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Development of a Novel Helmet Support Assembly for NASA Orion Crew Survival Suit

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Orion Spacecraft water landing environments have necessitated the design and testing of a novel Helmet Support Assembly (HSA) as part of the NASA Orion Crew Survival Systems (OCSS) launch and re-entry spacesuit. A series of development sled tests using 5th female, 50th male, and 95th male Hybrid III Anthropometric Test Devices (ATDs) simulated worst case water landings and identified the need for an integrated suit countermeasure to control the helmet during dynamic loading. Initial prototype countermeasures rigidly restrained the helmet keeping the helmet in place as desired, but led to large force and moment transmission to the upper neck. Further development led to a flexible HSA which used high-strength steel wire contoured to the size-matched ATD thorax and attached to both the front and rear of the neck ring. The selected wire diameter and contoured shape provided some ability to flex under the expected worst-case dynamic loads. The existing shoulder harness was used to restrain the helmet motion during “eyeballs out/down” loading while also attempting to prevent head-to-helmet contact in “eyeballs down” spinal-axis loading. A new small prototype helmet was also developed and tested for the 5th and 50th ATDs with both HSA devices. Dynamic impact tests were conducted on the HIA (Horizontal Impulse Accelerator) at Wright Patterson Air Force Base (WPAFB) under simulated off-nominal landing conditions using a representative Orion seat and 5-point harness. For each ATD size, peak Neck Injury Criteria (Nij) were compared to equivalent sled tests with an unsuited ATD configuration. Adding a helmet without attempting to control motion increased peak Nij values for all ATD sizes. The use of the rigid countermeasure showed decreased peak Nij results for the 5th female, but increased peak Nij values for both 50th configurations and the 95th male ATDs. By comparison, the flexible HSA showed reduced peak Nij values for all ATD sizes. Overall, this series of dynamic impact tests identified a risk of increased crew neck loading when under- or over-restraining the helmet during simulated Orion water landings and also demonstrated an effective strategy to mitigate those loads with a compliant HSA design.

Nomenclature

<i>ACES</i>	=	Advanced Crew Escape System	<i>HSA</i>	=	Helmet Support Assembly
<i>ATD</i>	=	Anthropometric Test Device	<i>MPCV</i>	=	Multi-Purpose Crew Vehicle
<i>CM</i>	=	Crew Module	<i>My</i>	=	Neck Y-axis Moment
<i>FHSA</i>	=	Flexible Helmet Support Assembly	<i>NASA</i>	=	National Aeronautics and Space Administration
<i>HIA</i>	=	Horizontal Impact Accelerator	<i>Nij</i>	=	Neck Injury Metric
<i>Fz</i>	=	Neck Z-axis Force	<i>OCSS</i>	=	Orion Crew Survival Systems
<i>HHP</i>	=	Human Health and Performance	<i>WPAFB</i>	=	Wright Patterson Air Force Base

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I. Introduction

NASA's Orion Multi-Purpose Crew Vehicle (MPCV) is currently under development to provide mankind access to the Moon, Mars, and future deep-space destinations. The MPCV Crew Module (CM) is a capsule with the capability of carrying up to four crewmembers beyond low earth orbit. Launch and re-entry will expose crew to vibration, sustained acceleration, and short-duration impact loading during splashdown. Orion water landings will impart three-dimensional accelerations to the crew with varying degrees of severity based on the location (Atlantic after an abort or Pacific after a nominal re-entry) and wind/wave states. Prior to water landing, the CM will descend under three parachutes at a prescribed hang angle relative to the water surface, which will place crew in a feet-down posture. During CM splashdown, the predominant loading direction along crew anatomical axes will be in the back-to-chest ("eyeballs in") and tail-to-head ("eyeballs down") directions. A series of thrusters within the CM will limit the amount of roll at splashdown and thereby maintain relatively low lateral (shoulder-to-shoulder) crew acceleration.

An updated launch and re-entry spacesuit is currently under development by the NASA Johnson Space Center Orion Crew Survival Systems (OCSS) team to protect crew during all Orion mission phases. The latest OCSS suit design was derived from the Shuttle Advanced Crew Escape System (ACES) architecture with a unique focus on improved injury mitigation and to accommodate a set of requirements developed for deep space travel. In general, the OCSS launch and re-entry suit retained the ACES thermal outer suit layer, quick-disconnect neck ring, and rigid helmet, but many aspects of the fit, form, and function have been updated to accommodate a larger anthropometric crew range (1st to 99th percentile), improve ingress/egress, increase unpressurized and pressurized mobility, and allow the crew to survive a an extended cabin depressurization event.

Despite these improvements, the original ACES design was developed to land in the Shuttle environment with an upright crew posture and limited spinal-axis loading. Findings and recommendations from the Columbia Accident Report illustrated the need to control the amount of loading imparted to the neck from the ACES helmet during extremal events [1-2]. Given the different crew posture and combined directional loading during Orion water landings, it was necessary to reassess the risk of neck injury with an ACES-derived suit/helmet configuration. A series of dynamic impact tests provided data to evaluate the current ACES design and countermeasures to limit neck loads.

II. Background

A. Orion Landing Environments

NASA developed a unique set of landing requirements for the Orion Crew Module (CM) to maintain structural integrity and crew safety. Specifically, the following scenarios were identified for design and assessment: 1) post-pad abort Atlantic Ocean landings with and without the loss of a parachute, 2) post-ascent abort Atlantic Ocean landings with full parachutes, and 3) nominal re-entry with and without the loss of a parachute. Each scenario contains unique distributions of wind speeds and wave heights depending on the landing location. The average nominal CM hang angle creates a medium pitch angle from the water surface, with dispersions due to wind angle, swing under parachutes, and wave angle/direction. All Orion missions will end with a water landing, thus emphasizing the importance of understanding the risk of injury to crew and designing appropriate countermeasures to limit landing loads.

B. Problem Description

The Orion seat was designed to provide adequate support surfaces for the head, back, arms, and legs during descent and landing. With the crew in a semi-recumbent posture, low-pitch landings will force crew into the seatback, seat pan, and headrest, which is referred to as an "eyeballs in/down" direction of loading (Figure 1, Left). Landing conditions with high wind combined with a high pitch angle can cause the CM to dive into the water at a steep angle, pitch forward, and end upside-down. During these high-pitch/high-velocity landings, crew motion is downwards into the seat pan, away from the seat back, and forward into the harness. This direction of loading is referred to as "eyeballs out/down" (Figure 1, Right).

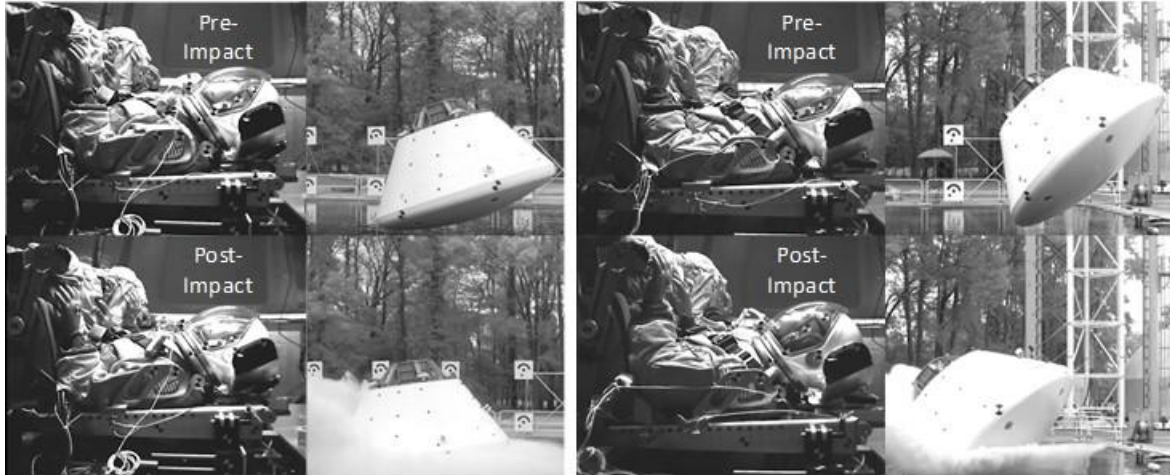


Figure 1. “Eyeballs In/Down” Loading during Low-Pitch Landings (Left); “Eyeballs Out/Down” Loading during High Pitch/High Velocity Landings (Right)

Both low- and high-pitch landing scenarios are important for crew injury assessment, but the “eyeballs out/down” landings were of particular interest due to the possibility of combined forces and moments applied to the cervical spine as a result of head contact inside the helmet. Preliminary dynamic impact sled tests of the “eyeballs out/down” Orion landing scenario were conducted on the Horizontal Impact Accelerator (HIA) at the Wright Patterson Air Force Base (WPAFB) Air Force Research Lab with 5th, 50th, and 95th Hybrid III Anthropometric Test Devices (ATDs) in a mockup Orion seat. Tests were run both unsuited and suited with a size-matched ACES and no additional countermeasures to restrain motion of the helmet during impact (Figure 2). To simulate the high-pitch, high-velocity landing scenario, the seat was reclined from vertical and accelerated under a simulated half-sine landing pulse. At the time of this preliminary sled test series, full-scale water impact testing had not been completed and off-nominal landing environments were still under development. Thus, impact tests were conducted at a higher severity than typical off-nominal landings to intentionally produce neck responses near acceptable limits.

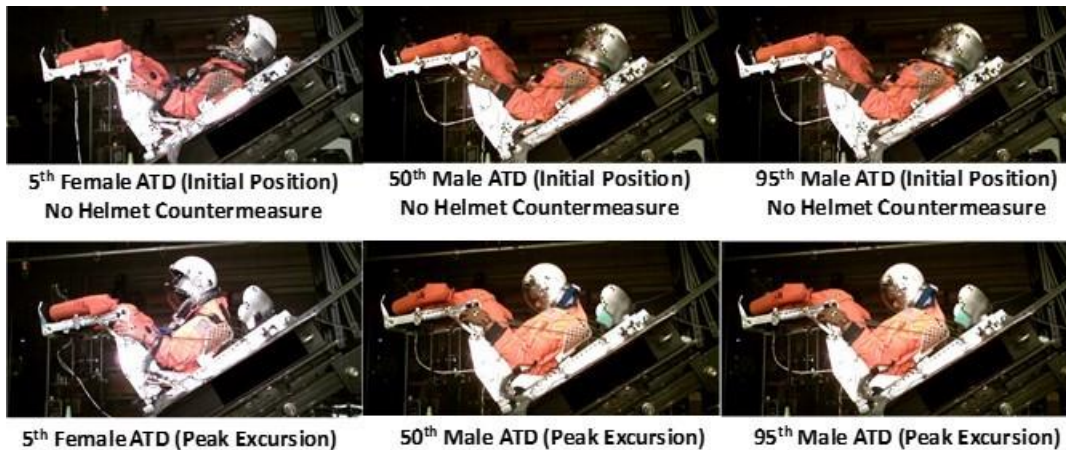


Figure 2. Snapshots of Preliminary Sled Tests of 5th, 50th, and 95th Suited Hybrid III ATDs with No Helmet Countermeasure (Upper Panel: Initial Position; Lower Panel: Peak Excursion)

Review of the suited sled test high-speed videos revealed two concerns with the unrestrained ACES helmet in the Orion “eyeballs out/down” loading environment: 1) the downward body motion towards the seat pan caused the helmet to contact the top/posterior portion of the head, causing an increase in neck compression force and extension moment and 2) during forward motion, the helmet contacted the back of the head pulling the neck into tension

combined with forward flexion. This trend was common across all three ATD sizes, as shown in the peak excursion screenshots in Figure 2. Measured neck forces and moments confirmed these responses, showing an increase in neck injury risk with an unrestrained helmet compared to unsuited runs with the same ATD size. Another concern was the possibility of face-to-neck ring contact due to the upward movement of the helmet when only restrained by the suit fabric. Additionally, concerns of helmet-to-head loading were raised for smaller crew due to the mismatch in size and mass of the standard helmet.

From these preliminary sled tests, it was clear countermeasures were needed to control motion of the ACES helmet during Orion landings. Considering the unique nature of deep space missions and the numerous associated design constraints for the Orion spacesuit, a custom designed countermeasure was needed. The following sections describe the process of development, test, and evaluation of two novel approaches to controlling helmet motion under simulated Orion landings.

III. Methods

C. Helmet Support Assembly (HSA) Design Constraints

Designing a spaceflight launch and re-entry suit is challenging due to the many functions it must perform, including injury prevention, thermal and oxygen regulation, and accommodating both unpressurized and pressurized mobility. Under normal re-entry conditions and after splashdown, the crew must be able to doff the restraint belts and exit the seat with limited visibility, navigate the CM cabin in potential wavy sea states, and operate with the effects of physical deconditioning after long-duration spaceflight missions. Additionally, suited crew may need to perform these tasks during off-nominal contingency scenarios such as the CM being upside-down, the cabin filled with smoke, or the presence of toxic chemicals in and around the vehicle. Given these scenarios, several design constraints were identified prior to designing the HSA.

Three-dimensional loading on the crew will occur during landing, but short-duration high accelerations may also occur during an abort and parachute deployment sequences. The suit and helmet, in concert with the seat and restraint, must maintain adequate body position and limit loads to the crew during all mission phases. In the case of an on-orbit cabin depressurization event, the CM pressure vessel will lose pressure with subsequent reduction in oxygen and temperature. This situation requires the helmet and suit to maintain a pressure-sealed connection and yet, still provide extensible range of motion and an adequate field of view as the crew navigate back to earth. Crew should be able to don the suit and connect to the Environment Control Life Support System.

The suit may be pressurized from 0.5-2 psi during normal operations and up to 8 psi for contingency operations. The HSA design must be able to accommodate the pressurization without detrimentally affecting its fit and function. Under suit pressure the helmet HSA an upward force, which otherwise unrestrained, will move the helmet up limiting visibility through the visor and increasing the chance of undesirable facial interaction with the neck ring. The design of the HSA must therefore maintain the vertical position of the helmet on a pressurized suited crewmember, whether or not they are restrained in the seat. For crew comfort during pre- and post-flight ground operations, the HSA should also minimize helmet or neck ring loading on pressure-sensitive portions of the body, such as the shoulders, head and neck.

With crew mobility and egress a primary concern during post-landing, one of the critical design features of an HSA was to conform to the suit and occupant, minimize the potential for snag hazards, and not impede normal crew operations. A logical location for an HSA countermeasure would be between the neck ring and thorax. However, countermeasures would need to accommodate motion under the shoulder belts during forward flail and maintain proper belt positioning for a broad range of crew anthropometry. HSA designs could be scaled to various sizes to best fit the range of crew sizes. Integration of the HSA into the suit was preferred, but not required if ingress/egress and normal operations were not affected and the device did not pose a snag hazard. When positioning the helmet, the HSA was required to maintain a downward field-of-view for crew to see and interact with the display units while restrained in the seat. Lastly, because the HSA would be worn during launch and re-entry, it had to accommodate normal range of motion of the arms, shoulders, and neck for flight operations.

D. Preliminary Countermeasure Designs

Since the beginning of the Orion program, NASA developed and evaluated several different neck injury countermeasure prototypes. Based on findings from the preliminary suited sled tests, the primary goal was to control

helmet motion during the worst-case “eyeballs out/down” loading scenario while maintaining safe neck loads across other off-nominal environments such as abort. A straight metallic tube protruding laterally to the width of the ATD shoulders was attached to the rear of the ACES neck ring. The tube was positioned under the shoulder belts, which allowed the belts to interact with the tube and restrain forward helmet motion. A limited set of proof-of-concept impact tests were conducted at WPAFB using this tube prototype. Although the number of tests with the straight bar countermeasure were limited and only run on the 5th female ATD, the results looked promising, which led to development of a more sophisticated version of the rigid tube concept.

Updated prototypes were curved to better match the contour of each ATD thorax and were sized laterally to catch the shoulder belts under “eyeballs out/down” loading. Several versions were developed with varying curvatures and heights from the neck ring and the ability to attach to the small prototype or standard ACES helmet (Figure 3). A small circular endplate was placed on the lateral face to prevent shoulder belts from slipping off the bar during off-axis loading. Prior to impact testing, the bar was positioned under the shoulder belts as shown.



Figure 3. Rigid Countermeasure Prototypes and Installation

E. Flexible Helmet Support Assembly (HSA)

Test results, LS-DYNA simulations, and overall lessons learned from previous dynamic testing led to the development of a flexible design to constrain helmet translation and rotation. A key aspect of the flexible HSA was utilization of the shoulder restraint belts to control helmet motion. In doing so, the HSA needed to conform to the shoulders, fit under the belts, and not interfere with the neck ring. Due to various possible anthropometric shoulder sizes combined with two possible helmet sizes, the flexible HSA, in some cases, needed to allow the shoulder belts to route inboard to the neck ring. Controlling vertical helmet motion was a preferred feature of the flexible HSA. This necessitated placement of vertical supports between the shoulder and neck ring. Supports were placed in the front and back of the helmet with spacing narrow enough to allow the belts to fit properly on the shoulders of representative 5th percentile small female (Figure 4). For consistency, the same vertical support positioning was used for anthropometric sizes with larger shoulder widths, in which case the shoulder belts were routed outboard of the neck ring.

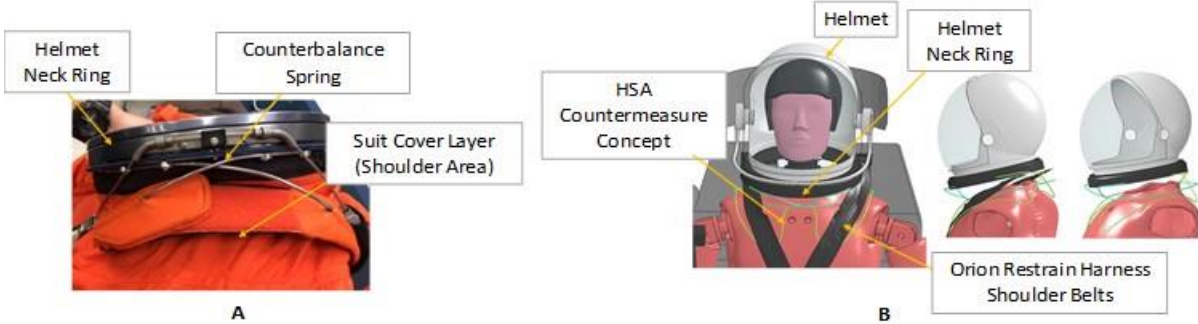


Figure 4. HSA Countermeasure Design Development. (A) Shuttle Suit Counterbalance Spring, (B) HSA Countermeasure Concept.

The flexible HSA consisted of high-strength steel wires bent to a desired shape on the shoulders and attached to the helmet neck ring (Figure 5A). Steel was used to ensure sufficient resistance during impact, consistent head positioning, and minimal flexion during pressurization. In the prototype configuration, steel wire connections were shrink-wrapped to prevent slippage and aid integration (Figure 5B). Once assembled, the flexible HSA was mounted

to the outer circumference of the neck ring via four brackets (Figure 5C). This provided a direct link to the neck ring disconnect and hence the helmet once mated. Integration of the flexible HSA to the suit was an important aspect of prototype development to ensure a similar method could be used on the flight suits. A soft goods cover was designed into the exterior cover of the suit to protect and cover the HSA wire. It was through the HSA cover and HSA that the hold-down was able to act on the helmet, ensuring that good head-helmet-seat coupling was maintained during dynamic loading (Figure 5D).

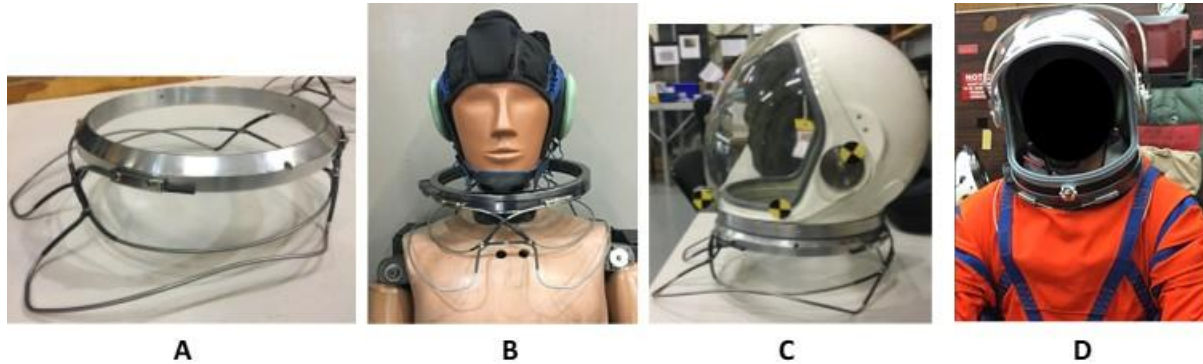


Figure 5. Prototype Design and Setup. (A) HSA with neck ring attached, (B) HSA with Neck Ring Mounted on ATD with No Suited Cover Layer, (C) HSA with Neck Ring and Helmet, (D) Integrated HSA with neck ring, helmet, and suited cover layer on human volunteer.

F. Countermeasure Prototype Manufacturing Process

Several mockups and prototypes were manufactured to develop the flexible HSA and to mature exterior cover integration. Initially, low stiffness wires were bent into desired positions to provide non-functional three-dimensional prototypes for pattern development and integration evaluations. High-strength steel wire prototypes were then produced to perform human-in-the-loop comfort and pressurized evaluations in a mockup of the Orion seat. Non-linear analysis of the flexible HSA designs under impact loading were combined with findings from the pressurized evaluations to finalize prototypes in multiple sizes. To aid fabric pattern development and confirm proper fit, the integrated prototypes were placed on full-scale 3D printed versions of the 5th female, 50th male, and 95th male Hybrid III ATD head and torsos (Figure 6). The 3D printed head/torso mockups proved extremely valuable in ensuring proper placement of the wire, helmet, and belts on each ATD size prior to impact testing.

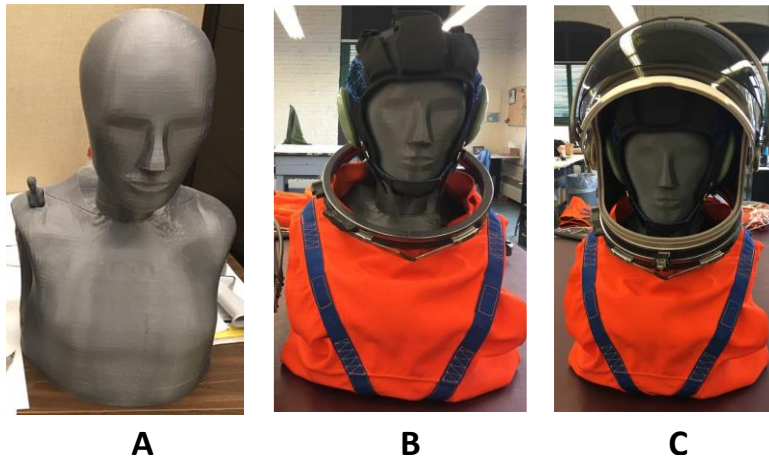


Figure 6. Using 3-D printed ATD head/torso mockups for adjusting fit of HSA prior to sled testing (A) 3-D printed 50th ATD head and torso, (B) 50th ATD mockup with positioned HSA and neck ring, (C) 50th ATD mockup with HSA, neck ring, and standard helmet.

G. Test Setup

The HIA at WPAFB provided a controlled method to simulate various Orion landing or abort conditions to evaluate the HSA designs. A large, adjustable fixture was mounted to the high-g sled to provide variable roll and pitch orientations of an Orion prototype seat. The seat could rotate from 0 to 180 degrees from the direction of travel, simulating the full spectrum of possible roll angles. Additionally, the seat could be pitched from an upright (normal to the direction of travel) to fully recumbent (parallel to the direction of travel) position (Figure 7). Once the desired seat orientation was selected, the fixture was locked into place and ATDs strapped in via a 5-point harness. Support surfaces on the Orion seat were adjusted to match ATD size prior to testing. With ATDs secured in the seat, a pressurized chamber and metering pin were used to accelerate the sled, fixture, seat, and ATD at a prescribed pulse shape representative of an Orion water landing.

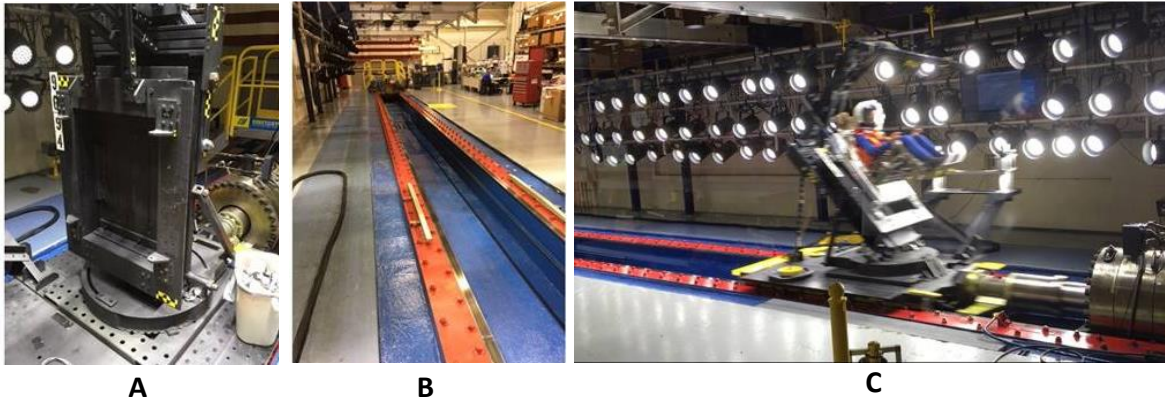


Figure 7. WPAFB HIA Sled Test Setup (A) Adjustable Sled Fixture (B) Sled Track (C) Suited ATD Sled Test.

Dynamic impact testing at WPAFB occurred over multiple series across several years. During each series, hardware used to represent the seat, harness, suit, comm cap, and helmet were the most flight-like available at the time. Three ATD sizes were tested to try to capture the countermeasure design performance across an anthropometric range for male and female occupants: 5th percentile small female, 50th percentile midsize male, and 95th percentile large male. Two helmet sizes were used in the tests to represent the sizes of the current standard and small helmets. The 5th female ATD used the small size; the 95th male ATD used the large; and the 50th male ATD separately used both the standard and small sizes. The helmets were Airforce prototypes with shuttle era neck rings representing the planned Orion helmet configuration. The helmet neck ring was modified with mounting holes to allow the HSA mounts to be attached.

The comm cap was a new prototype design with discrete pockets sewn into the cap allowing for different foam types and thicknesses to be inserted. The caps also included realistic hearing protection ear cups. The caps were tightened onto the ATD heads as they would be in the expected flight setup. Each ATD was dressed with thin capilene pants and a long sleeve shirt, as well as prototype flight style boots. To ease installation based on lessons from previous sled tests, the test suits were modified to remove the arm and leg sleeves, but include the upper torso, load bearing internal harnessing, HSA cover layer, and HSA straps. These were selected because they are the main load bearing components connecting the ATD to the HSA setup, and the sleeves are expected to have a minor contribution to the load path. The prototype HSA had four sizes corresponding to the four combinations of three ATDs and two helmet sizes (5th small, 50th small, 50th standard, 95th standard).

H. Test Cases

Sled tests at WPAFB were primarily focused on reproducing worst-case “eyeballs out/down” landing scenarios by placing the seat at a specific reclined angle relative to the sled travel direction. However, in each series, additional cases were run to investigate the effect of adding yaw (“eyeballs side”) to the seat, increasing severity beyond worst-case, or characterizing loading during a simulated abort. The predicted landing pulses at the seat for all scenarios were compared to the available WP sled pin data to get the closest match. Additional cases provided insight into the

robustness of each HSA design to maintain helmet control when direction of loading changed or severity increased. Table 1 shows a subset of the test matrix, including ATD size, suited configuration, and loading.

Table 1. Subset of Flexible HSA Test Series

ATD	Configuration		Load Cases	
	Suit	Helmet	Acceleration	Orientation
5th Female	Unsuited	None	Landing	Eyeballs Out/Down
	Suited	Small	Landing	Eyeballs Out/Down
50th Male	Unsuited	None	Landing	Eyeballs Out/Down
	Suited	Small	Landing	Eyeballs Out/Down
			Scaled 63% Above Landing Peak Accel	Eyeballs Out/Down
		Standard	Landing	Eyeballs Out/Down
Scaled 38% Above Landing Peak Accel	Eyeballs Out/Down/Side			
95th Male	Unsuited	None	Landing	Eyeballs Out/Down
	Suited	Standard	Landing	Eyeballs Out/Down

I. Measures of Performance

Based on recommendations from Columbia investigations [1-2], NASA adopted a comprehensive set of injury metrics from multiple industries to assess the potential for crew injury. During each sled test series, the primary metrics of interest for HSA performance assessment included upper neck forces and moments and combined Neck Injury Criteria (Nij) responses. Measurements of the neck axial force (Fz) and upper neck moment (My) were combined to calculate the quantitative Nij. To meet certification requirements, the four Nij combinations (Nte for tension extension, Nce for compression extension, Ntf for tension flexion, and Ncf for compression flexion) must stay below the NASA required limits [3-7]. The time history force and moment inputs that feed into the Nij metric were reviewed in real time between test runs to verify that the magnitude and direction of loading was reasonable and came close to expectations (ex. instrument channel polarity, within family of results from previous NASA sled tests and pretest analyses). High speed video was also reviewed after each sled run to assess qualitative ATD motion and suit interaction with the HSA. Visual inspection of high speed video was used to verify helmet position on the head and confirm any helmet-to-head interaction.

Since test series were run across multiple years and the severity of simulated landings changed between each series, direct comparison across countermeasure designs was not possible. Thus, HSA performance was evaluated by calculating a percent difference in peak Nij against the same unsuited run for each ATD size within a test series. The flexible HSA series had the same loading orientation, ATDs, and helmets, but used partial suits, had a lower seat pitch angle, and reduced g-levels compared to previous series. Many additional ATD responses were recorded, including head linear and rotational accelerations, chest and pelvis accelerations, and lumbar forces and moments.

J. Test Objectives

This sled test series had primary and secondary objectives. The primary objective was to quantitatively assess peak Nij results of the prototype HSA designs in simulated worst-case landings, with two helmet sizes, across three ATD sizes. The secondary objectives were to qualitatively assess fit across anthropometric range, ingress/egress availability, reach/mobility, and ease of don/doff. Suiting the ATDs for each test provided qualitative feedback on the secondary objectives, particularly on the fit, positioning the helmet, and ease of don/doff. The sequence of placing the ATDs in the seat and adjusting the restraint harnesses was helpful in understanding the ingress/egress and mobility. Visual inspection of the seat, foot restraints, restraint harness, helmet and HSA between each test run verified that no severe mechanical damage occurred.

K. Known Test Limitations

Every effort was made to meet the primary and secondary test objectives of this test series, but there were some known limitations. The seat and suited hardware used were as close to flight-like as possible using prototypes with up-to-date designs at the time of the test. With the available budget and schedule, each test series was limited to five days of testing. With that amount of time, including ATD changeouts, sled calibration runs, and the suiting process and setup of the ATDs, the number of test cases was limited to roughly 20 runs per series.

Sled pulses were governed by available machined pins at WPAFB. The pulse shape found analytically was converted to a horizontal vector and then matched to the closest pin. So the resulting pulse closely mimics the predicted landing impact but is not precisely the same. The goal of using the ATDs was to get the most realistic human response possible, but the ATDs does not perfectly predict every aspect of human motion. Additionally, the use of the 5th, 50th and 95th ATD sizes was intended to address the potential range of crew sizes, but test results were restricted to the anthropometric dimensions of those specific ATDs which do not have the diversity found in a human population. The flight suit cover layer was reduced by removing the arm and leg sleeves to make fitment to the ATD simpler between tests. This partial suit was expected to carry the same loads as the full suit with respect to the helmet and HSA, but limb motion may be slightly different with the addition of the rest of the fabric.

IV. Results and Discussion

Figure 8 shows percentage change in peak N_{ij} results from unsuited and suited ATD runs with or without an HSA countermeasure. Percent change data as shown is consistent within the given test series. With no countermeasure, the 5th ATD displays more sensitivity to adding the helmet and had a 92% increase in peak N_{ij} . The 50th and 95th ATDs were less sensitive to the helmet addition and showed 33% and 26% increases for adding the small and standard helmets to the 50th ATD, respectively, and 27% increase for the 95th ATD. Upper neck force and moment directions remained consistent after adding an unrestrained helmet across all ATD sizes, implying the added mass only exacerbates neck loads/moments, but does not affect load direction. With the suit and helmet in place but no added countermeasure, helmet motion is only limited by head contact and suit fabric.

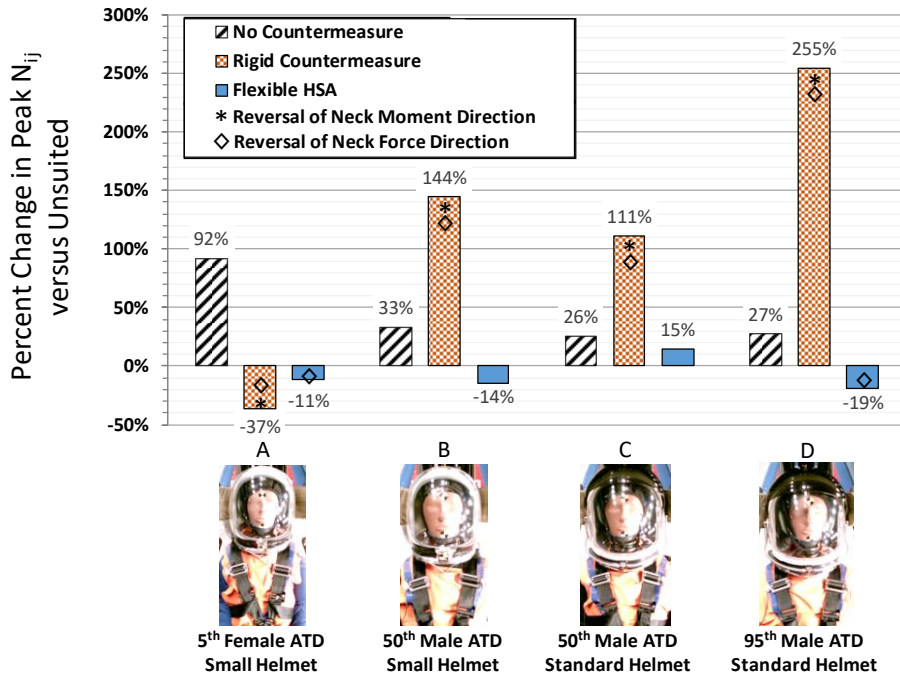


Figure 8. Percent Change in Peak N_{ij} and Direction of Force/Moment Versus Unsuited for: No Countermeasure, Rigid Countermeasure, and Flexible HSA.

Addition of the rigid countermeasure firmly restrained the helmet during ATD forward excursion, which had a varying effect on peak N_{ij} results across ATD sizes. For example, the 5th ATD showed a 37% decrease in peak N_{ij} while the 50th and 95th produced large increases in peak N_{ij} . The 50th ATD had 144% and 111% percent increases, respectively, for adding the small and standard helmets. The 95th ATD showed a 255% increase. Data showed the countermeasure reversed both the force and moment loading directions in the neck in all four ATD sizes. The bar style countermeasure was well restrained under the shoulder belts as designed, but the increased stiffness compared to the ATD body allowed no compliance when loaded. The rigidity of the bar kept the helmet in place, performing

the desired function of keeping the helmet from moving upward on the head. However, with frontal motion of the torso and head during “eyeballs out/down” loading and with the helmet held firmly in place, the front of the head impacted the helmet leading to a less desirable extension moment combined with neck compression.

The addition of the flexible HSA overall showed less sensitivity across all ATD sizes compared to the rigid concept and no countermeasure. The 5th ATD had an 11% decrease in peak Nij. For the 50th ATD, the small helmet case showed a 14% decrease, but the standard helmet case had 15% increase in peak Nij. The 95th ATD showed a 19% decrease in peak Nij. The results effectively include both the detriment of adding the mass of the helmet and the benefit of adding the countermeasure. Since, in three of the four cases, the flexible HSA showed overall decreases in Nij compared to unsuited, it likely means there was some energy absorption by the HSA that overcame the effect of adding the helmet mass. The flexible HSA showed reversal of worst case force direction in the 5th and 95th cases while maintaining moment direction. Keeping the neck moment direction the same as the unsuited was considered more natural for the “eyeballs out/down” scenario with the added benefit of avoiding the more stringent NASA requirements for neck extension moments.

Figure 9 shows high speed video snapshots at peak forward excursion for several configurations and test series. Figure 9A shows the unsuited 50th ATD case during the flexible HSA series. One of the preliminary higher-severity 50th ATD tests with no helmet countermeasure (Figure 9B) showed helmet and neck ring motion initially down onto the head and then forward to an unsafe position limited only by the suit fabric. This position would place the neck ring as high as the occupant midface with potential impact to the nose/mouth and back of the head. Because the unrestrained helmet was considered to be less predictable, showed large increases in Nij, and visually showed an unsafe helmet/neck ring position, NASA deemed it an unacceptable concept for the OCSS suit development. In addition to the qualitative comparisons, the qualitative assessment highlighted the need for the development of a countermeasure concept.

Figures 9C and 9D show rigid countermeasure and flexible HSA behavior, respectively. Although the peak sled acceleration and seat inclination were different between these two cases, the ATD, helmets, and restraint belts were the same, so the helmet was predicted to have similar motion. Both countermeasure concepts restrained the helmet compared to the no countermeasure case (Figure 9B), but the rigid countermeasure appeared to hold the head back while the torso moved forward. The flexible HSA appeared to hold the helmet in position while allowing the helmet and head to move together, thereby lessening the applied forces and moments, as indicated by the Nij results.

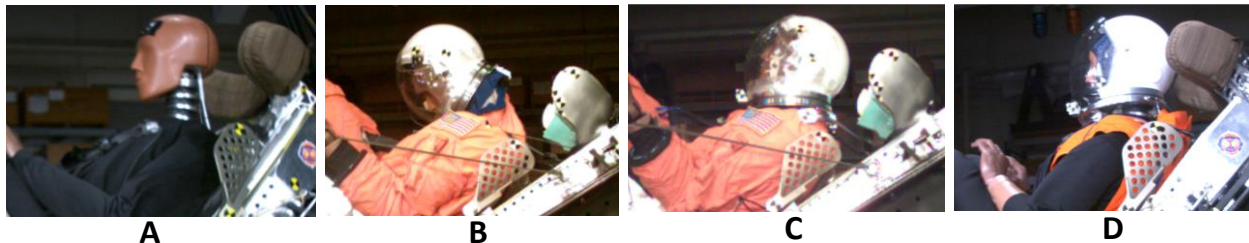


Figure 9. 50th ATD Body and Helmet Motion for (A) Unsuited, (B) Suited with No Countermeasure, (C) Suited with Rigid countermeasure, and (D) Suited with Flexible HSA Prototype.

In addition to the flight-like landing loads applied in the flexible HSA tests, two overload cases using the 50th ATD were performed as artificially extreme cases. All test parameters were kept the same, but the peak sled acceleration pulse was increased to represent overload cases. Due to limitations in schedule and with the potential to overload the prototype Orion seat, a 63% overload was performed for a 50th ATD with small helmet in frontal landing orientation, and a 38% overload was performed for a 50th ATD with standard helmet in frontal landing and yawed orientation. The acceleration sled increases were chosen based on the maximum available from the chosen sled pin, balanced with the goal of protecting the Orion prototype seat. Therefore, these cases do not represent real landing cases but provided some insight into robustness of the flexible HSA design beyond expected Orion landings.

In both overload cases, an increased Nij was found with the increased loading, but the 50th ATD was less sensitive in the standard helmet case with a 74% difference increase above unsuited, compared to the small helmet case with a 22% difference increase above unsuited. It is proposed that the tighter fit of the small helmet increases the potential for force transmission between the ATD head and helmet, and explains the increased sensitivity. Despite the artificially increased loading, the HSA maintained neck force and moment directionality while limiting peak Nij

magnitudes below NASA requirements. These overload cases were not part of the required testing but added confidence that an overload would not change the basic functionality of the flexible HSA, or reverse neck force and moment directions.

V. Conclusions

In order to minimize injury risk, NASA's extensive development ATD sled testing efforts have identified the need for a helmet countermeasure to be implemented into the OCSS Suit. Specific testing of prototype countermeasure designs showed that under-restraining or over-restraining the helmet during a forward landing configuration allowed the helmet to transmit forces and moments through the ATD head and neck and resulted in increased neck injury risk. Integrating a flexible HSA countermeasure into the OCSS Suit that rested on the shoulders, and was restrained by the seat harness, showed significant decreases in neck injury risk metrics compared to no countermeasure or a rigid style countermeasure. The HSA prototype displayed peak Nij responses below the quantitative NASA design requirements across all tested suited ATD configurations.

Review of high speed test video along with time-history force and moment plots, led to the flexible HSA meeting the qualitative design goals for this device. Comparing to previous prototypes, the flexible HSA importantly maintained the worst-case neck bending moment direction as flexion, avoiding the less desirable extension neck moment. Two additional extreme overload cases provided confidence that the flexible HSA will perform as expected and maintain neck moment directions. Overall this series of development tests identified an increased neck injury risk and followed the development of prototypes leading to the integrated flexible HSA. The supporting data showed overall low injury risk for worst case water landings and provided confidence in moving towards design certification.

VI. Forward Work

This development test data focused on understanding the effects of including prototype hardware, particularly the new helmet support assembly, but additional work is needed to improve our understanding and ensure safety to the Orion crew. The ATD data is useful for quantifying the required injury metrics to help to protect the crew from head and neck injury, but the ATD data does not provide feedback on the comfort of the device as part of the suit nor if any of the planned HSA loading into the shoulders and upper torso will cause any discomfort for the crew. Initial trials wearing the prototype device with the suit did not cause any discomfort for the users. However, it is expected that the fit of the HSA on each individual crew shoulder will play a role in the comfort and the final design may need to allow for minor adjustments or padding. Further testing is planned to obtain feedback on comfort and mobility for a range of occupant sizes. Additionally, from initial concept to prototype through design maturity, the crew office will be asked to provide feedback because there is no substitute for opinions from users experienced in space flight.

Another round of sled tests, likely of the same scope as this development testing, is planned as the prototype design matures in order to meet flight certification. Due to limitations in testing budget and schedule, dynamic simulations will be generated using LS DYNA to first recreate and match these development test results, and then cycle through a series of other landing cases predicted to be less severe. These additional cases will be run to verify that the head and neck injury metrics are not more severe than expected. The results of this development testing, along with future certification testing and simulation results will mitigate injury risk for worst-case water landings and abort scenarios, as well as provide confidence in integrating the flexible HSA into the OCSS suit for use in Orion spaceflight.

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