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Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) Generation I Main and Cluster Development Test Results

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The Orion spacecraft is currently under development by NASA and Lockheed Martin. Previously known as the Crew Exploration Vehicle (CEV), Orion is the next generation spacecraft for human spaceflight. The Orion Crew Module (CM) resembles the Apollo capsule, but is much larger. Like Apollo, Orion will return to Earth under a parachute system. This parachute system is being designed by NASA, Jacobs Engineering, and Airborne Systems. The Generation I CPAS parachute system configuration consists of two mortar-deployed Drogue parachutes, three mortar-deployed Pilot parachutes, and three Pilot-deployed Main parachutes. A series of tests was planned and executed to test the CPAS Generation I Main parachutes individually, and a second series of tests was executed to analyze the effects of the Mains in a cluster configuration. These tests occurred between August 2007 and July 2008 at the US Army Yuma Proving Ground (YPG). The goal of each test was to determine the performance of the parachutes at the established test conditions. A variety of test techniques were used to establish the desired test conditions at parachute deployment. Prior to each flight, rigorous analyses were accomplished 1) to establish the validity of the test technique, 2) to establish sequencer timing, 3) to keep the predicted parachute loads within the parachute and hardware capability, and 4) to plan the test to operate within the required constraints of the range. Analysis tools included simulations such as the Decelerator Systems Simulation (DSS), an aircraft extraction tool Decelerator Systems Simulation Application (DSSA), Decelerator Dynamics (DCLDYN), a modified two degree of freedom version of DSS called DTV-Sim, and a landing footprint predictor tool (Sasquatch). After each test, the tools were used to reconstruct the parachute performance during the flight using the data gathered on-board and by the range. Reconstructions were used to update the existing parachute models/simulations for on-going development work. The performance parameters were found to be consistent between tests for the individual Main parachutes. Test techniques, preflight predictions, test instrumentation, reconstruction results and challenges, and a brief discussion of the lessons learned from each test will be presented.

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Nomenclature

C_d = drag coefficient
S = area (general)
D_o = nominal parachute diameter
λ = canopy porosity
n = fill constant
Ck = opening shock factor

CDT = Cluster Development Test
CMS = Cradle Monorail System
CPAS = Crew Exploration Vehicle (CEV) Parachute Assembly System
DCLDYN = Decelerator Dynamics
DGPS = Differential GPS (Global Positioning System)
DSS = Decelerator Systems Simulation
DSSA = Decelerator Systems Simulation Application
DTV = Drop Test Vehicle
EFTC = Extraction Force Transfer Coupling
GFE = Government Furnished Equipment
KTM = Kineto-Tracking Mount
MDT = Main Development Test
M-DTV = Medium Drop Test Vehicle
NSI = NASA Standard Initiator
TSPI = Time-Space Position Information
VPCR = Variable Porosity Conical Ribbon
YPG = Yuma Proving Ground

I. Introduction

THE Orion spacecraft is currently under development by NASA and Lockheed Martin. The Orion Crew Module (CM) resembles the Apollo capsule, but is much larger. Like Apollo, Orion will return to Earth under a parachute system. This parachute system is being designed by NASA, Jacobs Engineering, and Airborne Systems. The Generation I CPAS parachute system configuration consists of two mortar-deployed Drogue parachutes, three mortar-deployed Pilot parachutes, and three Pilot-deployed Main parachutes.[1,2]

A series of tests was planned and executed to test the CPAS Generation I Main parachutes individually, and a second series of tests was executed to analyze the effects of the Mains in a cluster configuration. These tests occurred between August 2007 and July 2008 at the US Army Yuma Proving Ground (YPG). This paper provides a description of the constructed geometry of the Main parachutes, the test objectives of the drop tests, test configurations, data acquisition, and ultimately the flight simulation and analysis of each test flight. Note that the final cluster test, CDT-2, is not addressed in this paper; details of that test can be found in Ref. 3.

The primary goal of the individual parachute tests was to determine the performance of a single parachute at the established test conditions. The cluster tests had the additional objective of examining the performance of the parachutes in a cluster configuration, with particular emphasis on drag reduction in a cluster and individual parachute motion in the cluster. The test techniques used to achieve the test goals were similar for all tests in the series; most were standard Low Velocity Air Drop (LVAD) extractions from aircraft, though one used a NASA Medium Drop Test Vehicle (M-DTV) mounted in a Cradle Monorail System (CMS) extracted from an aircraft.

The CPAS instrumentation team provided data acquisition and event sequencing capability for the Main and cluster tests. The primary component of the CPAS Generation I data acquisition system was a set of DataBrick analog recorders, manufactured by GMH Engineering. The tests used event sequencers designed and built by the CPAS instrumentation team to control parachute events.

Prior to each flight, rigorous analyses were accomplished 1) to establish the validity of the test technique, 2) to establish sequencer timing, 3) to keep the predicted parachute loads within the parachute and hardware capability, and 4) to plan the test to operate within the required constraints of the range. Analysis tools included simulations such as Decelerator System Simulation (DSS), an aircraft extraction tool Decelerator System Application (DSSA), Decelerator Dynamics (DCLDYN), a degree of freedom parachute simulation called DTV-Sim, and a landing footprint predictor tool (Sasquatch).

After each test, the tools were used to reconstruct the parachute performance during the flight using the data gathered on-board and by the range. Reconstructions were used to update the existing parachute models/simulations for on-going development work. The performance parameters were found to be consistent between tests.

An examination of both the preflight and postflight analyses, along with detail on test techniques, test instrumentation, reconstruction results and challenges, and a brief discussion of the lessons learned from each test will be presented in detail throughout the paper.

II. Overview of the Main Parachute

The Irvin Quarter Spherical Ringsail is a polyconical design that takes the constructed shape of a faceted quarter sphere. Important parameters are summarized in Table 1. The constructed geometry of the Main parachute is shown in Fig. 1.

Table 1. Main Parachute Planform Parameters.

Parameter	**Value**
Parachute Type	Quarter Spherical Ringsail
Parachute Diameter	116 ft
Number of Gores	80
Number of Rings	4
Number of Sails	9
Crown Geometric Porosity (λ_{gc})	6.89%
Line Length Ratio (L_s/D_o)	1.15
Line Length	133 ft
Riser Length	97 ft

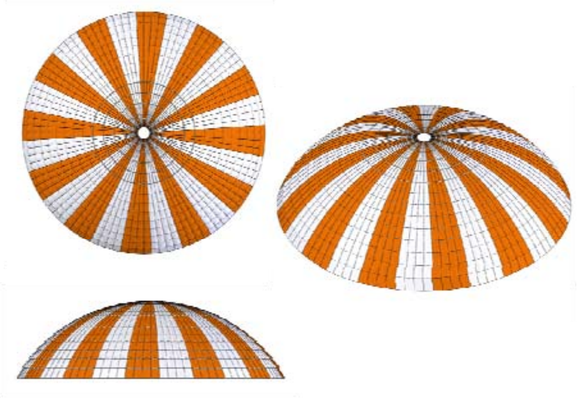

Figure 1. Main Parachute Constructed Geometry.

III. Instrumentation and Data Acquisition

The main component of the CPAS Generation I data acquisition system was a set of DataBrick analog recorders, manufactured by GMH Engineering. The DataBricks have eight analog input channels and two counter channels used for triggering the recording process. The trigger was a switch held in the open position by a piano wire pull pin, which was then tied to the extraction line or a deck ring on the aircraft to activate the bricks at first motion or load transfer. The DataBricks used a pretrigger buffer to save data prior to the triggering of the recording process.

The DataBricks are ruggedized and certified to withstand shock loads of up to 100 G. Some of the DataBricks used on CPAS have survived shock loads of 150 G and over 200 G. The major drawback of the DataBricks was their extremely limited memory (only 524,218 data points) which often forced the project to fly extra bricks or to trade off high sample rates for longer record times.

The sensors flown during CPAS Generation I testing included Crossbow triaxial accelerometers, MicroStrain orientation sensors, strain links, instrumented confluence fittings, and pressure transducers. Two accelerometers were flown for redundancy. Two orientation sensors were also flown; one was used to read pitch, roll, and yaw angles, while the other read pitch, roll, and yaw rates. (This was necessary because the DataBricks read only analog inputs – had the project used a data recorder with an RS232 port, a single orientation sensor could have read all the sensor's outputs.) Because the yaw sensor measured a magnetic compass heading, the sensor did not produce a valid reading when the load was nose-down. 50k strain links were often placed on the slings below the confluence on tests using weight tubs. A single absolute pressure transducer was flown on each test to measure atmospheric pressure. During tests using the missile-shaped drop test vehicles, two differential pressure transducers were connected to a pitot-static probe to measure dynamic pressure.

Various instrumented confluence fittings were flown depending on the test configuration. The four-to-one and three-to-one confluences proved to give fairly accurate measurements on the single Main parachute tests. However, the instrumented three-to-three and four-to-two confluences used on the cluster tests had more trouble. The confluences were calibrated using a straight pull on each strain gauge (with the applied forces 180 degrees apart). Once the parachutes in a cluster opened and started to spread out, the load on the strain gauges was no longer at 180 degrees and the confluence readings were no longer accurate. The only way to deal with this problem would be to calibrate each strain gauge at multiple angles and use some form of instrumentation to measure the angles of each parachute riser during flight.

The last sensors used during Generation I was the Tension Measuring System (TMS) units. TMS units are aluminum enclosures containing a strain plate, circuit board, battery, and pull pin for activation. They were installed on each parachute riser for each Generation I test. The TMS units currently used by CPAS suffered severe reliability issues, with multiple failures to function or to produce viable data during each test. The problems are most likely due to the age and extensive past use history of the units, as they were originally purchased in 1998 for the X-38 parachute development project. Plans to have new TMS units designed and built are in the works for Generation II testing.

During Generation I testing, the project used some instrumentation provided by Yuma Proving Ground (YPG). They provided two differential GPS units that were flown on the load, a windpack that was dropped after the load to provide air data, time-space position information (TSPI) provided by the ground-based kineto-tracking mounts (KTM), and a preflight weather balloon that provided wind data prior to the test.

All of the Main and cluster tests used event sequencers designed and built by the CPAS instrumentation team to control parachute events, such as strap cuts and mortar firings. The event sequencer system was composed of two metal boxes – an indicator box, which contained the system power switch and LEDs displaying the system status, and a timer box, which contained two Leech time delay relays and four outputs. Firing lines connected each output to a NASA Standard Initiator (NSI). A first motion switch connected to the indicator box was closed when a pin was pulled (same as the activation of the DataBricks), starting the countdown. The event time was controlled by setting a certain resistance on the decade resistor box on each of the Leech relays in the timer box. Because the resistance on each relay had to be tuned individually, changing the event times was a fairly time-consuming process.

For redundancy, two identical but independent systems were flown for every event on a given test, with separate batteries, sequencers, firing lines, switches, and NSIs. Each event sequencer system required its own 24 V battery, which occupied considerable space in the instrumentation compartment – particularly in later tests with several events. Each sequencer system also required at least one first motion switch; two switches were used for hazardous events such as mortar firings and vehicle separation cuts to prevent accidental activation in the aircraft.

The sequencers worked with 100 percent reliability throughout every Main and cluster test of Generation I, even firing after the load moved wildly through severe platform dynamics. The DataBricks had nearly 100 percent reliability – their single anomaly was later determined to have been caused by a loose power connection to the instrumented confluence fittings. The accelerometers and orientation sensors worked well throughout the test series. The absolute pressure transducer had only one anomaly, failing on the CDT-3 test. The reason for this anomaly was never determined. The pitot-static probe functioned normally on MDT-3, the only Main test on which it was used. The instrumented confluence fittings had the calibration problem described above as well as the power problem previously mentioned. The 50k strain links and the instrumented confluence fittings had some failures due to the data cable being cut during platform dynamics. As discussed above, the TMS units had an extremely poor record, which should be fixed in Generation II by the design of a new, more advanced TMS II unit.

The YPG-provided data had persistent problems with dropouts from the differential GPS. This resulted in a 20 to 25 second loss of GPS data from both the windpak and the test vehicle immediately after aircraft extraction, causing the loss of data from a vital portion of the flight. This is a known system deficiency. Thus far, a solution has not been found.

Several improvements are being planned for the instrumentation system during Generation II testing. Rather than the DataBricks and event sequencers, both data recording and event sequencing functions will be controlled by a National Instruments CompactRIO chassis. The CompactRIO will allow considerably more flexibility in instrumentation, recording speed, and recording duration than the DataBricks. It will also allow for smart release event sequencing, making it possible to trigger a parachute event off an instrumentation input, rather than a time. The CompactRIO has an RS232 serial input, so it can record data digitally off the orientation sensors, allowing us to read far more of the sensor’s outputs. A new TMS design is in work, which will have considerably greater recording time and easier calibration.

IV. Test Overviews and Results

A. MDT-1

1. Test Purpose and Objectives

The purpose of the first Main parachute development test (MDT-1) was to deploy a single Main Parachute. The programmer parachute was reefed to achieve a Main parachute deployment target dynamic pressure of ~42 psf (± 5 psf). The primary objectives were to obtain measurement and instrumentation data, obtain Main parachute inflation loads, inflation fill times from line stretch, and drag area growth curves, verify Main parachute drag coefficients, full opening shock factors, and disreefing time & loads, demonstrate single Main deployment bag functioning, confirm Main Parachute Restraint System, and video record Main deployment bag de-lacing and deployment. The secondary objectives were to evaluate packing procedures, investigate any Main parachute canopy damage during deployment and recovery, and gather data on the Pilot parachute.

2. *Test Description and Configuration*

MDT-1 was conducted at the Sidewinder Drop Zone at the US Army Yuma Proving Ground (YPG). The test consisted of four parachutes: 1) a 15 ft ringslot GFE extraction parachute, 2) a 19 ft ringslot programmer parachute permanently reefed to 30%: D_o = 19 ft, 24 gores, 21 ft line length, 20 ft riser , 3) the Generation I CPAS Pilot ringslot parachute: D_o = 9.86 ft, 12 gores, 11.3 ft line length, 53.7 ft riser, and 4) the Generation I CPAS Main quarter spherical ringsail parachute: D_o = 116 ft, 80 gores, 133 ft line length, 97 ft riser.

The test load consisted of a 9x12 ft Type V airdrop platform with an 8-ft load tub. The Main parachute compartment was located in the weight tub. The platform/load tub weighed 6,240 lb at extraction. The extraction parachute was released by the Extraction Force Transfer Coupling (EFTC) and deployed the programmer parachute as the platform/weight tub cleared the C-130 aircraft ramp using standard LVAD procedures. The platform was oriented horizontally under the programmer parachute. At 30 seconds, as referenced to the EFTC event, the programmer parachute was cut away deploying the Pilot parachute. The Pilot parachute immediately deployed the Main parachute. The programmer and Main parachute harnesses were connected to attach points at each of the four top corners of the load tub.

3. *Test Results*

For the most part, the Main performed similar to expectations. Table 2 compares the preflight predictions with actual flight results for several key parameters.

Table 2. MDT-1 Predictions and Results.

	Predicted	**Actual**
Initial opening		
Peak load	9,450 lb	10,680 lb
n	22.7	30
First disreef		
Peak load	8,050 lb	6,190 lb
n	9	6
Disreef to full open		
Peak load	8,820 lb	9,140 lb
n	3.3	2
Max dynamic pressure	42 psf	55.2 psf
Full open C_d	0.90	0.88-0.98

The first stage opened roughly 1.3 times slower than predicted. Conversely, the disreef to the second stage and the disreef to full open happened faster than expected. A shock factor of 1 was used for all stages. Figure 2 shows the Main parachute loads for each stage.

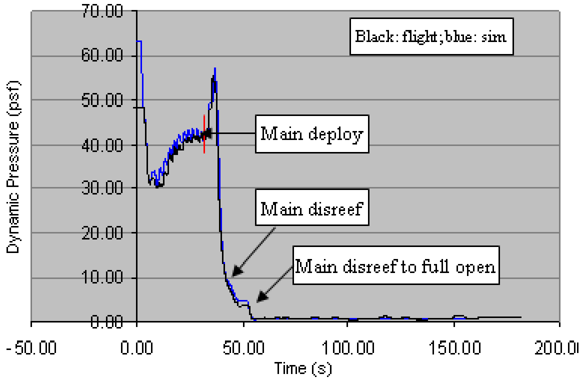

Figure 3. MDT-1 Dynamic Pressure from Flight Data.

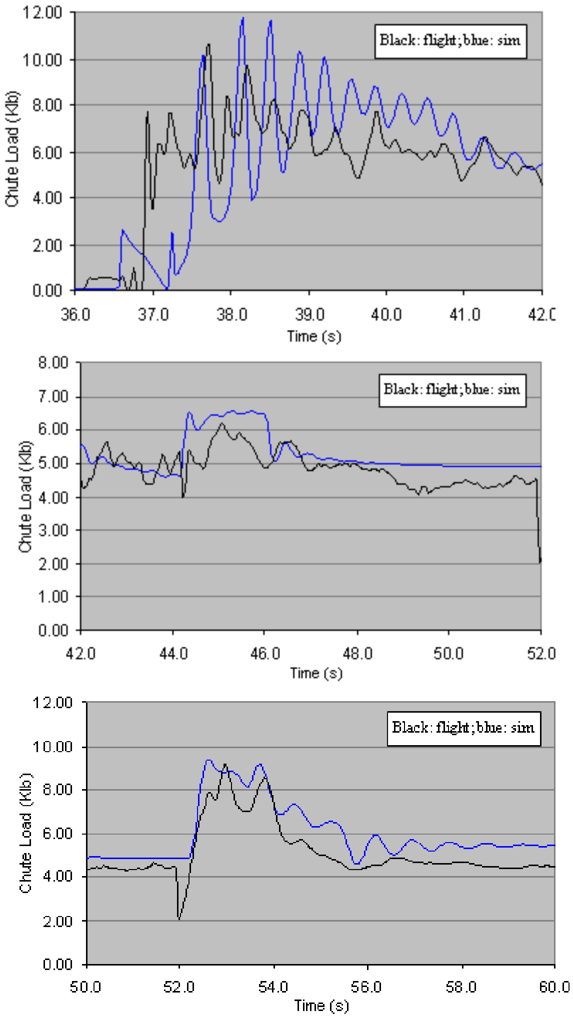

Figure 2. MDT-1 Parachute Loads from Flight Data.

Figure 3 shows the dynamic pressure trace. The vehicle reached a peak dynamic pressure of 55.2 psf under the Main parachute. This is ~12 psf higher than the preflight prediction. The difference was caused by test techniques; the platform unexpectedly inverted at Main deploy. The inversion and higher dynamic pressure did not adversely affect the test results or the parachute. Under the Main, the vehicle decelerated as expected and landed safely.

Two reconstruction methods were used to determine the drag coefficient. Direct calculation using the dynamic pressure and suspended weight to calculate the drag area yields a drag coefficient of 0.98, higher than the preflight prediction of 0.9. Reconstruction of the flight in DSSA yields a drag coefficient of 0.88.

B. MDT-2

1. Test Purpose and Objectives

The purpose of MDT-2 was to deploy a single Main Parachute at a dynamic pressure of ~42 psf (± 5 psf). The reefing schedule was intended to provide conditions consistent with those projected to occur at CEV nominal Main parachute deployment. The test objectives were the same as MDT-1.

2. Test Description and Configuration

MDT-2 was conducted at the Laposa Drop Zone at YPG. The MDT-1test configuration was repeated, although a different reefing schedule was used on the Main parachute.

3. Test Results

Preflight predictions for this test were updated based on the results of MDT-1. For the most part, the Main performed similar to expectations. Table 3 compares the preflight predictions with actual flight results for several key parameters.

The first stage opened nearly twice as fast as expected. The quick opening was influenced by platform dynamics at inflation. The other stages opened with fill constants consistent with the values seen on MDT-1. The loads on all stages were higher than expected. Shock factors of 1 were used for all three stages. The parachute loads from the accelerometer data is shown in Fig. 4.

Figure 5 shows the dynamic pressure trace. The vehicle reached a peak dynamic pressure of 46.3 psf under the Main parachute, within 1 psf of the predicted value.

	Predicted	**Actual**
Initial opening		
Peak load	9,500 lb	12,000 lb
n	22.7	12
First disreef		
Peak load	8,050 lb	9,000 lb
n	6	10
Disreef to full open		
Peak load	8,800 lb	11,000 lb
n	2	2
Max dynamic pressure	47.2 psf	46.3 psf
Full open C_d	0.90	0.88-0.94

Table 3. MDT-2 Predictions and Results.

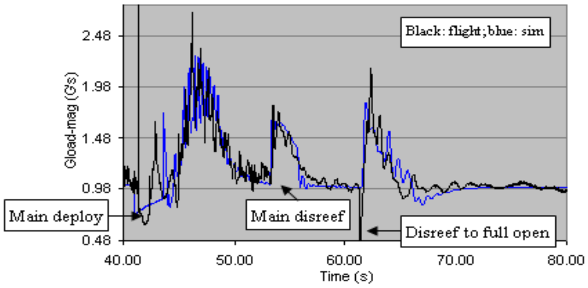

Figure 4. MDT-2 Parachute Loads from Flight Data.

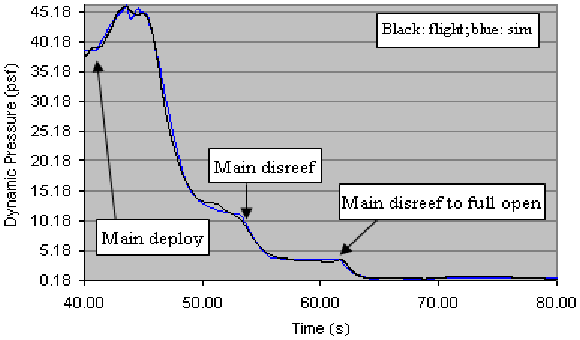

Figure 5. MDT-2 Dynamic Pressure from Flight Data.

As on MDT-1, two reconstruction methods were used to determine the drag coefficient. Direct calculation using the dynamic pressure and suspended weight to calculate the drag area yielded a drag coefficient of 0.88 to 0.94, bounding the preflight prediction of 0.90. Reconstruction of the flight in DSSA yielded a drag coefficient of 0.92.

C. MDT-3

1. Test Purpose and Objectives

The purpose of MDT-3 was to deploy a Main parachute at a target dynamic pressure of 78 psf (± 5 psf) at line stretch. The programmer reefing schedule was chosen to match conditions for Main parachute deployment under nominal entry with a single failed Drogue parachute. The primary objectives were the same as on MDT-1 and MDT-2 with the additional requirements to capture time, space, position data (TSPI) and atmospheric properties, and to video record the Main parachute events to characterize extraction, deployment and inflation. The secondary objectives were to record extraction and “tip-off” dynamics, Cradle Monorail System (CMS) loads during all flight phases, landing rates and conditions, and programmer and saver parachutes performance and loads, validate Sasquatch (a landing footprint tool) prediction and accuracy, demonstrate Differential GPS performance, obtain meteorological data, and record the M-DTV landing velocity.

2. *Test Description and Configuration*

MDT-3 was conducted January 29, 2008 on the Robby Drop Zone at YPG. The test consisted of five parachutes: 1) one 28 ft ringslot GFE extraction parachute; 2) one Generation I 23 ft CPAS Drogue parachute, 65.4 ft riser, 34.5 ft suspension line length, which was reefed to 47% permanently to achieve the desired test condition; 3) the test parachute, one Generation I CPAS Main parachute, 97 ft riser, 133 ft suspension line length; 4) two 9.85 ft AFSAT Drogue parachutes used as stabilizer parachutes, with deployment bags attached to the Main deployment bag.

The Medium Drop Test Vehicle (M-DTV) is two feet in diameter and 23 feet long with three fins attached to the aft end. The estimated drag area of the M-DTV is 1.7 ft^2. The final combined weight at extraction of the M-DTV on the CMS was approximately 19,020 lb. The suspended weight of the M-DTV under the programmer (CPAS Drogue) was 6,988 lb. The suspended weight under the CPAS Main parachute was 6,760 lb.

The Cradle Monorail System (CMS) was constructed to allow the extraction of the M-DTV from fixed-wing aircraft at high altitude in order to obtain the necessary test conditions. It is 338 in long, 84 in wide, and 89 in tall. The constructed weight is 7,185 lb. The M-DTV was mounted on the CMS and was extracted from a C-130A aircraft.

After the CMS cleared the aircraft the extraction parachute oriented the M-DTV and CMS downward. The M-DTV was released from the CMS 8 seconds after EFTC transfer and a static line attached to the CMS deployed the programmer parachute after the M-DTV separated from the CMS. The programmer was cut away 12 seconds after M-DTV release (20 seconds after EFTC) deploying the stabilization parachutes and Main parachute. The test vehicle was brought safely to the ground under this final configuration.

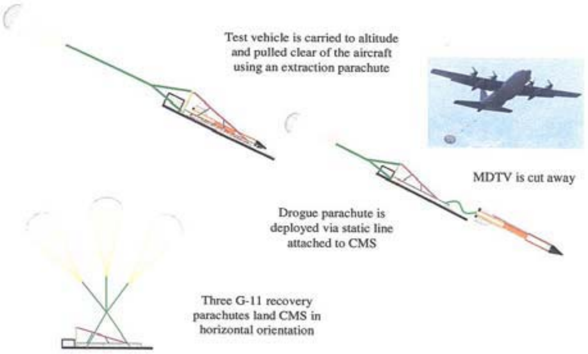

Figure 6. M-DTV and CMS Extraction and Release

After the M-DTV was cut away, the CMS fell away under the extraction parachute, eventually deploying three G-11 parachutes. When the G-11 parachutes deployed, the CMS reoriented to a horizontal position as shown in Fig. 6. The CMS landed under the G-11 parachutes.

3. *Test Results*

Data was gathered on two parachutes: the Drogue and the Main.

The CPAS Generation 1 Drogue parachute was previously used on three Drogue Development Tests.[4] The Drogue parachute on MDT-3 opened at a speed consistent with previous tests; the fill constant was n = 3-5, compared with the prediction of n = 4. However, the load on the parachute was higher than expected. Preflight

Table 4. MDT-3 Main Parachute Predictions and Results.

	Predicted	Actual
Initial opening		
Peak load	16,000 lb	12,500 lb
n	30	30
First disreef		
Peak load	11,000 lb	11,000 lb
n	10	13
Disreef to full open		
Peak load	15,000 lb	14,000 lb
n	2	1.1
Max dynamic pressure	78 psf	79 psf
Full open C_d	0.94	0.76-1.18

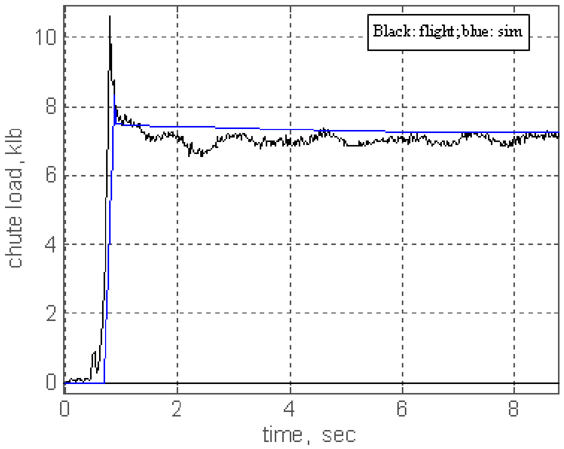

Figure 7. MDT-3 Parachute Loads during Drogue Phase from Flight Data

analysis showed a load of ~8,000 lb, but the confluence recorded a peak load of ~10,300 lb. The shock factor was calculated to be 1.49-1.75. It should be noted that one analysis put the shock factor at 1.2, lower than the prediction of 1.3. The parachute loads from the confluence data is shown in Fig. 7.

As on the previous tests, the Main performed similar to expectations. Table 4 compares the preflight predictions with actual flight results for several key parameters on the Main parachute. The fill constant on the first stage was n = 30, confirming the preflight prediction. The second stage opened slightly slower than predicted. Conversely, the fill constant on the disreef to full open was calculated to be n = 1.1, faster than anticipated. The opening loads for each stage were equal to or lower than the predicted values. Shock factors of 1 were used for all three stages. The parachute loads from the accelerometer data is shown in Fig. 8.

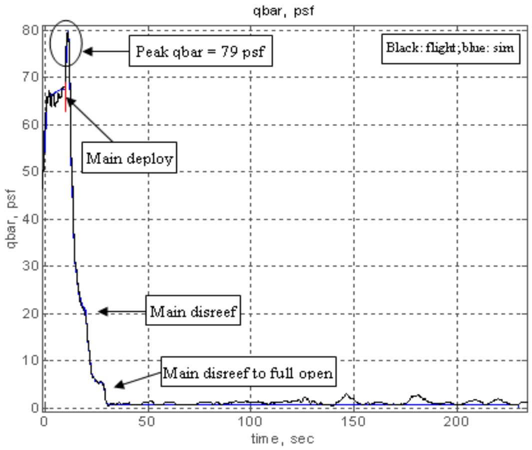

Figure 9. MDT-3 Dynamic Pressure from Flight Data

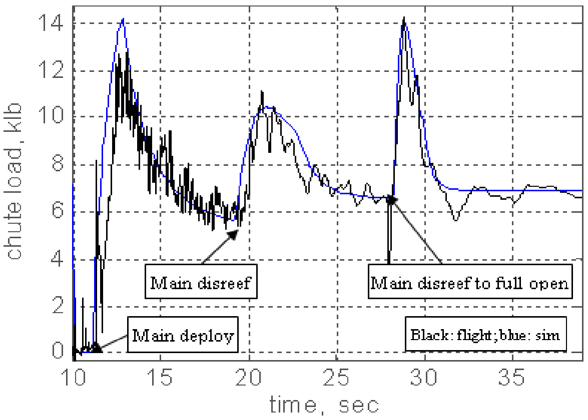

Figure 8. MDT-3 Parachute Loads during Main Phase from Flight Data

Fig. 9 shows the dynamic pressure trace. The vehicle reached a peak dynamic pressure of 79 psf under the Main parachute, close to the target value of 78 psf.

Two reconstruction methods were used to determine the drag coefficient. Direct calculation using the dynamic pressure and suspended weight to calculate the drag area yields a drag coefficient of 0.76-1.18, bounding the preflight prediction of 0.94. Reconstruction of the flight in DTV-Sim yields a drag coefficient of 0.94-0.97.

D. CDT-1

1. Test Purpose and Objectives

CDT-1 was the first drop test to use a parachute compartment, mortar-deployed Pilot parachutes, and clusters of the CPAS parachutes. The primary objectives were to obtain measurement and instrumentation data, obtain Main parachute inflation loads, prove the Pilot parachute ability to deploy Mains from the parachute compartment, determine inflation fill times from line stretch and drag area growth curves, verify Main parachute drag coefficients, full opening shock factors, and disreefing time and loads, capture Time-Space Position Information, document condition of parachute structural elements after test, and video record Main parachute events to characterize extraction, deployment and inflation. The secondary objectives were to evaluate packing procedures, measure Drogue parachute effectiveness (using TMS instrumentation and accelerometers), evaluate confluence/strain instrumentation performance, parachute compartment based extraction dynamics/geometry, Pilot/mortar deploy of Main parachutes, parachute compartment based line routing and restraint system, and confluence fitting extraction and deployment, and demonstrate Differential GPS performance.

2. Test Description and Configuration

CDT-1 was conducted October 18, 2007 on the Robby Drop Zone at YPG. The test consisted of nine parachutes: 1) one 28 ft ringslot GFE extraction parachute, 2) two 23 ft CPAS Drogue parachutes deployed immediately to full open: D_o = 23 ft, 24 gores, 34.5 ft line length, 65.4 ft riser, 3) three Generation I CPAS Pilot ringslot parachutes: D_o = 9.86 ft, 12 gores, 11.3 ft line length, 53.7 ft riser, and 2) three Generation I CPAS Main quarter spherical ringsail parachutes (targeted reefing ratios: 6.5% for 8 seconds, 13.3% for 8 seconds, to full open): D_o = 116 ft, 80 gores, 133 ft line length, 97 ft riser.

The test load consisted of an 8 ft load tub on a 20 ft Type V cargo platform with the parachute compartment on the weight tub. The total load weighed 17,350 lb at extraction. The extraction parachute was released by the EFTC and deployed the Drogue parachutes as the platform/weight tub cleared the C-130A aircraft ramp using standard LVAD procedures. The platform was oriented horizontally under the Drogue parachutes. At 25 seconds, as referenced to the EFTC event, the Drogue parachutes were cut away. The Pilot parachutes were mortar deployed

0.2 seconds later to deploy the Main parachutes. The Drogue parachute harnesses were connected to attach points at each of the four top corners of the load tub. The Main parachute harnesses were connected to three attach points on the load. The test vehicle was brought safely to the ground under this final configuration. Table 12 presents the test timeline.

3. *Test Results*

Data was gathered on both the Drogue and Main clusters. Table 5 compares the preflight predictions with actual flight results for several key parameters on the Drogue parachutes. The Drogues opened at a speed consistent with previous tests. The opening shock factor was calculated to be 1.6, higher than predicted. Figure 10 shows the parachute loads from flight data. Load sharing for the two parachute cluster was determined from TMS data. One parachute took 52% of the peak load, with the other taking 48%. This balanced load sharing is attributed to the Drogue deployment bags being tied together. The steady state drag coefficient was 0.57 based on vertical velocity data.

Table 5. CDT-1 Drogue Parachute Cluster Predictions and Results.

	Predicted	Actual
Peak load	27,850 lb	25,000 lb
n	4	4.3
Ck	1.3	1.6
Dynamic Pressure at line stretch	48 psf	33 psf
Full open C_d	0.5	0.57

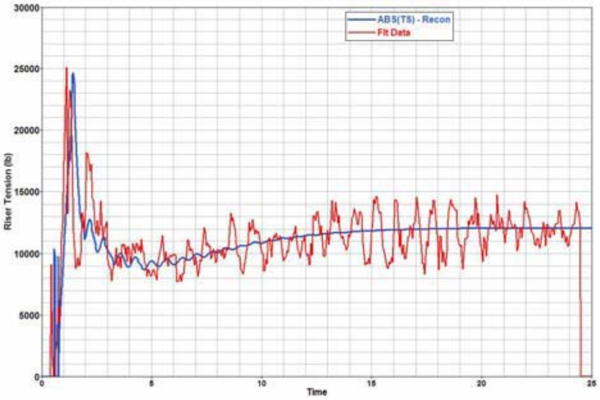

Figure 10. CDT-1 Drogue Parachute Force-Time History Plot During Inflation.

Table 6. CDT-1 Main Parachute Cluster Predictions and Results.

	Predicted	Actual
Initial opening		
Peak load	23,000 lb	27,800 lb
n	30	27
First disreef		
Peak load	36,000 lb	24,900 lb
n	10	16
Disreef to full open		
Peak load	24,000 lb	27,500 lb
n	2	2.5
Max dynamic pressure	48.6 psf	50 psf
Full open C_d	0.94	0.98

Table 6 compares the preflight predictions with actual flight results for several key parameters on the Main parachutes. The loads plot is depicted in Fig. 11. The reefing ratios for the Main parachute reefing stages were calculated to be lower than expected. The different reefing ratios account for much of the difference between the predicted and actual loads.

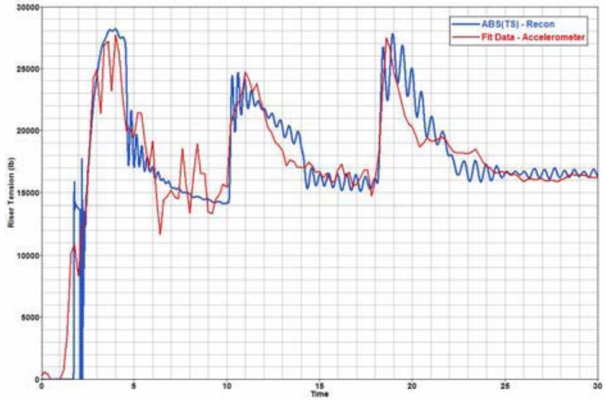

Figure 11. CDT-1 Main Parachute Force-Time History Plot During Inflation.

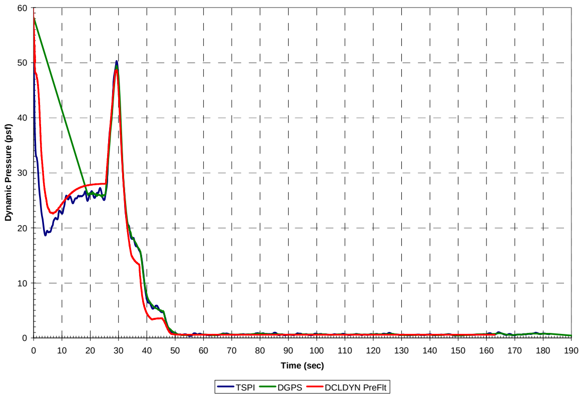

Figure 12. CDT-1 Dynamic Pressure: TSPI and DGPS vs Preflight Simulation.

Load sharing was determined from TMS loads data for the opening load and two disreefing events. The loads were well balanced, with no parachute taking more than 37% of any peak load.

As shown in Fig. 12, the vehicle reached a peak dynamic pressure of 50 psf at 30 seconds under the Main parachute, close to the target value of 48.6 psf.

E. CDT-3

1. *Test Purpose and Objectives*

The purpose of CDT-3 was to test a cluster of two Main parachutes (simulating a one-Main-out condition) with a target dynamic pressure condition of 42 (± 5 psf) at Main line stretch. The primary test objectives were to test the two Main parachute cluster under nominal dynamic pressure conditions (two full open Drogues), determine inflation performance and cluster efficiency for a cluster of two, measure the Drogue and Main steady state performance, and determine Drogue & Main parachute opening performance and reefing ratios. The secondary objectives were to simulate the planned PA-1 steady state reefing ratio of two Drogues at 80%, to collect loads and performance data associated with one Drogue skipping a reefing stage, and to acquire video coverage of the test events.

2. *Test Description and Configuration*

CDT-3 was conducted June 17, 2008 on the Robby Drop Zone at YPG. The test consisted of five parachutes: 1) one 28 ft ringslot GFE extraction parachute, 2) two 23 ft CPAS Drogue parachutes: D_o = 23 ft, 24 gores, 34.5 ft line length, 65.4 ft riser, one reefed at 45% for 6 seconds then 80% for 18 seconds to full open, the other reefed to 80% for 24 seconds then to full open, 3) two Generation I CPAS Main quarter spherical ringsail parachute (targeted reefing ratios: 3% for 8 seconds, 10% for 8 seconds, to full open) : D_o = 116 ft, 80 gores, 133 ft line length, 97 ft riser.

Unlike CDT-1, CDT-3 did not use a parachute compartment. Instead, the test load consisted of a 16 ft load tub on a 20 ft Type V cargo platform with the parachutes mounted on the weight tub. The load weighed 17,250 lb at extraction. The extraction parachute was released by the EFTC and deployed the Drogue parachutes as the platform/weight tub cleared the C-130A aircraft ramp using standard LVAD procedures. The platform was oriented horizontally under the Drogue parachutes. The Drogue parachute harnesses were connected to attach points at each of the four top corners of the load tub. At 45 seconds, as referenced to the EFTC event, the Drogue parachutes were cut away. The Drogue parachute harness was connected by a lazy leg which was connected to the Main deployment bags through an energy modulator. Once the Drogues were released, this deployed the Main parachutes. Like the Drogue harnesses, the Main harnesses were connected to attach points at each of the four top corners of the load tub. The test vehicle was brought safely to the ground under this final configuration.

3. *Test Results*

Data again was gathered on both the Drogue and Main clusters. Table 7 compares the preflight predictions with actual flight results for several key parameters on the Drogue parachutes. The total peak loads on the Drogue cluster for all events was lower than expected. The shock factors were similarly lower. The loads trace is shown in Fig. 13.

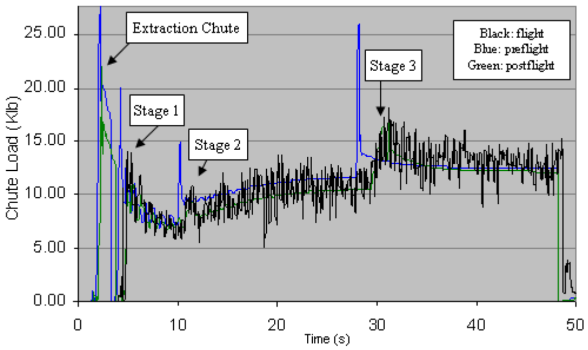

Figure 13. CDT-3 Parachute Loads during Extraction and Drogue Phase from Flight Data.

Table 7. CDT-3 Drogue Parachute Cluster Predictions and Results.

	Predicted	**Actual**
Initial opening		
Peak load	17,900 lb	14,000 lb
n	4	8-10
Ck	1.3	1.0-1.36
First disreef		
Peak load	13,100 lb	10,500 lb
n	2	2.4
Ck	1.3	1.18-1.25
Disreef to full open		
Peak load	23,900 lb	18,150 lb
n	2	4-6
Ck	1.3	1.15-1.22
Dynamic pressure at Drogue release	27 psf	25 psf
Full open C_d	0.53	0.57

The unusual reefing schedule on the Drogues on this test caused some difficulties in determining the opening characteristics of the parachutes. The fill constant on the initial opening was calculated to be n = 8 to 10, both for the cluster together and for the individual parachutes. This indicates a slower opening than anticipated (the preflight fill constant was n = 4). The fill constants for the disreef events were somewhat obscured by the fact that the two parachutes did not disreef concurrently. When the cluster is modeled as a single, larger parachute, the fill constant for the first disreef is n = 10 to 16. However, video analysis indicated an fill constant of n = 2.4 for the single parachute disreefing. Similarly, individual parachute fill constants of n = 6 and n = 4 were calculated from video evidence for the disreef to full open, while the combined cluster fill constant was calculated at n = 18 to 20. The lower values, taken from video analysis, are similar to the fill constants observed on other Drogue applications and are likely more correct.

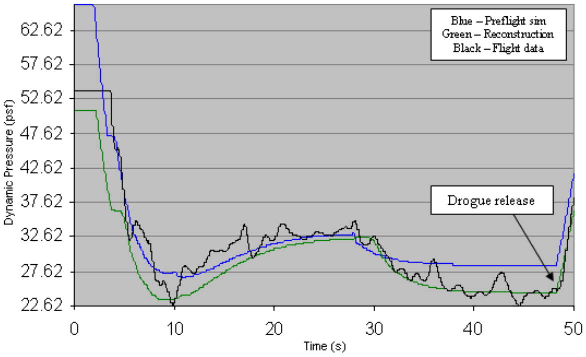

Figure 14. CDT-3 Dynamic Pressure during Extraction and Drogue Phase from Flight Data.

The dynamic pressure profile from flight data, shown in Fig. 14, was similar to the predicted profile. Extraction occurred at a lower velocity than expected, but the difference did not impact the Drogue flight. Drogue release occurred at a dynamic pressure of ~25 psf, ~2 psf lower than predicted.

Two reconstruction methods were used to determine the drag coefficient. Direct calculation using the dynamic pressure and suspended weight to calculate the drag area yields a drag coefficient of 0.48 to 0.53, lower than the preflight prediction of 0.58. Reconstruction of the flight in DSSA yields a drag coefficient of 0.60.

Table 8. CDT-3 Main Parachute Cluster Predictions and Results.

	Predicted	Actual
Initial opening		
Peak load	19,600 lb	20,000 lb
n	30	30
First disreef		
Peak load	26,400 lb	24,500 lb
n	10	10
Disreef to full open		
Peak load	38,900 lb	35,000 lb
n	2	4.4
Max dynamic pressure	45 psf	40.5 psf
Full open C_d	0.94	0.93-0.95

Table 8 compares the preflight predictions with actual flight results for several key parameters on the Main parachutes. The Mains continued to perform similar to expectations. The loads on all stages were close to predictions. The opening factors for the first two stages were confirmed, while the disreef to full open was slower than anticipated, possibly because of lead-lag (one parachute opening before the other). Shock factors of 1 were used for all three stages. The loads plot is depicted in Fig. 15.

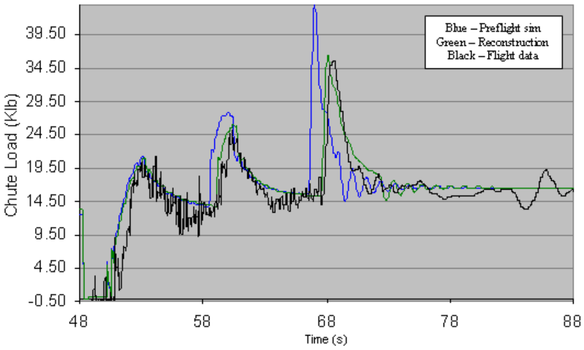

Figure 15. CDT-3 Parachute Loads during Main Phase from Flight Data.

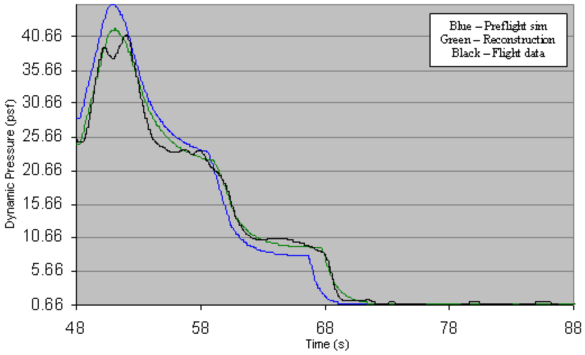

Figure 16. CDT-3 Dynamic Pressure during Main Phase from Flight Data.

As shown in Fig. 16, the vehicle reached a peak dynamic pressure of 40.5 psf under the Main parachute cluster, roughly 5 psf less than the target value of 45 psf.

Two reconstruction methods were used to determine the drag coefficient. Direct calculation using the dynamic pressure and suspended weight to calculate the drag area yields a drag coefficient of 0.93 to 0.95, very close to the preflight prediction of 0.94. Reconstruction of the flight in DSSA yields a drag coefficient of 0.94 exactly.

V. Summary of Results

The Generation I testing resulted in consistent performance parameters for the CPAS Main parachutes. The inflation and disreef times, drag values, and inflation loads displayed during the tests were consistent with the pre-test Design and Analysis Reports. However, more variation in opening times and drag occurred than was expected. Through the course of testing it was hypothesized that the variations in drag were primarily due to an oscillatory motion of individual parachutes along with movement of the parachutes in a cluster configuration. The second generation of testing will focus on gathering time space position of the parachutes in relation to the load along with open parachute area versus time. This information will allow the analysts on CPAS to reconstruct the physics to a higher degree of fidelity and predict an instantaneous drag value. The second generation testing will also endeavor to collect atmospheric data and payload velocity in a high fidelity manner since it was found that the current methods are insufficient for reconstructing a complex trajectory with moving and oscillating clusters of parachutes.

Each of the tests reported in this paper met all of the criteria for test success. Performance data was gathered to reconstruct opening fill times and drag area growth curves. Several areas were identified as possible improvements that will lead to higher fidelity models and a deeper understanding of the next design of CPAS parachutes. These improvements include greater data storage capability, higher fidelity wind, atmospheric, and payload velocity measurements that will lead to a more representative physical model of oscillating and moving parachutes, and next generation Tension Measuring Systems that will yield higher fidelity riser load data.

VI. Lessons Learned

A. Simulation and Analysis

Throughout the course of the Generation I test program, a number of improvements were made to the simulation tools as aspects of the parachute physics that were not originally of concern became more interesting over time.

Additional fidelity was added to the simulations, including the ability to utilize more parachutes including stabilization parachutes, apparent and entrained air mass effects, the ability to match the inflation process more accurately, and a variety of user friendly GUIs and animations.

It was found through testing that the Main parachutes exhibited a change in diameter over time and parachutes in a cluster move in relation to each other. As a result of this physical phenomena, the team had a renewed interest in modeling these data. Through the postflight analysis process it became obvious that real time winds and accurate tracking data are paramount in accurately modeling the physics of breathing and oscillating parachutes.

B. Instrumentation

It was found that the data gathering success rate on the Generation I instrumentation system was lower than anticipated. As a result, the Generation II instrumentation system will have a number of improvements to ensure valuable data is gathered. The primary improvement includes installing a redundant system where feasible with redundant sensors, power sources, and data storage.

It was also necessary to sacrifice data acquisition rates due to the storage limitation of the Generation I system. The Generation II system will utilize a National Instruments system to alleviate those concerns.

The Generation I TMS success rate was lower than anticipated. A new TMS design is in work, which will have considerably greater recording time and easier calibration.

Once the parachutes in a cluster opened and started to spread out, the load on the strain gauges was no longer at 180 degrees and the confluence readings were no longer accurate. The only way to deal with this problem would be to calibrate each strain gauge at multiple angles and use some form of instrumentation to measure the angles of each parachute riser during flight.

VII. Conclusion

A series of tests were planned and executed to test the CPAS Generation I Main parachutes individually, and a second series of tests was executed to analyze the effects of the Mains in a cluster configuration. This paper provided a description of the constructed geometry of Main parachutes, the test objectives of the drop tests, test configurations, data acquisition, and ultimately the flight simulation and analysis of each test flight executed during the Generation I Main and cluster development tests.

A variety of test techniques and equipment was used. Test vehicles included the NASA Medium Drop Test Vehicle, standard LVAD platforms, and a Cradle Monorail System that deployed the M-DTV.

The primary goal of the individual parachute tests was to determine the performance of a single parachute at the established test conditions. The cluster tests had the additional objective of examining the performance of the parachutes in a cluster configuration, with particular emphasis on drag reduction in a cluster and individual parachute motion in the cluster.

The Generation I testing resulted in consistent performance parameters for the CPAS Main parachutes. However, more variation in opening times and drag occurred than was suspected. Through the course of testing it was hypothesized that the variations in drag were primarily due to an oscillatory motion of individual parachutes along with movement of the parachutes in a cluster configuration. The next generation of CPAS testing will provide additional data to begin to understand and predict these phenomena.

It was found that the data gathering success rate on the Generation I instrumentation system was lower than anticipated. As a result, the Generation II instrumentation system will have a number of improvements to ensure valuable data is gathered.

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