LandIR 10/15/2008	22	35	0	0	0

Table 2: ASNA Gen 2 Drop Testing Matrix

Drop Test #	Target/ Test Vertical Velocity (ft/s)	Target/ Test Horizontal Velocity (ft/s)	Target/ Test Pitch Angle (deg)	Target/ Test Yaw Angle (deg)
1	25 / 24.0	0 / 0	0 / -0.88	0 / 0.41
2	25 / 25.0	0 / 0	-10 / -9.7	0 / 0.25
3	25 / 24.4	20 / 19.2	0 / -2.7	0 / -1.84
4	25 / 24.3	40 / 38.4	0 / 0.57	0 / -4.09
5*	25 / 24.6	40 / 38.7	0 / 0.56	0 / 1.86
6	25 / 25.1	40 / 39.0	-10 / -10.47	0 / 1.74
7	25 / 24.7	40 / 38.7	10 / 11.99	0 / 1.22**

Table 3: ILC Gen 2 Drop Testing Matrix

* Test #4 included an unintentional yaw angle of 4.09° and was repeated as Test #*5*
** Yaw angle was derived, rather than taken from photogrammetry results

Figure 9 illustrates both the ILC Gen 2 airbag system and the ASNA Gen 2 airbag system design.

Figure 9: Gen 2 Airbag Test Fixtures, ILC left, ASNA right

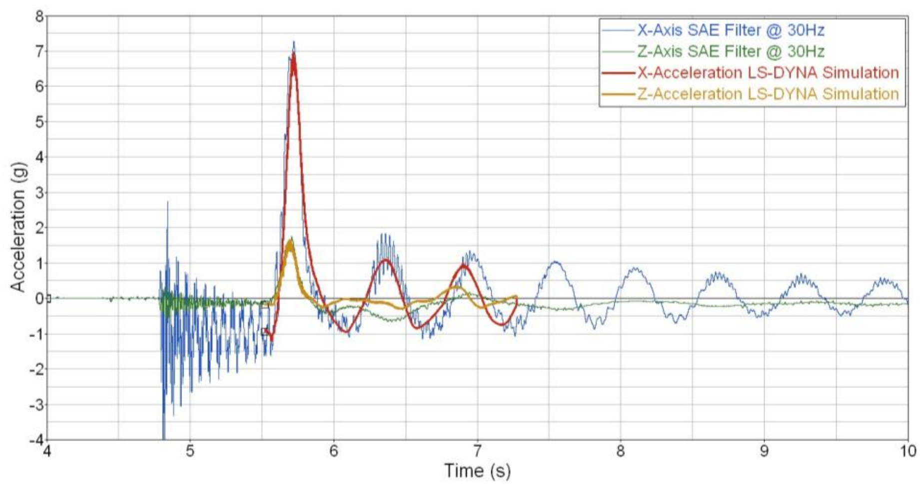

Figure 10: ASNA Drop Test #2, Test Data and LS-DYNA Model Correlation

Gen 2 drop testing generated copious volumes of test data; pressure transducers recorded airbag pressures, tri-axial accelerometers were placed in several locations on the test vehicle, rate sensors were positioned at the test article 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. Perhaps the most important aspect of the Gen 2 testing was the high level of correlation achieved with the LS-DYNA model predictions. This correlation is demonstrated in Figure 10.

Both the ASNA and ILC Gen 2 airbag designs ultimately demonstrated that a full circumferential airbag landing system was capable of safely landing the crew while simultaneously protecting the CM for future re-use.

VI. Singular Landing Architecture Airbag System Development

The nominal land landing airbag system was designed to operate with a CM at, or close to, a 0 degree pitch angle when landing on land. During emergency landings, primarily pad abort or high altitude abort scenarios, the CM could either utilize the airbag system, or select not to jettison the heatshield, reorient to approximately a 28 degree pitch angle, and land in the ocean in a manner similar to Apollo.

In parallel to the Gen 2 system drop testing, separate investigations were conducted to determine the feasibility and the relative advantages and disadvantages of a Singular Landing Architecture. A Singular Landing Architecture is defined as one in which the same landing system hardware and operations are employed for landing on both water and on land without prior knowledge of where the landing will take place. This approach would encompass all possible landing scenarios including situations such as a pad abort when the launch abort system would carry the CM away from the pad and over the Atlantic Ocean for a water landing. However, depending on the prevailing wind conditions at various altitudes there is a probability that the CM, under the parachute system, could drift back over land prior to touchdown. In these cases, a singular landing architecture would provide a robust landing capability independent of whether the CM landed in water or on land.

Figure 11 illustrates Apollo CM testing of a similar land landing scenario. The Apollo program accepted this as a potential outcome of emergency land landings.

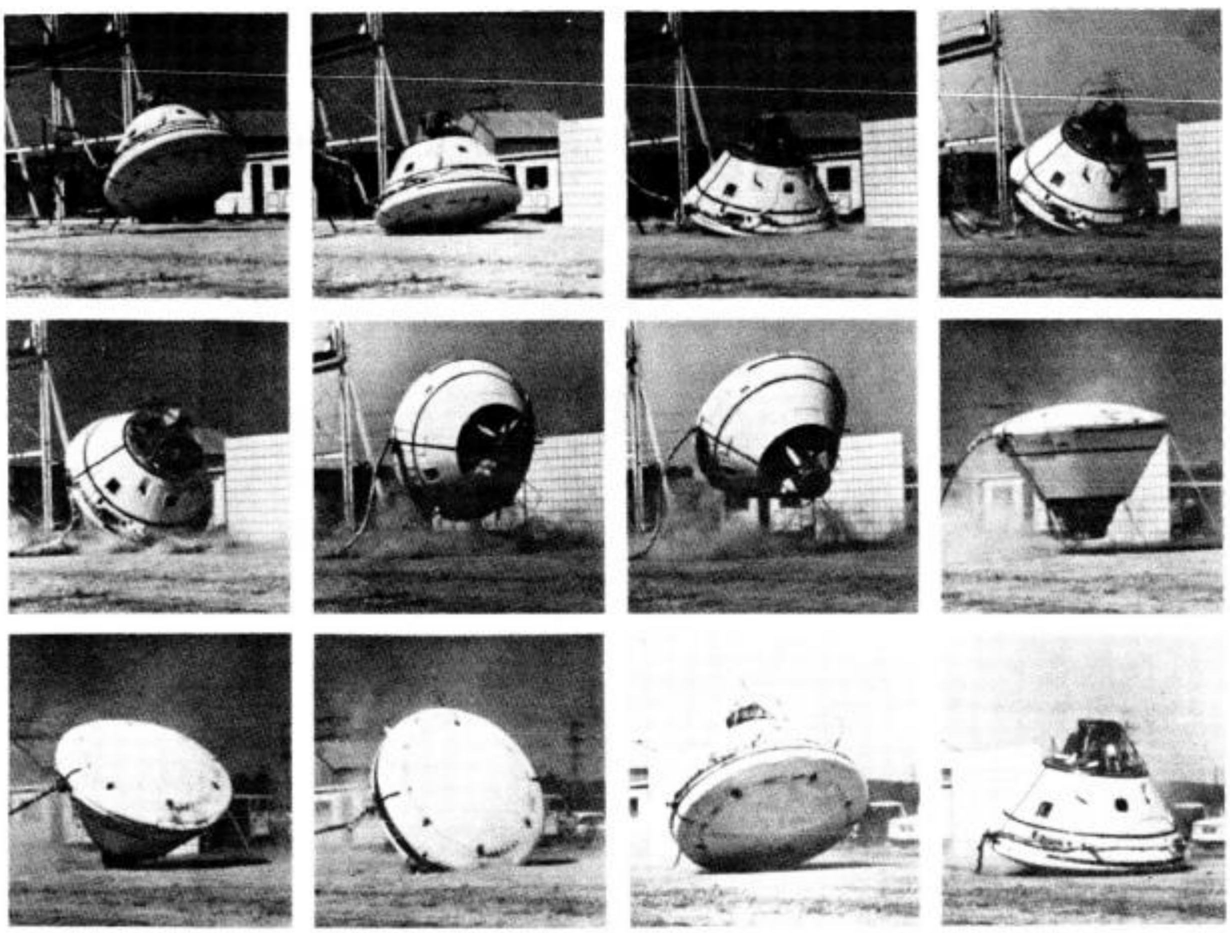

Figure 11: Apollo Land Landing Dynamics of CM-009 During Test #63

It was understood that a capability for CM nominal land landing would represent a significant Orion mass penalty. This mass penalty is comprised not only of the airbag system mass but also the associated CM modifications: heatshield jettison device, structural reinforcements, and additional fuel. However, this mass penalty would result in significant programmatic benefit to NASA in terms of reducing life cycle costs of the CM by maximizing re-usability of the primary structure and subsystems. Additionally, it could also reduce the cost and hazards associated with ocean based recovery operations. The singular landing architecture was viewed as a means of trading land and water landing as either the primary or contingency landing media with CM reusability as a dependent variable.

To provide NASA with the best possible landing solution ILC and ASNA formed a team and worked together to design a suitable airbag singular landing architecture. Table 4 defines a selection of the potential landing scenarios for a prospective landing system. This table was initially used to assess the ASNA Gen 2 nominal land landing system during water landing scenarios. The fluid structure interaction (FSI) capabilities within LS-DYNA were utilized to evaluate the performance of the landing system, with particular emphasis on CM bulkhead pressure loading and dynamic stability. Preliminary analysis indicated that the Gen 2 airbag system could safely land the CM in the water, but there was no room for system mass reductions within the current performance requirements.

Landing Scenarios	V_v (ft/s)	V_h (ft/s)	Pitch Angle	Ground Slope	Wave Slope
6000 Land Landing Cases					
6001 (3C-Nom V_v)	26.0	0	0°	0°	NA
6002 (3C-Nom V_v, High V_h)	26.0	40	0°	0°	NA
6003 (3C-Nom V_v, High V_h, Toe-in, Up)	26.0	40	5°	5°	NA
6004 (3C-Nom V_v, High V_h, Heel-in, Down)	26.0	40	-5°	-5°	NA
6005 (2C-Nom V_v, High V_h)	35.8	40	0°	0°	NA
6006 (3C-Nom V_v High V_h, Bag Failure)	26.0	40	0°	0°	NA
7000 Water Landing Cases					
7001 (3C-Nom V_v, Calm)	26.0	0	0°	NA	0°
7002 (2C-Nom V_v, Calm)	35.8	0	0°	NA	0°
7003 (3C-Nom V_v, SS5, 2σ gust, 2σ wave)	38.1*	41	0°	NA	-16.5°
7004 (3C-Nom V_v, SS5, 2σ gust, 2σ wave)	13.9*	75	0°	NA	16.5°
7005 (3C-Nom V_v, SS3, 2σ gust, 2σ wave)	33.0**	26	0°	NA	-14.4°
7006 (3C-Nom V_v, SS3, 2σ gust, 2σ wave)	19.0**	52	0°	NA	14.4°
7007 (2C-Nom V_v, SS3, 2σ gust, 2σ wave)	42.8**	26	0°	NA	-14.4°
7008 (2C-Nom V_v, SS3, 2σ gust, 2σ wave)	28.8**	52	0°	NA	14.4°
7009 (3C-Nom V_v, Calm, Bag Failure)	26.0	0	0°	NA	0°

***** Includes SS5, 2σ wave vertical velocity of 12.1 ft/s
****** Includes SS3, 2σ wave vertical velocity of 7.0 ft/s

Table 4: Singular Landing Architecture System, Landing Scenario Matrix

The singular landing architecture study subsequently changed direction to develop an airbag system that was capable of providing impact attenuation for nominal water landings and contingency land landings (CLL). A contingency land landing was considered to be an unlikely event in which the CM would land on land without prior operational knowledge; a land landing following a pad abort is an example of this scenario. The resulting CLL airbag system incorporated two discrete airbag assemblies each comprised of four cells arranged into two airbag volumes. Incorporated into each volume was an active vent that allowed the entrapped gas to exit the control volume. The size of the vent was tailored to control the flow-rate of the exiting gas. These airbag assemblies were designed to be stowed and deployed from the CM backshell and wrap around only the leading edge of the base heatshield. The CM would be suspended under the parachute system at a predetermined pitch angle (~28 degrees), which in turn would allow for a safe water landing.

The result of the CLL airbag system development study is shown in Figure 12. The system comprised two discrete airbag assemblies each spanning 30 degrees. Each assembly consisted of 4 cylindrical cells with hemispherical end-caps. Cells 1 and 2 (shown in yellow) are connected to form a single airbag volume, and cells 3, and 4 (orange) are connected to form a second volume. Once again, LS-DYNA was used to evaluate system performance over the full range of landing scenarios.

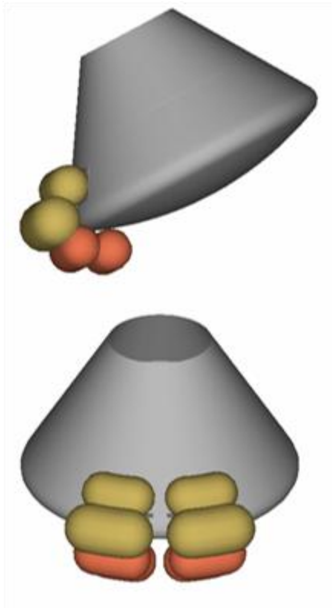

Figure 12: CLL Airbag Configuration

A prototype of the configuration depicted in Figure 12 was rapidly fabricated, while in parallel, the system was further defined and optimized. The prototype assembly was used for packing, stowage, and inflation testing. Figure 13 reproduces three frames from a rapid inflation test. Three successful inflation tests were conducted that demonstrated deployment and inflation to operational pressure within 10 seconds. Rapid deployment and inflation was required to comply with the foreshortened timeline associated with pad abort scenarios.

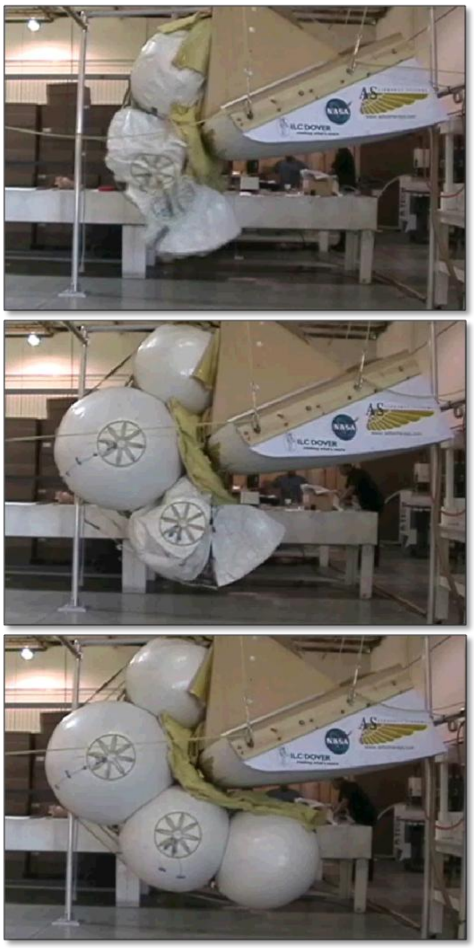

Figure 13: CLL Rapid Inflation Test

The prototype fabrication and testing task demonstrated the feasibility of packing and deploying an airbag assembly from a representative stowage compartment. It also confirmed the ability to reliably and repeatedly position the assembly around the shoulder of the CM base heatshield. The inflation testing also acted as a validation of the inflation models, which accurately predicted the inflation sequence and timeline.

In parallel to the fabrication task, a separate study was conducted which developed the CLL configuration further. This included enhancing the fidelity of the LS-DYNA model, interfacing with the Lockheed Martin CM model and structure, evaluating landing performance on several different landing surfaces, assessing system mass reduction opportunities, and improving system master equipment lists and interface requirements.

A relatively complex LS-DYNA model was developed to evaluate component loads during the landing event. Of particular interest was the load distribution throughout the assembly and the force developed in the fabric structures used to attach adjacent cells to each other. Figure 14 depicts a single airbag assembly from the LS-DYNA model, the assembly is shown with principal stress contours and tensors.

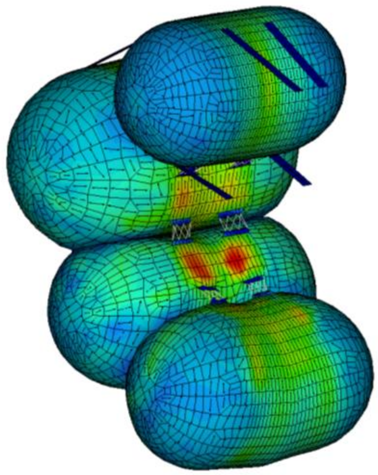

Figure 14: CLL LS-DYNA Model

VII. Conclusions

This paper has provided a summary of the development of an airbag landing system capability for the Orion CM. The project has progressed through initial Gen 1 and Gen 2 phases of a nominal land landing capability to the detailed analysis and prototyping of a contingency land landing capability. This entire project was exceptionally fluid with technical and programmatic direction changing focus on several occasions. The ability to react to these changes, both technically and contractually, reflects extremely well on the contractors and on NASA. The outcome of this was two highly capable nominal land landing systems, and a crew survivable solution to contingency land landing scenarios.

The Gen 1 and Gen 2 drop testing activities encompassed a variety of landing scenarios which assessed the influence of rate of descent, CM pitch, roll and yaw under the parachutes, prevailing wind conditions, vent arming failure, and landing media. 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 landing orientation, electrical malfunctions, test set-up issues, airbag damage, and soil conditions.

In addition to demonstrating a successful landing system for the Orion Crew Module, the drop tests generated a wealth of data for model validation purposes. Throughout the design, fabrication, and analysis phases of this project the LS-DYNA models have proven invaluable. In the majority of cases the 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. This was demonstrated during Gen 2 testing when the pressure transducer configuration resulted in a pressure monitoring time lag. The progression of the credibility of the model results and the resulting confidence in the predictions has been immeasurable. Demonstrating the robustness of the airbag landing systems and the ability to accurately predict the system landing performance through analytical simulations has been a valuable accomplishment. The modeling techniques conceived, developed, and validated throughout this project will prove beneficial for follow-on work as well as other programs where inflatable impact attenuation systems are applicable.

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