Orion Capsule Parachute Assembly System (CPAS) Airdrop Test Program Techniques, Challenges, and Solutions

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The Orion Capsule Parachute System (CPAS) project has completed qualification testing. Throughout the airdrop test program, CPAS employed a number of test techniques, including Low Velocity Air Drop (LVAD), single parachute darts, subscale parachute airdrop, and full scale capsule and dart airdrop tests. This paper will discuss the advantages and disadvantages for each type of test technique, the challenges encountered, and the lessons learned. Special attention will be given to the issues and solutions required to perform airdrop test extraction at 35,000ft above mean sea level (MSL).

I. Nomenclature

CDT = Crew Development Test
CM = Crew Module
CMS = Carriage Monorail System
CPAS = Capsule Parachute Assembly System
CPSS = CPAS Pallet Separation System
DTV = Drop Test Vehicle
EA = Mail Code for Engineering Directorate at Johnson Space Center
EDU = Engineering Development Unit
EFTA = Extraction Force Transfer Assembly
EFTC = Extraction Force Transfer Coupling
FBC = Forward Bay Cover
FBCP = Forward Bay Cover Parachute
GPS = Global Positioning Device
IMU = Inertial Measuring unit
JETS = JSC Engineering, Technology, and Sciences
JSC = Johnson Space Center
LM = Lockheed Martin
LVAD = Low Velocity Air Drop
M-DTV = Medium Drop Test Vehicle
MDS = Mid-Air Separation System
MSL = Mean Sea Level
NASA = National Aeronautics and Space Administration
PC = Parachute Compartment
PCDTV = Parachute Compartment Drop Test Vehicle
PTU = Power Transfer Unit
PTV = Parachute Test Vehicle
PCDTV = Parachute Compartment Drop Test Vehicle
RCS = Reaction Control System
RDL = Reposition Deployment Line
S-DTV = Small Drop Test Vehicle
TPS = Thermal Protection System
TSE = Test Support Equipment

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II. Introduction

The Orion spacecraft uses a series of parachutes to slow its descent and splash down safely. The parachute system, known as the Capsule Parachute Assembly System (CPAS), is being designed by National Aeronautics and Space Administration (NASA); Jacobs Engineering's Johnson Space Center (JSC) Engineering, Technology, and Sciences (JETS) consortium; and Airborne Systems. The CPAS configuration consists of three (3) mortar-deployed Forward Bay Cover Parachutes (FBCPs), two (2) mortar-deployed Drogue parachutes, three (3) mortar-deployed Pilot parachutes, and three (3) Pilot-deployed Main parachutes.

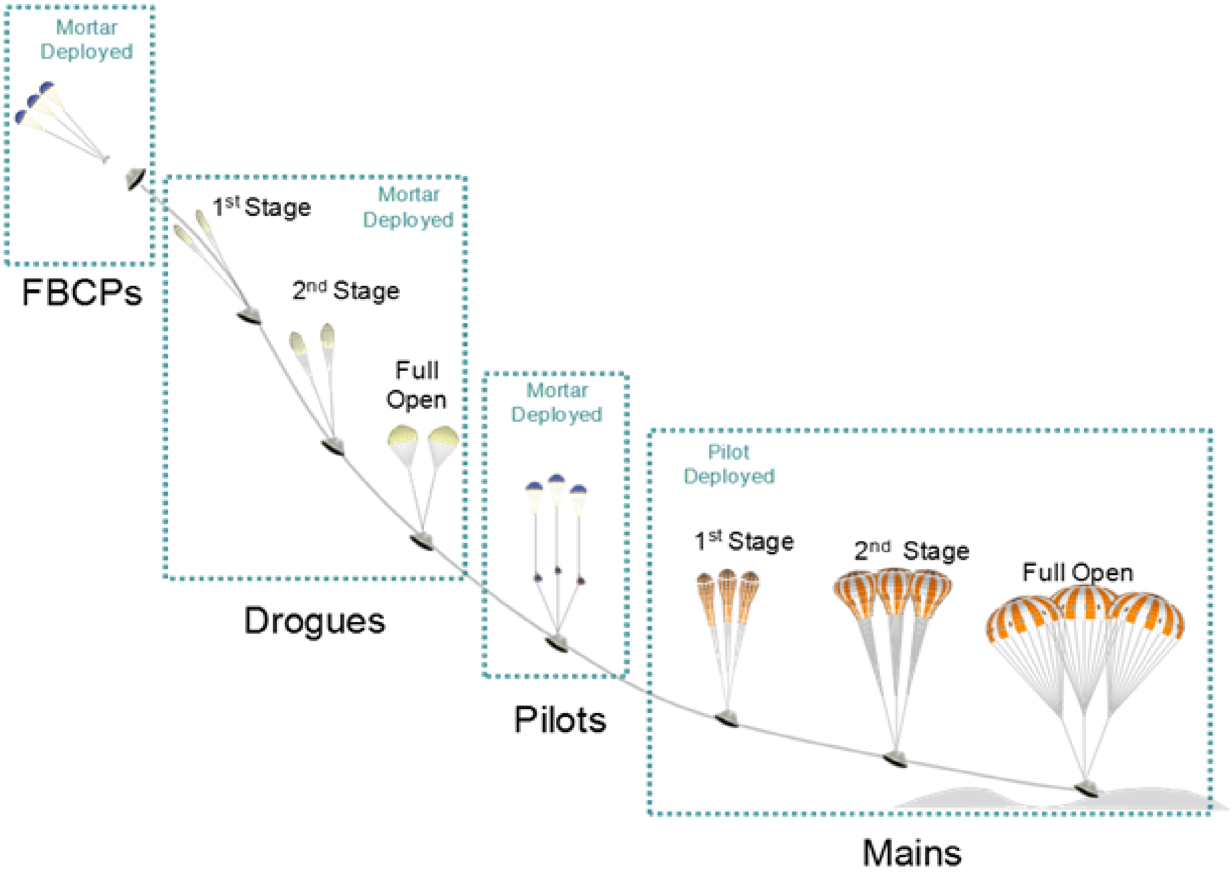

Fig. 1 CPAS Deployment Sequence - Nominal Mission

The CPAS project executed a rigorous set of airdrop tests, starting with simple test techniques and building up to more complicated test techniques throughout the test program. CPAS identified a set of criteria to select or develop a test technique.

Simple test techniques can be turned around more quickly than complicated test techniques. Simple tests also cost less per test to execute. The test vehicle mass needs to provide the desired canopy loading. The start-of-test altitude needs to provide enough headroom to meet the parachute sequences required to meet the test objectives. The test vehicle needs to be aerodynamically stable enough to meet dynamic pressure test objectives. The test vehicle needs to provide a flight-like structure to observe rigging, retention, and deployment test objectives. The mortar deployed parachutes need to be mortar deployed during tests. Parachutes need to be tested in their flight-like clusters. The test vehicle needs to provide a flight-like wake environment during testing. Test techniques need to provide flight-like deployment altitudes at deployment.

Based on these criteria, the CPAS test team evolved from simple tests, collecting single parachute performance data, to more complex tests to collect preliminary parachute cluster performance date, and then on to very complex tests to collect full parachute system data in flight-like environments.

Information on the avionics systems for each of these test techniques can be found in "Orion Capsule Parachute Assembly System (CPAS) Airdrop Test Program Avionics, Imagery, and Instrumentation Systems".[1]

III. Single Parachute, Small Dart Tests

The CPAS project began airdrop testing with small and medium dart-shaped drop test vehicles (DTVs). The carrier aircraft were helicopters. This test technique included very simple avionics consisting of sequence timers and riser load sensors. The avionics were constrained to fit within the bodies of the DTV's. The target parachutes and recovery parachutes were also contained within the DTV bodies.

The small drop test vehicle (S-DTV) mass provided a canopy loading suitable for a pilot parachute. The CPAS test team executed four (4) pilot parachute tests using this test technique.

Fig. 2 Small Drop Test Vehicle and Helicopter Release Mechanism

Fig. 3 Avionics Access for Small Drop Test Vehicle

Fig. 4 Small Drop Test Vehicle Test Sequence: helicopter carry, Programmer release, Pilot steady state, Recovery parachute

These tests provided very early single parachute performance data. The test technique is limited by the sling weight and altitude restrictions of the carrier aircraft. The release mechanism for a helicopter-based airdrop test is always a concern. The drop test vehicle (DTV) is generally free to rotate under the sling. Wrapping up the sling can affect the release mechanism function.

IV. Single and Cluster Parachute, Medium Dart Tests

The medium drop test vehicle (M-DTV) mass provided a canopy loading suitable for a single Drogue or Main parachute. The CPAS test team only attempted one helicopter airdrop test using the medium drop test vehicle (M-DTV). A cutter failure prevented the deployment of recovery parachute, planned to be a CPAS Main parachute.

Fig. 5 Medium Drop Test Vehicle Test Sequence: helicopter carry, Drogue steady state, M-DTV recovery

The CPAS test team required altitudes higher than provided by helicopter for combined Drogue/Main tests. A more controlled, higher reliability test technique was also desired. The test team relied heavily on the U.S. Army standard Low Velocity Airdrop (LVAD) processes, procedures, and hardware systems to develop a fixed wing M-DTV test technique.

LVAD provided a standard structural and extraction interface to C-130 and C-17 aircraft with a Type V platform. LVAD provided rigging and extraction standards and hardware.

The CPAS team designed a structure, Carriage Monorail System (CMS), which would restrain the M-DTV while in the aircraft, and release the M-DTV after extraction. The CMS was lashed to a Type V platform, using LVAD standards and hardware.

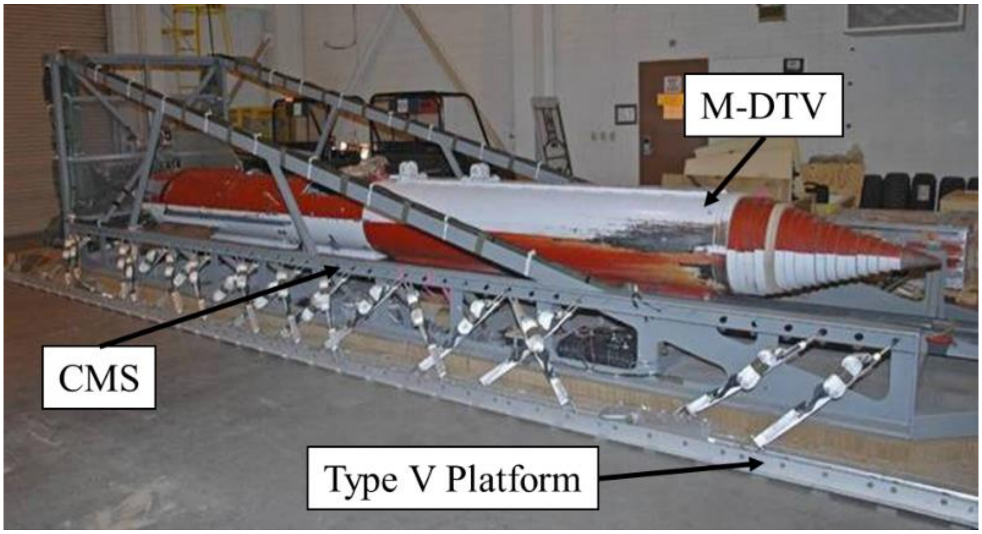

Fig. 6 M-DTV on CMS

The M-DTV had a T-shaped center rail captured by a center rail on the CMS.

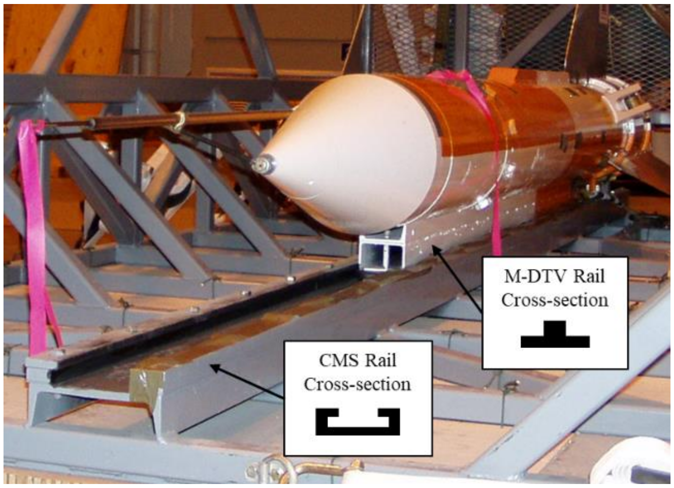

Fig. 7 Details of the M-DTV and CMS Rail System

The M-DTV was held to the CMS by a strap. After extraction the strap was cut, allowing the M-DTV to slide off the CMS. Separating the M-DTV from the CMS deployed the M-DTV programmer parachute. The sequencer on the M-DTV deployed the target parachutes. The CMS landed under its own recovery parachutes.

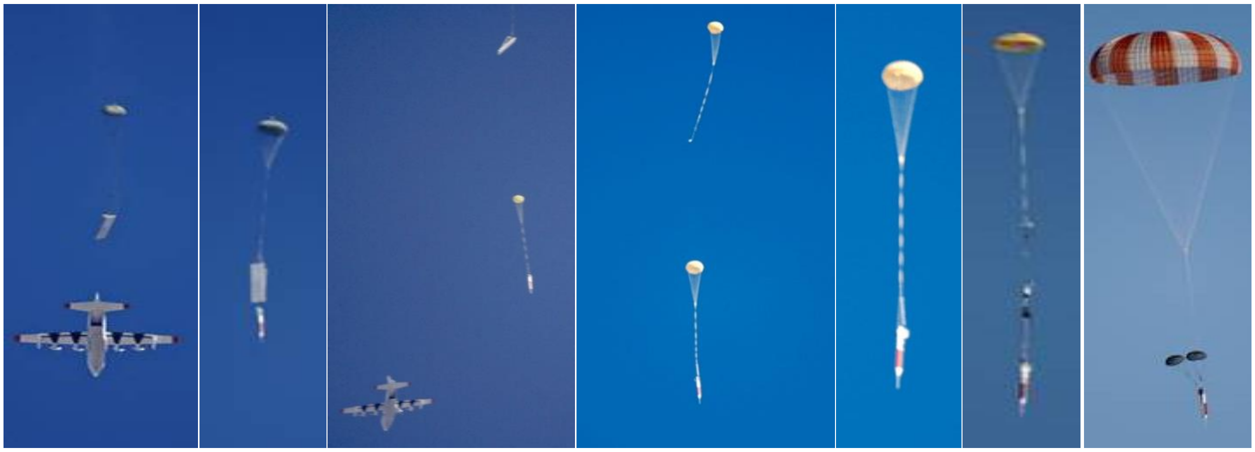

Fig. 8 Example of LVAD Medium Drop Test Vehicle Test Sequence: C-130 extraction, M-DTV/CMS separation, Programmer deploy, Drogue deploy, Drogue steady state, Main deploy, Main steady state

This test technique included very simple avionics consisting of sequence timers and riser load sensors. Global positioning system (GPS) sensors and antennae were added to the avionics system to provide more accurate rate of descent information. The avionics for this test technique were housed within the body of the M-DTV. The CPAS test team executed six (6) M-DTV/CMS tests.

This test technique provided enough altitude to test both a single Drogue parachute and a single Main parachute in series in the same test. However, the M-DTV did not have the mass nor the volume to test Drogue or Main clusters. More space was also required for more complex avionics.

V. Platform/Weight Tub LVAD Tests

The CPAS early parachute design activities required parachute cluster data in addition to single parachute data. None of the dart-shaped test vehicles could accommodate Drogue or Main cluster tests. The CPAS test team turned to weight tub based test techniques.

The test vehicle consisted of a weight tub lashed to a Type V platform. Three layers of cardboard honeycomb were stacked between the platform and weight tub to provide landing attenuation. For some tests, a parachute container was added to restrain the Main parachutes or provide a flight-like bay shape.

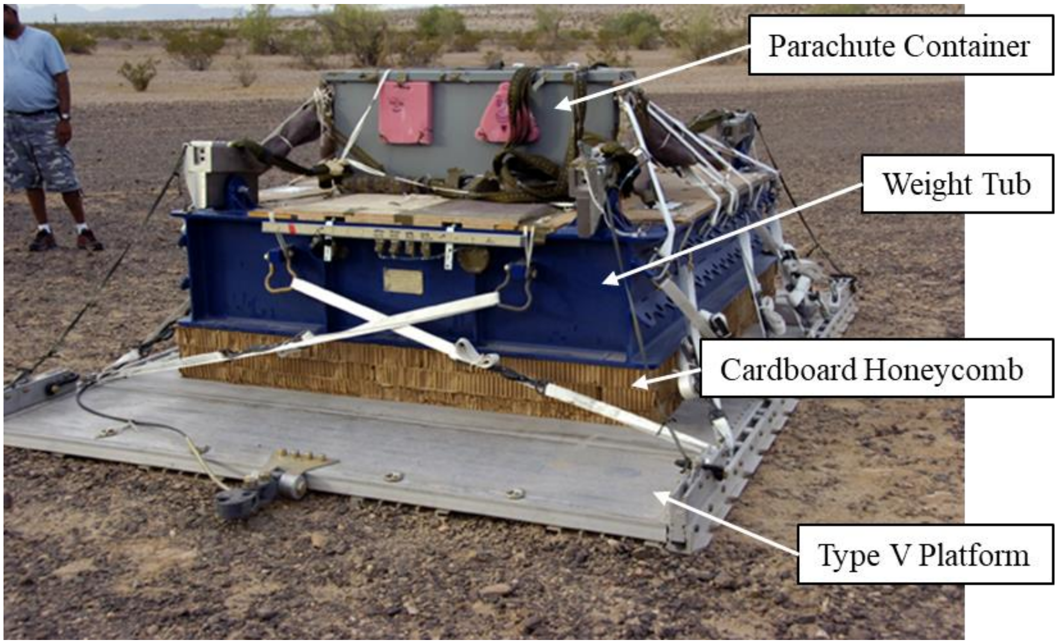

Fig. 9 Example 12ft Platform / 8ft Weight Tub Test Vehicle

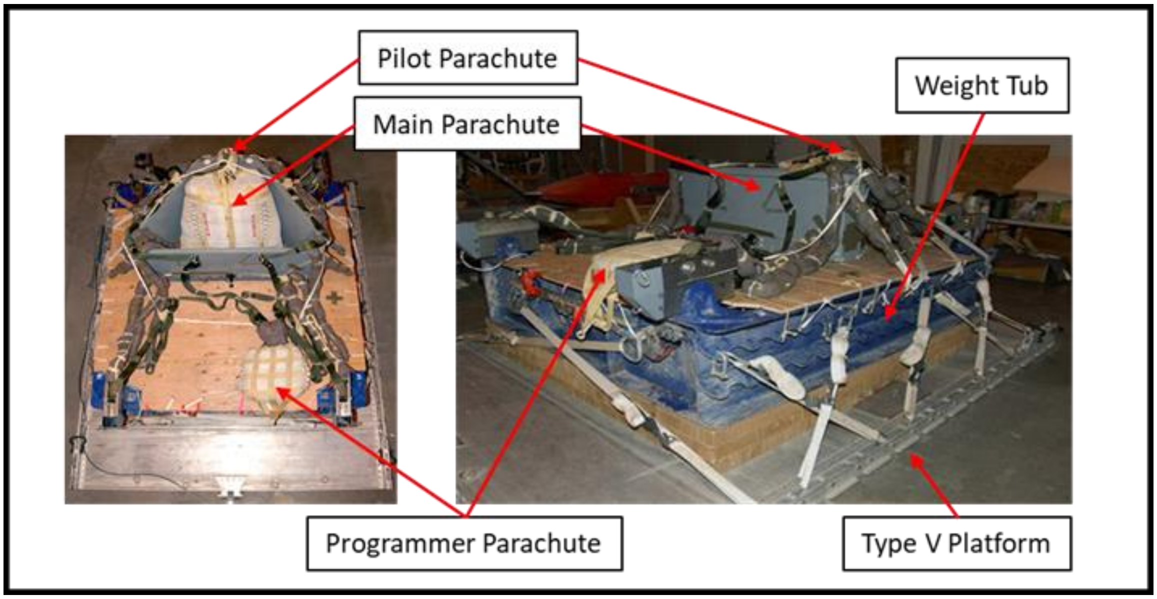

Fig. 10 Example 12ft Platform / 8ft Weight Tub Test Vehicle Rigging

A weight tub is a rectangular structure with slots for weight plates on the inside. In Figure 11 below, the slot numbers 14-22 can be seen. Weight plates were placed within the slots to achieve the desired test vehicle weight. The weight tub test vehicle masses were configured to represent the full Orion vehicle mass, approximately 20,000lbs, for parachute cluster testing.

Fig. 11 Avionics Bay within a Weight Tub Test Vehicle

For the CPAS tests, avionics were stowed inside the weight tub to protect the avionics from the parachute systems. This provides much more room for the avionics than within the S-DTV and M-DTV. The avionics still consisted of sequence timers, riser load sensors, and GPS.

The CPAS test team observed that full sheets of cardboard honeycomb did not provide as much landing attenuation as desired to reduce the shock environment for the avionics. The team cut out large squares within the sheets to further reduce the landing loads.

For the first few tests, CPAS used 8ft long weight tubs on 12ft platforms. Those test vehicles were not very stable when handing off from one parachute to the next. The test vehicles were much more stable when using 16ft weight tubs with 25ft platforms.

Fig. 12 Example 20ft Platform / 16ft Weight Tub Test Vehicle No Parachute Container

The CPAS team performed both single parachute and parachute cluster testing using platform/weight tub test vehicles. CPAS performed ten (10) airdrop tests using this test technique.

Fig. 13 Example 20ft Platform / 16ft Weight Tub Test Vehicle Test Sequence: C-130 extraction, Drogue steady state, Main first stage, Main second stage, Main full open, landing

For one of those airdrop tests, the CPAS team added a parachute compartment (PC) which was a high-fidelity representation of the Orion Crew Module (CM) forward bay, where the CPAS components will be stowed in and deployed from during spaceflight missions. This allowed a test of the spaceflight rigging, retention, and deployment, including mortar deployed Pilot parachutes.

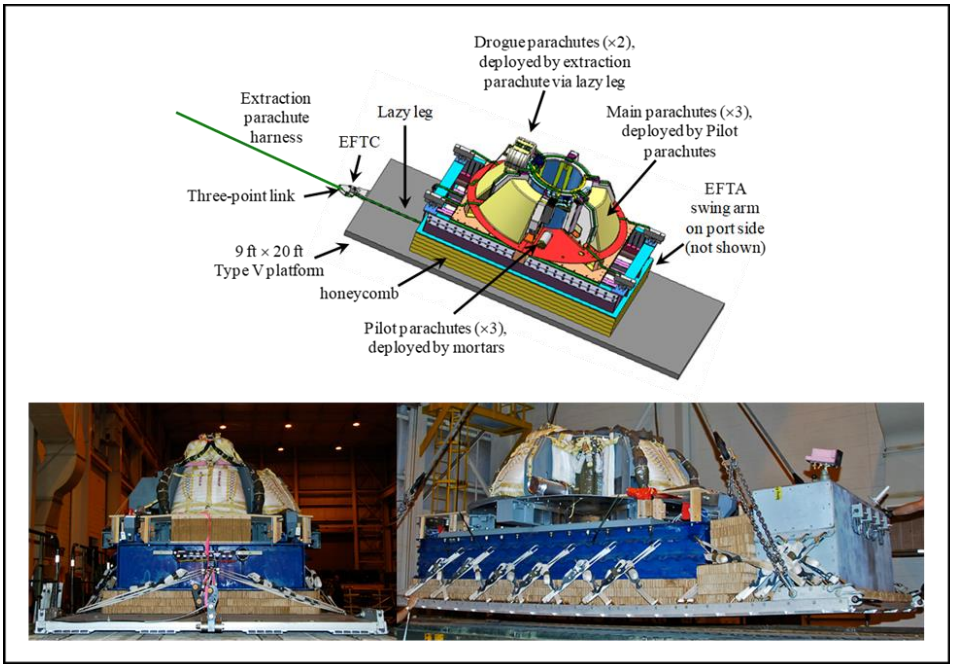

Fig. 14 Test Configuration for Parachute Compartment on a Platform/Weight Tub Test Vehicle

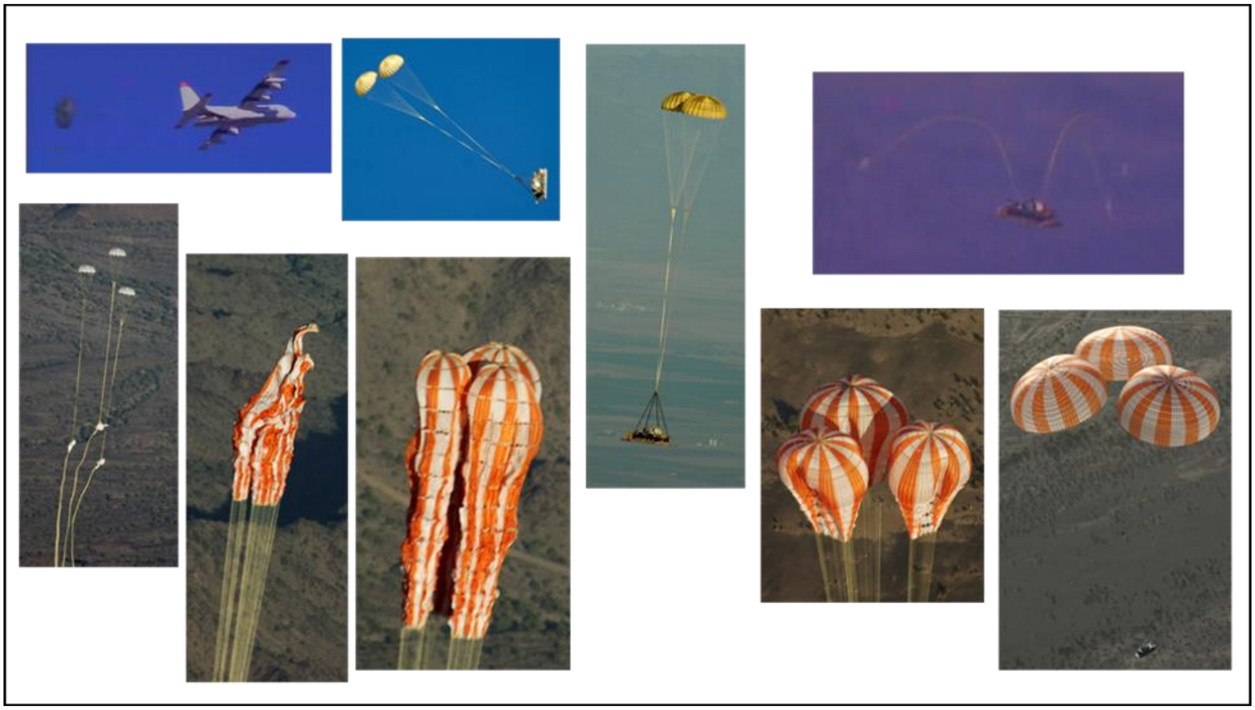

Fig. 15 Platform/Weight Tub/Parachute Compartment Test Sequence: C-130 extraction, Drogue deploy, Drogue steady state, Pilot mortar fire, Main deployment bag lift, Main deploy, Main first stage, Main second stage, Main steady state

This configuration was only viable because the Main parachute attach points allowed the test vehicle to land flat. Later CPAS configurations would have landed the test vehicle edge-on, which would have damaged the test vehicle.

The advantages of the simple platform/weight tub test technique within LVAD standards include the ability to extract from altitudes up to 25,000ft MSL and accommodations to configure the test vehicle mass to achieve the desired canopy loading.

Disadvantage of this test technique include the difficulty in providing a forward bay geometry to observe deployments. Test vehicle instability limits the maximum reasonable dynamic pressure of test points. The test vehicle does not provide a flight-like forebody wake to the parachute systems. For these reasons, the CPAS test team moved on to more complicated test vehicles.

VI. Full Scale, Full System Dart Tests

As the CPAS parachute test program progressed, the test team developed two (2) test techniques, which together would meet all of the full system test objectives. A very aerodynamically stable dart-shaped test vehicle provided high dynamic pressure test conditions. A less stable, capsule shaped test vehicle provided flight-like wake environments during tests.

Each test vehicle would use a parachute compartment (PC) reflecting the geometry of the CM forward bay. Over the life of the CPAS design cycle, there were four (4) versions of the parachute compartment. The Engineering directorate (EA) at JSC designed the first referred to as EA PC. It reflected a preliminary design of the forward bay. The Orion prime contractor, Lockheed Martin (LM), provided a second, higher fidelity test vehicle referred to as LM PC. The LM PC had interfaces to allow integrated airdrop testing with an Orion Forward Bay Cover (FPC). Both of these versions were designed for CPAS Main and Drogue parachute steel risers.

When the CPAS design was modified to include textile risers, a second EA PC and a second LM PC were used for airdrop testing. Again, the LM PC included interfaces for a FBC. The final LM PC included the most flight-like forward bay geometry.

Fig. 16 Rotational View of EA PC before Parachute Integration

Fig. 17 Rotational View of EA PC after Parachute Integration

Fig. 18 Overview of EA PC after Parachute Integration

For some tests, to get more mortar deployed demands on the FBC parachute, brackets were installed in the center of the PC tunnel to install and deploy FBC parachutes. Thermal Protection System (TPS) tile mass simulators were added to the FBCP mortar lids for a more flight-like deployment.

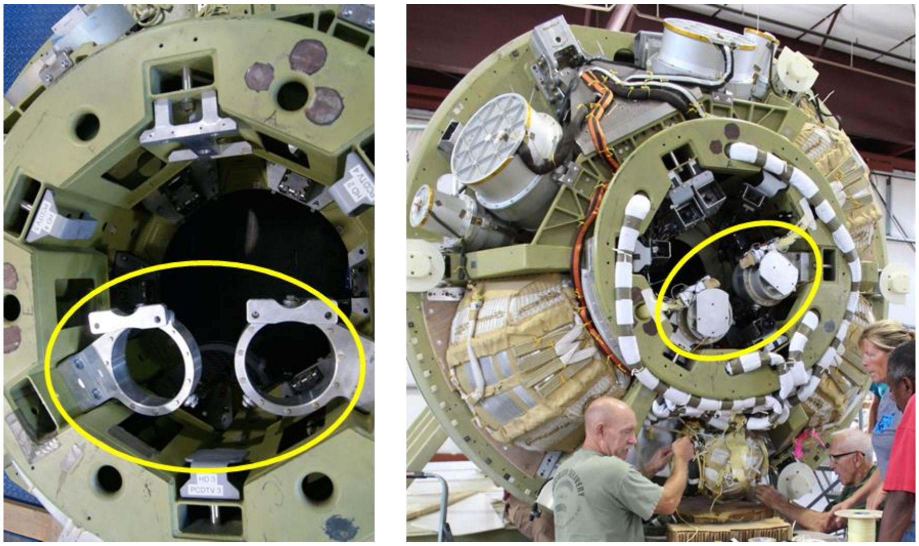

Fig. 19 FBCP Tunnel Integrations. Left: Tunnel Brackets.
Right: Test Configuration including TPS Mass Simulators

The dart-shaped test vehicle was called the Parachute Compartment Drop Test Vehicle (PCDTV). The PCDTV had four (4) structural components: the PC, the flair section, the avionics tube, and the nose/ballast. Each structure had its own handling fixture. The parachutes were installed into the PC at ground level. Then the PC was integrated into the flair section, and lower fins and skins were installed. Next the flare section and avionics tube were joined. The final step in the PCDTV assembly mated the nose to the avionics tube and adding the upper fins and skins.

Fig. 20 Assembly of the PCDTV

The PCDTV was sized to use either a C-130 or C-17 as it carrier aircraft. The EA PCs were trimmed so the PCDTV could be extracted from a C-130. Only the EA PCs could be used with the PCDTV. Both types of aircraft were used during PCDTV testing. The PCDTV required an extraction system. The test team kept as many of the aircraft interfaces within LVAD specification to avoid a certification program with the US Air Force. The PCDTV extraction system was called the Mid-Air Separation System (MDS). It consisted of a cradle weldment lashed to a standard 32ft, Type V platform. The MDS extraction parachute attach point was a standard military Extraction Force Transfer Assembly (EFTA), using an Extraction Force Transfer Coupling (EFTC).

Fig. 21 MDS Assembly

The PCDTV was held to the MDS by a keel pin, to take forward and aft loads, and six (6) Kevlar straps to manage up loads. The weldment managed down and side loads. NASA Single Event Fittings cut the Kevlar straps to release the PCDTV after extraction.

Fig. 22 PCDTV / MDS Assembly

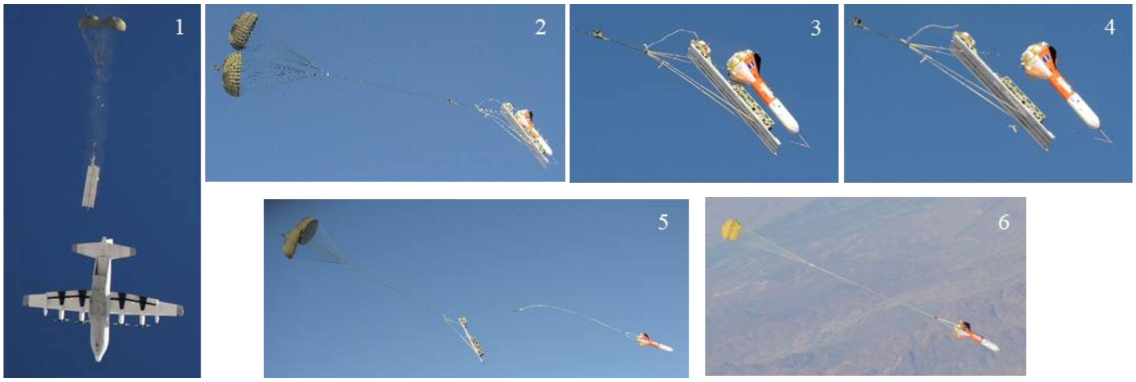

Fig. 23 PCDTV/MDS Separation Sequence: C-130 Extraction, PCDTV/MDS Separation, Programmer Deploy

The PCDTV provided a technique to test the full Drogue/Main CPAS system, in a flight-like sequence. Some PCDTV tests included two (2) FBC parachutes, mortar deployed from brackets mounted inside the PC center tunnel. The PCDTV would not accommodate a FBC structure for a jettison test.

Fig. 24 Nominal (no FBCP) PCDTV Parachute Sequence: Drogue mortar fire, Drogue line stretch, Drogue release, Pilot mortar fire, Main bag lift, Main line stretch, Main first stage, Main full open

The aerodynamically stable PCDTV allowed test points at higher than required dynamic pressures to demonstrate system load margins. The CPAS test program included nine (9) PCDTV tests.

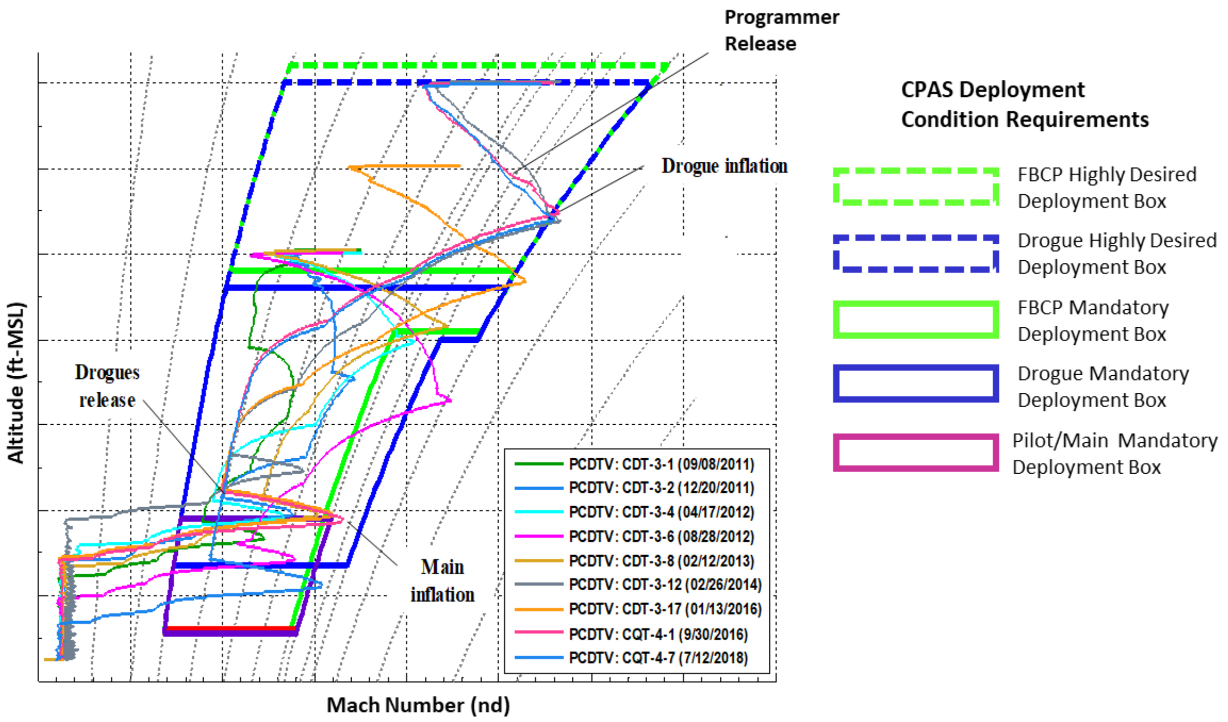

Fig. 25 PCDTV EDU and Qual Test Trajectories

VII. Full Scale, Full System Capsule Tests

While the PCDTV tests provided higher dynamic pressure test conditions, they did not provide flight-like wake environments for the parachutes. This wake environment is most important for the FBC, Drogue, and Pilot parachutes. To create flight-like wakes, the CPAS test team designed and employed a full scale capsule shaped test vehicle, the Parachute Test Vehicle (PTV).

To create a flight-like wake during airdrop testing, the most important geometric feature is a full size heatshield and shoulder, at least 24in up the backshell. A full width PTV fit within the C-17 extraction capability. The PTV height had to be truncated to fit within the C-17 extraction limit.

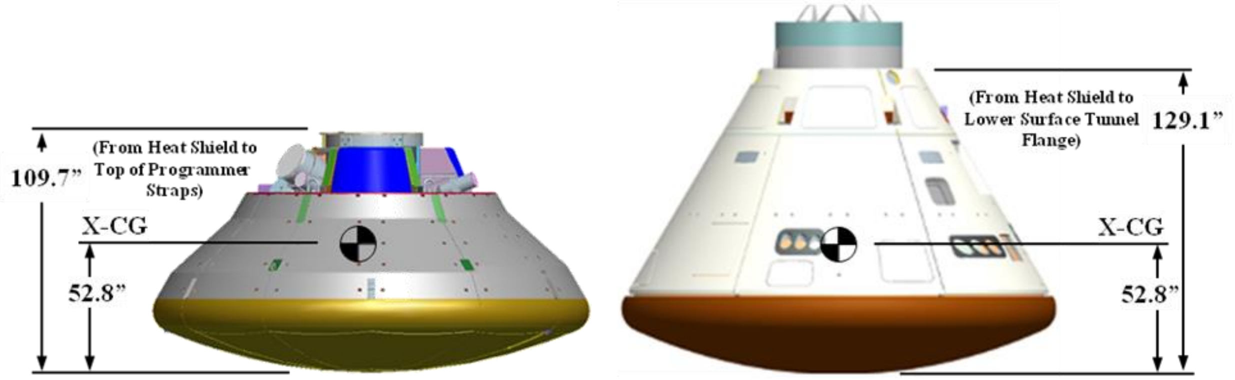

Fig. 26 PTV vs Orion Dimensions

The PTV center of gravity was located in an Orion-like position with respect to the bottom point of the heatshield, so that aerodynamic properties would be similar. The taller Orion capsule is more stable than the PTV. The Orion capsule has a Reaction Control System (RCS) to maintain attitude and rates prior to Drogue parachute deploy. The PTV did not include an RCS, so the test technique relied on suitable vehicle attitude and rates at the time of Programmer parachute release to provide vehicle stability throughout the FBC parachute and Drogue phases of each test. Both Orion and the PTV rely on releasing the Drogue parachutes at favorable attitude and rates to maintain vehicle stability during the Pilot/Main parachute deploy.

Like the PCDTV, the PTV used parachute compartments to provide the geometry of the Orion forward bay for parachute retention and release. The PTV could use either the EA PCs or the LM PCs. Only the LM PCs had interfaces to secure and jettison an FBC, so integrated testing with the FBC required the LM PCs.

Assembly of the PTV was simpler than the PCDTV assembly. The parachute systems were installed into the PC at ground level, then the PC was lifted and bolted onto the capsule shaped forebody. Foam panels, bolted to the forebody, provided the correct outer mold line.

Fig. 27 Payload Test Vehicle (PTV) Assembly

The PTV extraction system was called the CPAS Platform Separation System (CPSS). It consisted of a weldment bolted to a standard 24ft, Type V platform. The CPSS extraction parachute attach point was a standard military EFTA using an EFTC.

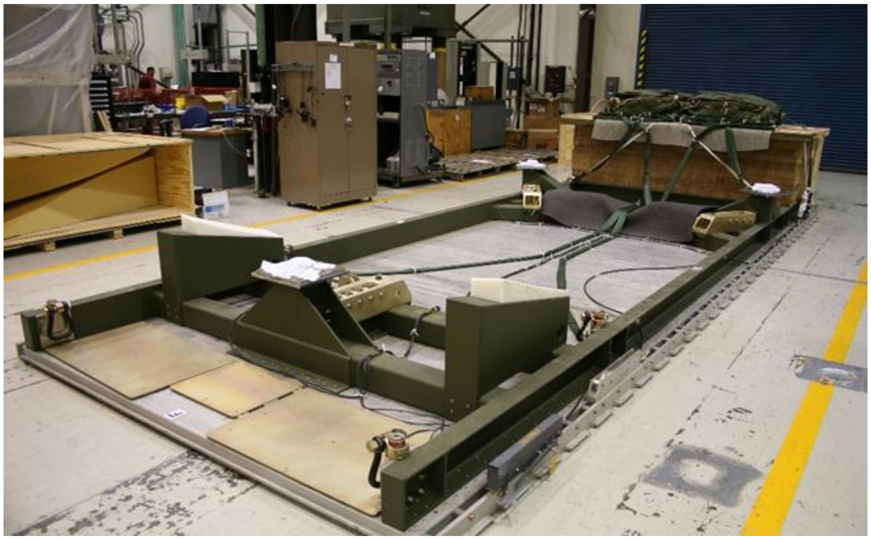

Fig. 28 CPAS Pallet Separation System (CPSS) configuration

The PTV integrated onto the CPSS using three (3) ball and cup joints. Vectran cords were laced between spools on the PTV and CPSS. Tensioning the Vectran provided a preload between the PTV and CPSS, which maintained the integrity of the joint. After extraction, cutting the Vectran cords released the PTV from the CPSS.

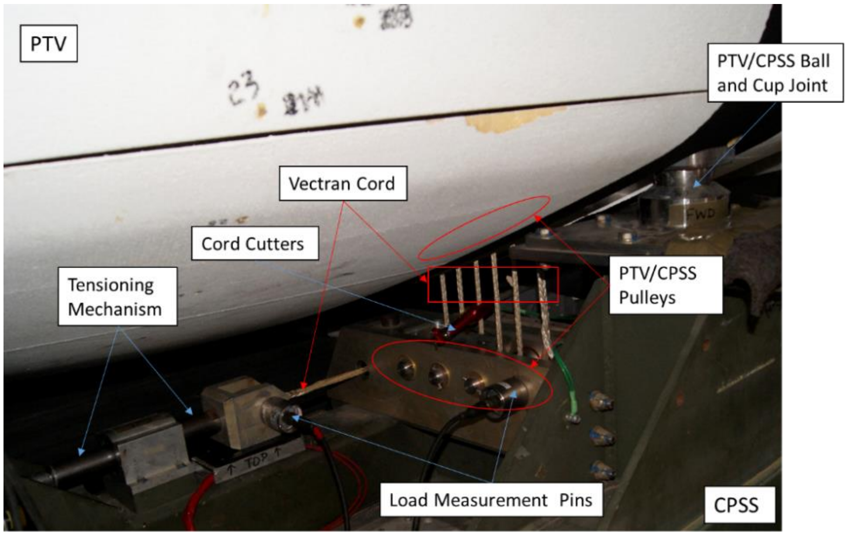

Fig. 29 PTV/CPSS Joint

The PTV avionics were located within the forebody structure. The CPSS avionics were placed within the weldment.

Fig. 30 PTV / CPSS Assembly

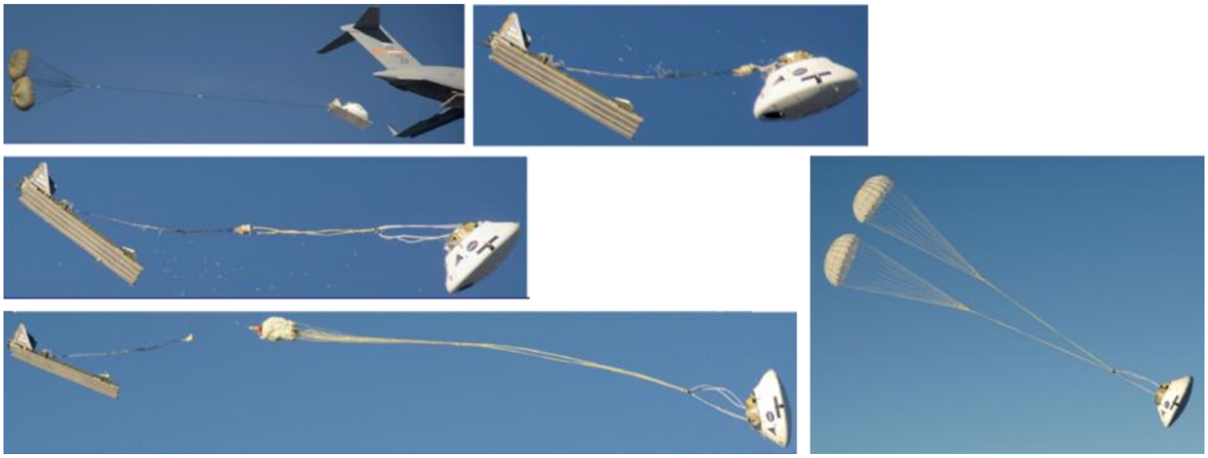

Fig. 31 PTV/CPSS Separation Sequence: C-17 extraction, PTV/CPSS separation, Programmer deploy

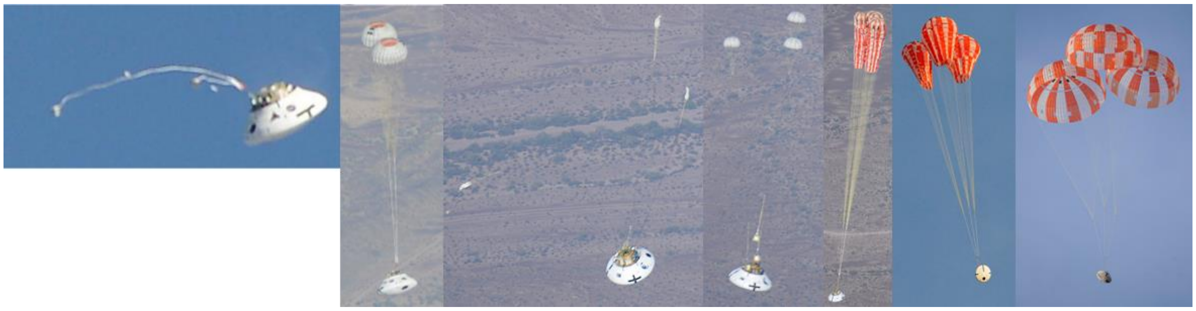

Fig. 32 Nominal PTV Parachute Sequence: Drogue mortar fire, Drogue full open, Pilot mortar fire, Main first stage, Main second stage, Main full open

As the test team collected data about the aerodynamic characteristics of the PTV, the test sequences included PTV freefall phases to increase the dynamic pressures of PTV test points. "Bail-out" software was added to the PTV sequence control software to terminate a PTV freefall if undesirable rates built up during the freefall phases.

Some PTV tests included two FBC parachutes, mortar deployed from brackets mounted inside the PC center tunnel. The PTV with LM PC were used four (4) times to perform airdrop tests. There tests provided test data and observations of the interactions among a capsule-like vehicle, the CPAS parachutes, and FBC jettison and parachute systems.

Fig. 33 PTV/FBC Test Sequence: Programmer release, FBC parachute deploy, FBC jettison

The capsule-shaped PTV provided test points with representative wake environments. The CPAS test program included 16 PTV tests.

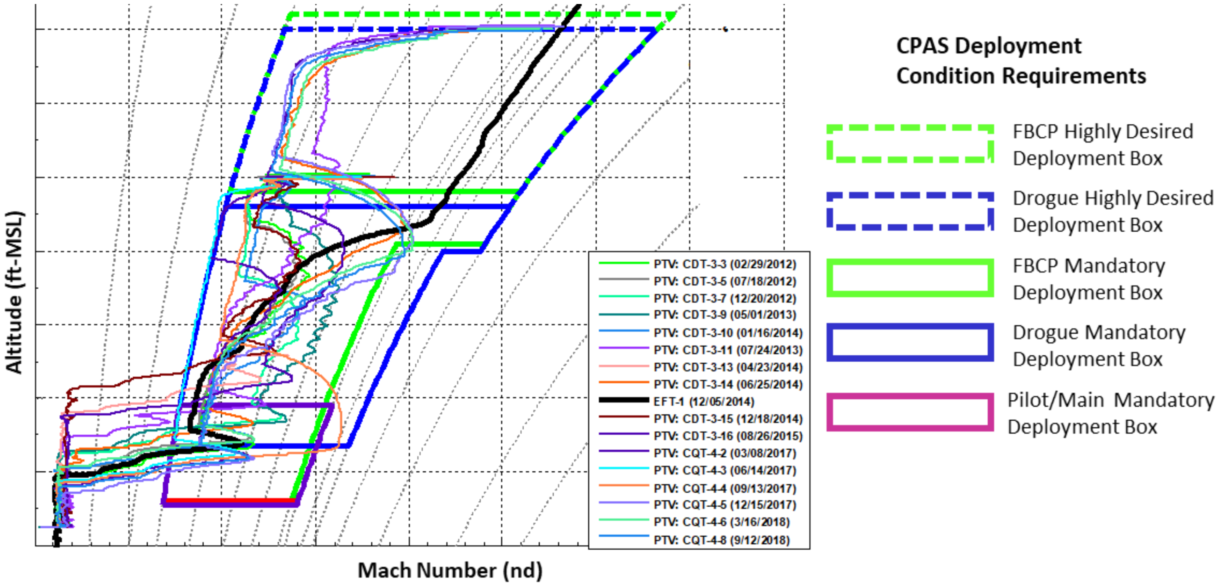

Fig. 34 PTV EDU and Qual Test Trajectories, Space Flight Test EFT-1 included for comparison

VIII. Subscale Main Parachute Tests

As CPAS airdrop testing proceeded, analysts noticed that tests with a two (2) Main parachute cluster experienced a pendulum motion of the PCDTV or PTV. The Orion CM had not been designed to withstand the increased loads from pendulum at the time of splashdown. The CPAS test team designed a test technique and test vehicle to rapidly execute a large number of 30% subscale Main parachute tests to evaluate design options which could reduce pendulum dynamics.

The test vehicles were simple steel box structures, weighted to achieve the desired canopy loading for single and cluster parachute testing. Closeout plates were made of steel, wood, or polycarbonate. Landings were attenuated with cardboard honeycomb and foam sheets. The avionics were mounted inside the steel box. The carrier aircraft was a Skyvan. The team executed around 40 airdrop tests in this series. Unfortunately, the performance data collected at the subscale level did not repeat at the full scale level.

Fig. 35 Subscale Airdrop Testing

IX. Airdrop Testing above 25,000ft MSL

The mandatory deployment envelope for CPAS FBCP and Drogue parachute certifications was restricted to less than 25,000ft MSL because the maximum altitude of standard LVAD extractions is limited to below that altitude. Testing above 25,000ft MSL would require costly, time-consuming U.S. Air Force certification of non-standard equipment, processes, and procedures. However, there were off-nominal Orion trajectories which required higher altitude parachute deployments.

During the CPAS EDU test series, a Department of Defense funded program performed the testing and system design required to certify 35,000ft extractions for a payload weight class which would include the CPAS PCDTV and PTV. The CPAS test team worked with the U.S. Air Force 412 Test Wing to perform airdrop tests at both 35,000ft and 30,000ft MSL.

The aircraft airspeed for 25,000ft extractions is 145KIAS. The aircraft airspeed for 35,000ft extractions is 190KIAS, which result in a higher energy extraction despite reefing of the extraction parachutes. CPAS test vehicles and U.S. Army standard hardware were not designed for the increased loads and dynamics at the higher altitude. CPAS test simulations did not have the fidelity or validation data to accurately predict loads on the hardware after extraction. CPAS and the test wing performed a series of tow tests to quantify and predict the extraction parachute loads.

The PCDTV/MDS test vehicles did not require modifications for 35,000ft extraction.

EDU test CDT 3-11, using a PTV, was the first CPAS test extracted from 35,000ft. The initial PTV/CPSS test technique held on to the EFTC extraction point on the CPSS until recovery parachutes deployment. While this worked well for 25,000ft extractions, for 35,000ft extractions the increased energy and change in PTV/CPSS attitude before separation damaged the EFTC bracket.

There was an extraction system anomaly noted on crew development test (CDT) 3-1. The extraction deployment line whipped vertically in the C-17 during extraction parachute inflation. This whip action slammed the EFTC into the aircraft deck, damaging the deck. In subsequent tests, this dynamic was controlled by revising the line bag packing procedures and tying the extraction line to the deck at several locations.

A reposition backstop was added to the CPSS so that the EFTC was released immediately upon ramp clear, similar to a standard LVAD sequence. Releasing the EFTC repositioned the extraction parachute load to a confluence fitting and harness legs attached to the backstop.

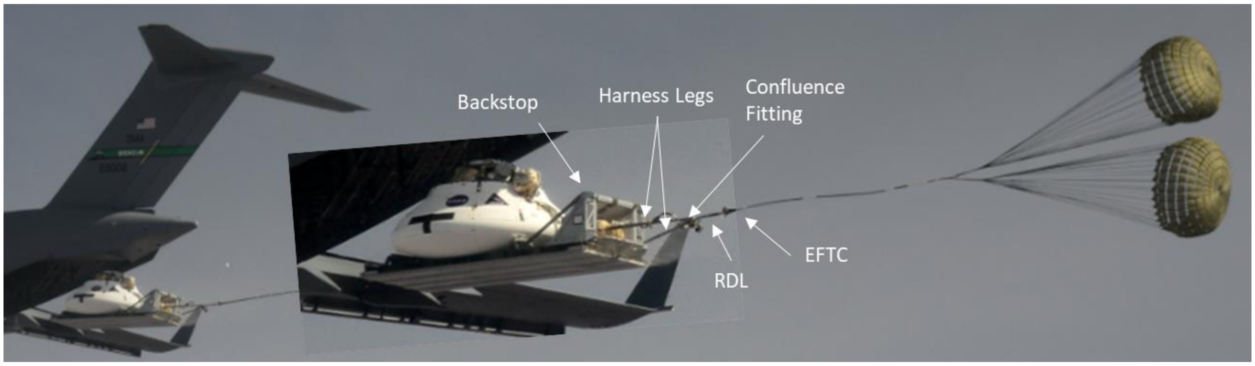

Fig. 36 PTV/CPSS Extraction Reposition System

Three (3) hardware configurations were tried for the confluence fitting. A mid-air release mechanism (MARM) was successfully used once, but had a mechanical failure once, and then a premature release of the CPSS recovery parachutes during reposition. An existing design 6:2 confluence was tried, resulting in a near failure of the Reposition Deployment Line (RDL). Finally, a custom designed 3:2 confluence fitting was successful.

The 6:2 confluence fitting failure resulted in an assessment of the applicability of Nylon vs Kevlar material usage for the RDL and the harness legs. Kevlar straps had higher load capability while Nylon straps stretched, adding load attenuation. The CPAS test team needed to be able to model and verify the extraction and reposition dynamics to use this test technique without excessive risk to the test vehicles. The premature release of the MARM system caused the only PTV apex forward PTV/CPSS separation in the test program, which resulted in loss of some test objectives. The CPAS team executed a series of ground tests to understand the loads and dynamics, and to characterize Nylon and Kevlar responses and contributions to the system performance. The team instrumented the 3:2 confluence fitting and CPSS harness attach points and collected data from several 25,000ft tests to inform the models predicting the reposition loads and dynamics. Photogrammetry was also used to characterize the dynamics.

Once the loads were better understood, the team modified the reefing of the extraction parachutes to reduce loads. C-17 tow tests were required to verify the new reefed extraction parachute loads. A hybrid RDL composed of longer loops of Nylon encompassing shorter loops of Kevlar. This hybrid RDL had the stretch of the Nylon, and should the Nylon loops fail under load, the Kevlar would maintain the integrity of the RDL. This final PTV/CPSS configuration was successfully used on the last three (3) PTV CPAS qualification tests from 35,000ft.

Fig. 377 Hybrid RDL attached to EFTC Hardware

The CPAS project spent considerable time and money to understand and develop a test technique which provide test data above 25,000ft. This effort paid off when the models used to certify CPAS performance included test derived data points instead of relying on extrapolation from lower altitude test points.

More details on the ground testing and model development are documented in “Extraction-Separation Performance and Dynamic Modeling of Orion Test Vehicles with Adams Simulation: 4th Edition”[2].

X. Test Failures and Lessons Learned

A parachute test program as extensive as the CPAS test series, should expect to spend time and money developing the test techniques needed. Many of the loads and dynamics will not be predictable until after the first test execution collects data and observations. The following are examples of test executions and failures experienced during the CPAS test program, and how the lesson learned from those failures contributed to a success CPAS design and qualification testing.

A. CDT 2 Test Failure

CDT 2 was the first test to attempt a PTV/CPSS test technique. The extraction and PTV/CPSS separation models were not mature and could not predict whether the PTV separation attitude would be apex forward (not desired) or heatshield forward. An apex forward separation, with some rotation could result in a tumbling vehicle, putting the Programmer parachute phase at risk, propagating a failure onto the CPAS system and loss of test vehicle.

In an attempt to mitigate this failure mode, the CDT 2 test technique added an initial Programmer side attach point to arrest an apex forward separation. Stabilization parachutes were added to the Programmer phase to reduce the time where the PTV was not controlled by a parachute. The Programmer parachute risers were shortened to reduce deployment time, bringing the PTV under parachute control more quickly.

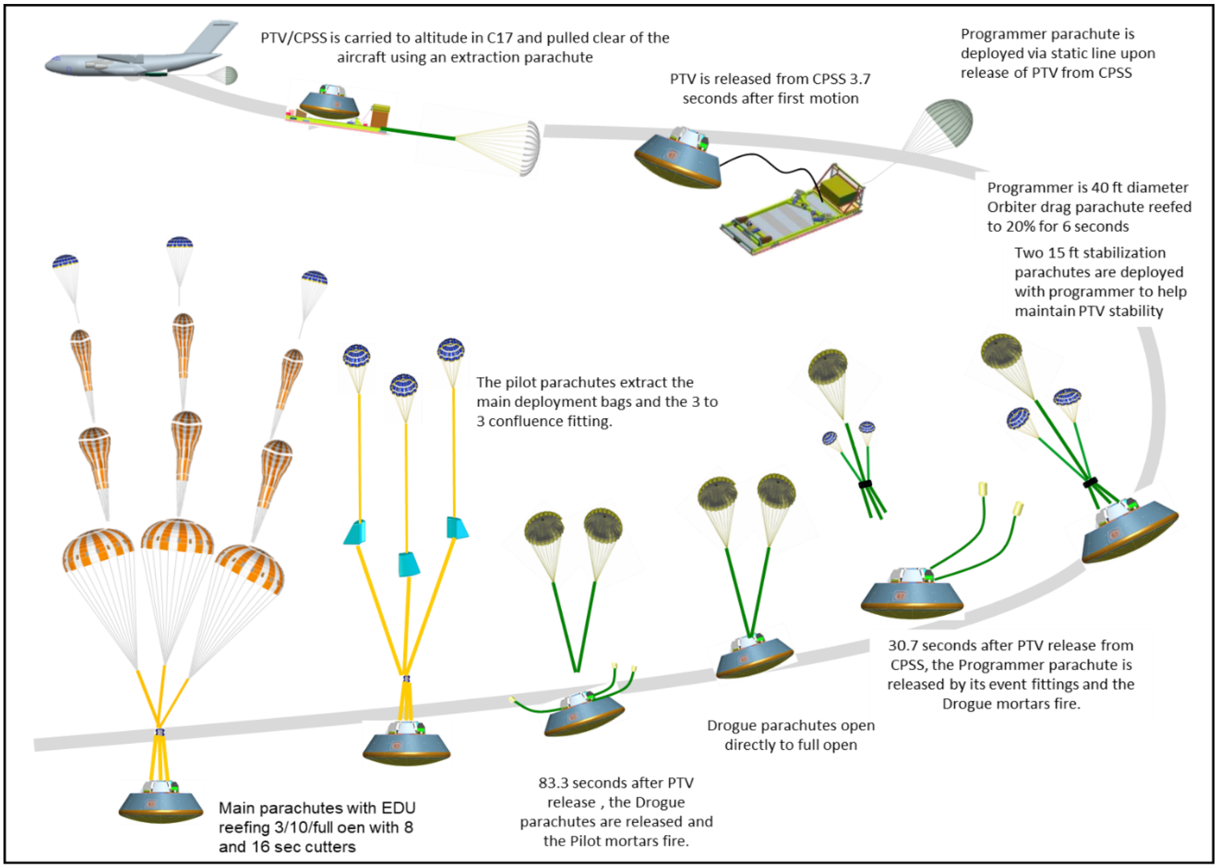

Fig. 388 CDT-2 Test Operation Concept

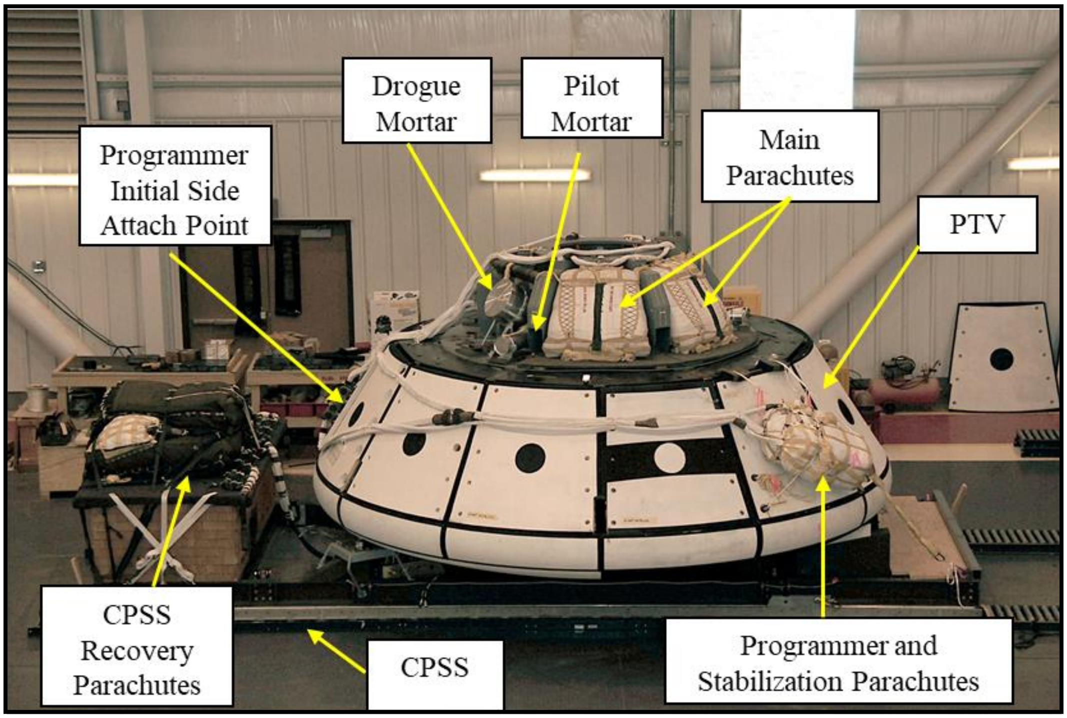

Fig. 39 CDT-2 Test Configuration

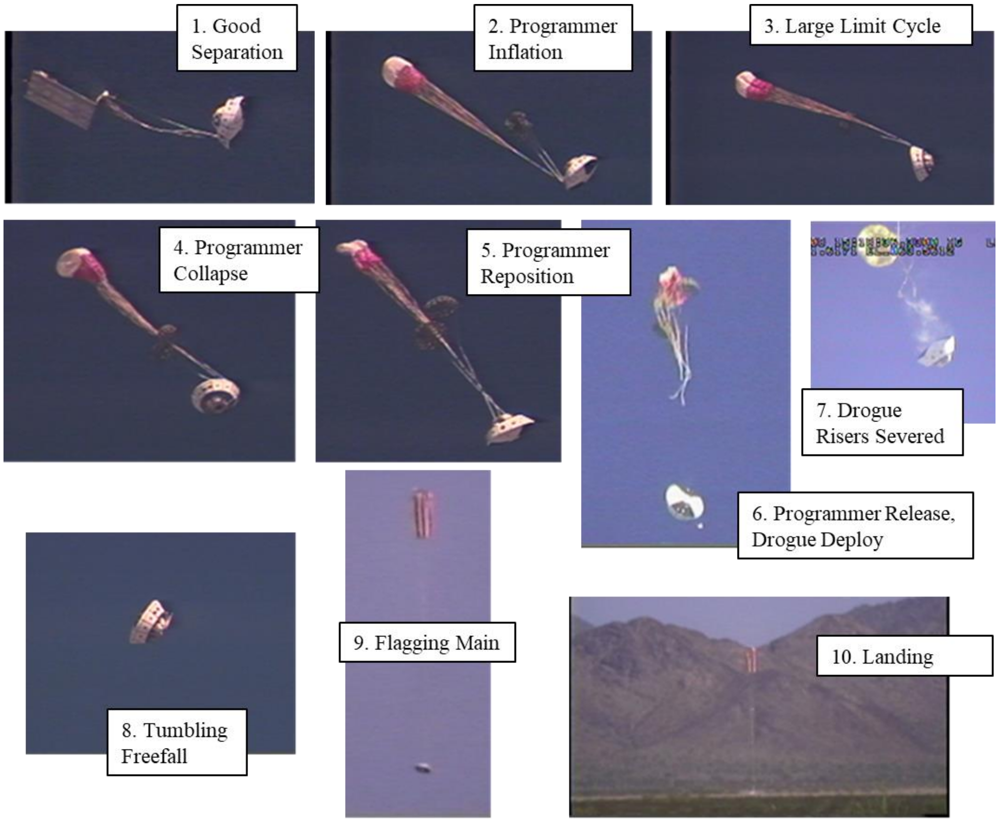

Fig. 390 CDT-2 Test Results

The PTV separated from the CPSS in a heat shield forward orientation. The Programmer inflated as expected, the stabilization parachutes did not inflate initially. The Programmer inflation load went through the initial side attach point, causing the PTV to pitch over past apex forward.

The motion of the rotation caused the Programmer and stabilization parachute risers to wrap up around the vehicle, decreasing the trailing distance of the parachutes with respect to the PTV, pulling the parachutes further into the vehicle wake. The Programmer parachute collapsed during the initial pitch oscillation. As the PTV completed the first limit cycle and started the second, the Programmer and stabilization attach point repositioned to above the PTV. Reposition from the initial side attach point to the three point attach on the top of the PTV released an additional 16ft harness assembly, which increased the trailing distance between the parachutes and the PTV. Following reposition, the Stabilization parachutes inflated, which prevented the Programmer parachute re-inflation.

Without an inflated Programmer, the PTV continued to oscillate and pick up speed. The PTV avionics released the Programmer and Stabilization parachutes and mortar deploying the Drogue parachutes at the planned time. The PTV was inverted when the Drogue parachutes started to inflate at which point both of the Drogue parachute risers were severed as they loaded across the remaining structure from the Programmer initial attach point on the side of the PTV.

The brief load from the Drogues inflation imparted a tumbling moment to the PTV. With no Drogue parachutes, the tumbling PTV continued to pick up speed and rotation velocity. Centrifugal forces deployed the Main parachutes before the Pilot mortars were fired. The disorderly deployment of the Main parachutes caused two of them to fail and release from the PTV. A single, heavily damaged Main parachute remained attached to the PTV. The test avionics completed the test sequence, firing the three Pilot mortars just before the PTV struck the ground. The PTV impacted at approximately 190 fps. The PTV was damaged beyond repair.

Several lessons were learned from this test failure. The most important observation for future CPAS testing was that the PTV/CPSS separation resulted in the desired heat shield forward attitude with low rates. Video photogrammetry and some recovered test data were used to validate future models of the separation.

After CDT 2, the CPAS team invested in an avionics upgrade which allowed control of the PTV/CPSS release based on pitch and pitch rate, rather than time, providing very repeatable test initial conditions.

All subsequent test techniques carefully reviewed the trailing distance of test parachutes and maintained sufficient distance, even at the cost of longer periods without control.

More information about this test failure and the return to testing can be found in “Cluster Development Test 2 an Assessment of a Failed Test”[3] and “Orion Boiler Plate Airdrop Test System”[4].

B. TSE-01C Test Failure

To test the upgraded CPAS test avionics, a set of three (3) platform/weight tub tests were executed. These tests were designated as Test Support Equipment-01 (TSE) A, B, and C. The test technique included holding the extraction parachute at the EFTC attach point until reposition to a backstop structure. It was planned to hold the EFTC for around 12 seconds.

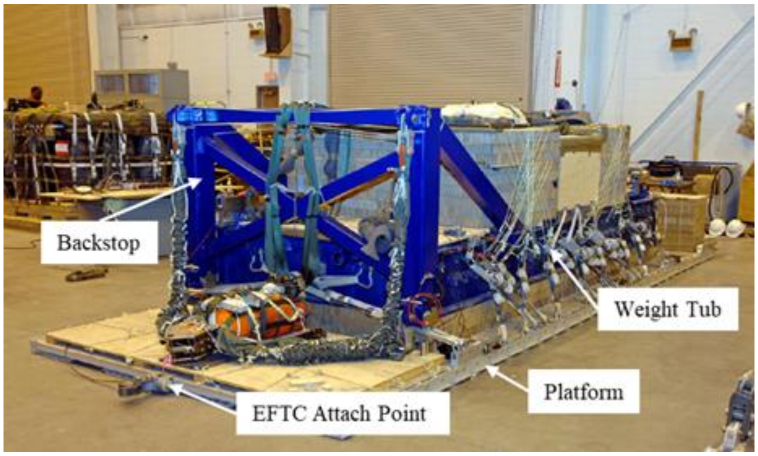

Fig. 401 TSE-01 Test Vehicle

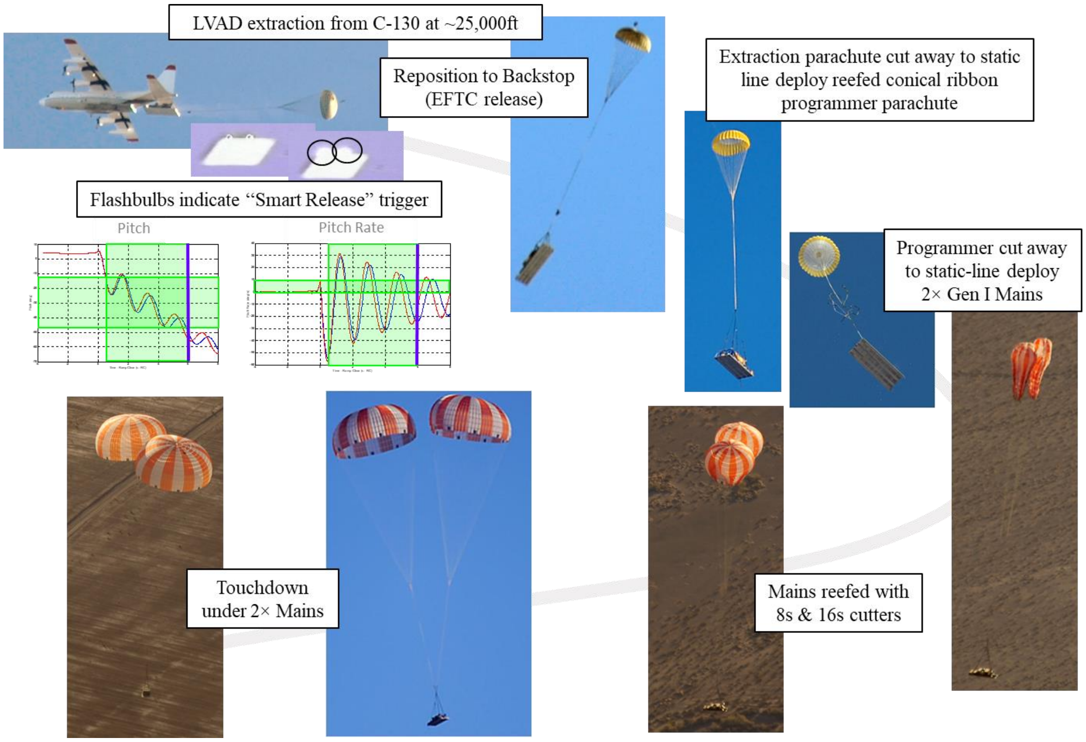

Fig. 412 TSE-01 Concept of Operations

Fig. 43 TSE-01C Test Execution

The test technique was successful for the first two (2) tests. On the third test, the EFTC failed to release the Extraction parachute. The EFTC was undamaged by the test failure. The CPAS project tried unsuccessfully to reproduce the failure-to-release on the ground.

The lesson learned on this test was to be cautious using test hardware, especially hardware received from another organization, outside its design or nominal operating envelope. All of the subsequent CPAS airdrop tests were designed so that a heavy test vehicle did not reach a negative angle of attack prior to EFTC release.

C. CDT 3-1 Test Anomaly

The first airdrop test with the PCDTV was CDT 3-1. That test technique called for landing the MDS end on. There were concerns with damaging the MDS or the MDS avionics with the landing loads, so a stack of cardboard honeycomb was rigged to the front of the MDS using Kevlar straps.

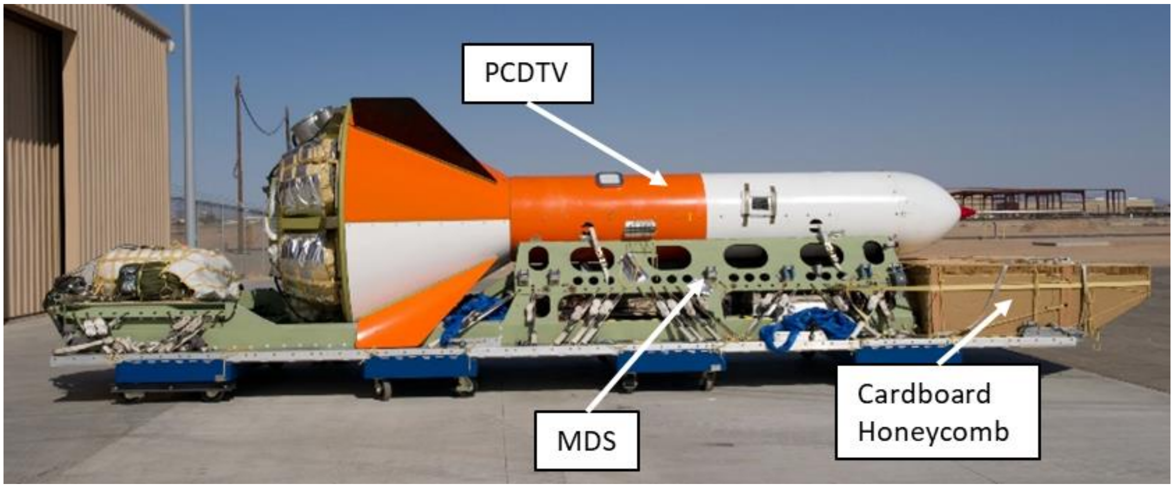

Fig. 44 CDT 3-1 Pre-Test Configuration

During extraction, the honeycomb stack came loose and was speared by the PCDTV nose pitot tube. The honeycomb fell away from the PCDTV during the Main parachute phase. Test execution appeared nominal for the rest of the test.

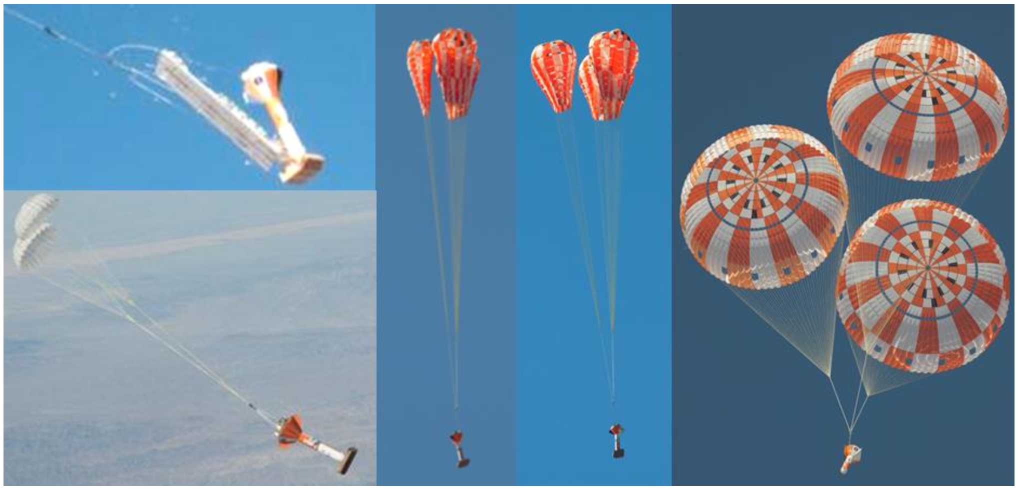

Fig. 425 CDT 3-1 Test Execution

However, during recovery, it was noted that one string of the avionics had been switched off by the Kevlar honeycomb straps. If both strings of avionics had been switched off, the test vehicle would have landed under the programmers alone, probably destroying the test vehicle.

Fig. 46 CDT 3-1 Avionics Control Panel – Left to right: Both Strings Off (Down) in the Hangar; One String On (Up) and One String Off (Down) on the Drop Zone; Control Panel Location

The lessons learned from this test were always have redundant avionics command strings and recess or guard important switches. There was a plastic guard on these switches, but the strap broke through the guard. In following tests, the switches were recessed into the PCDTV.

D. CQT 4-5 Software Anomaly

Because the PTV created a flight-like wake environment, it was highly desirable to test at the highest safe dynamic pressure. Freefall phases, letting the PTV fall with no parachutes attached, would provide higher dynamic pressure test points. To end the freefall if the PTV became unstable, software was added to the PTV avionics system to monitor the PTV pitch and yaw rates, calculating the root sum square of the rates. A limit of 40fps was chosen. This "bailout" software would deploy the next parachute in the test sequence if rate limits were exceeded. The freefall phase always had a timer to deploy the next parachute, if the rate limits were not exceeded.

The bailout software used PTV onboard inertial measuring units (IMUs) as the rate sensors. CPAS verified that the bailout software algorithms worked properly using generated test data, rather than actual airdrop test data, because the airdrop data would not trigger the logic. Test data collected while the PTV sat on the ground would also not trigger the logic.

There was a "units" error in the bailout software which was not detected during software development. The generated test data also included the "units" error, so the error was not detected during software testing. The bailout software was used on the PTV many times, until more than midway through CPAS qualification testing. Reviewing the airdrop test data from CQT 4-5, it was noted that the bailout logic should have triggered and did not. Luckily the freefall timed out 0.5 seconds after the trigger, so the test execution was not affected.

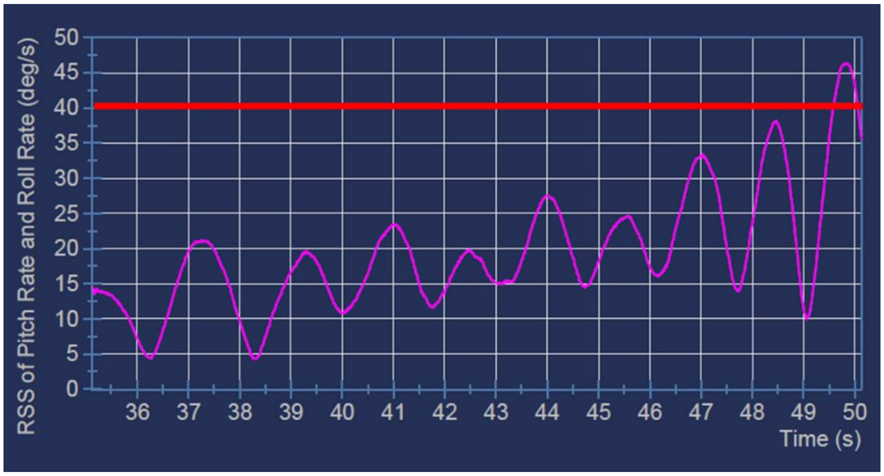

Fig. 437 Plot of CQT 4-5 Bailout Software Calculation and Limit vs Test Time for a 15 Second Freefall

After the software "units" error was corrected, the test team used an IMU emulator to generate software test data which exactly matched data as if it had come from the IMU. The lesson learned from this test is to be cautious whenever actual system data cannot be used to validate control software. Strong coordination and communication between the hardware avionics team and the software team is critical. Testing the software using data collected from the IMU on a programmable rate table would have detected this error.

XI. Conclusion

The CPAS project, through an evolution of airdrop test vehicles and test techniques, has successfully completed qualification testing of the Orion Crew Module parachutes. The test program started with a single parachute, small dart tests, progressed to larger dart and platform/weight tub single and cluster parachute tests, and finished with full system, parachute compartment dart and capsule tests.

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