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Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) Generation I Drogue and Pilot 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 Pilot and Drogue parachutes separately. These tests occurred between January and December 2007 at the US Army Yuma Proving Ground (YPG) and The Naval Air Warfare Center, WPNS Division, China Lake, CA. The goal of each test was to determine the performance of a single parachute 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 both the Pilot and Drogue parachutes. Test techniques, preflight predictions, test instrumentation, reconstruction results and challenges, and a brief discussion of the lessons learned from each test are presented.

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Nomenclature

C_d	=	drag coefficient
S	=	area (general)
S_o	=	surface area of parachute canopy
D_o	=	nominal parachute diameter
λ	=	canopy porosity
n	=	fill constant
Ck	=	opening shock factor
CPAS	=	Crew Exploration Vehicle (CEV) Parachute Assembly System
CMS	=	Cradle Monorail System
DDT	=	Drogue Development Test
DGPS	=	Differential GPS (Global Positioning System)
DCLDYN	=	Decelerator Dynamics
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
LVAD	=	Low Velocity Air Drop
M-DTV	=	Medium Drop Test Vehicle
NSI	=	NASA Standard Initiator
PDT	=	Pilot Development Test
TMS	=	Tension Measuring System
TSPI	=	Time Space Position Information
YPG	=	Yuma Proving Ground
VPCR	=	Variable Porosity Conical Ribbon

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]

This paper provides a description of the constructed geometry of the Pilot and Drogue parachutes, the test objectives of the drop tests, test configurations, data acquisition, and ultimately the flight simulation and analysis of each test flight.

These tests were planned and executed between January and December 2007 at the US Army Yuma Proving Ground (YPG) and The Naval Air Warfare Center, WPNS Division, China Lake, CA. The primary goal of each test was to determine the performance of a single parachute at the established test conditions. A variety of test techniques were used to meet the desired test conditions at parachute deployment: helicopter drops, standard Low Velocity Air Drop (LVAD) extractions from aircraft, and 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 Pilot and Drogue tests. The main component of the CPAS Generation I data acquisition system was a set of DataBrick analog recorders, manufactured by GMH Engineering. The Pilot tests used a sequencer system designed and built by the CPAS parachute contractor, Airborne Systems. The three Drogue tests used event sequencers designed and built by the CPAS instrumentation team to control parachute events. The CPAS instrumentation is described in detail in section III of this paper.

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 two 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 for both the Pilot and Drogue parachutes.

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 throughout the paper.

II. Overview of the Pilot and Drogue Parachutes

A. Ringslot Pilot Parachute

The ringslot Pilot parachute planform is summarized in Table 1. The constructed geometry is presented in Fig. 1.

Table 1. Pilot Parachute Planform Parameters.

Parameter	Value
Parachute Type	Ringslot
Parachute Diameter (D_o)	9.8 ft
Average Drag Coefficient (C_D)	0.59
Number of Gores	12
Number of Rings	4
Geometric Porosity (λ_g)	10.86%
Line Length Ratio (L_s/D_o)	1.15
Line Length	11.3 ft
Riser Length	57 ft

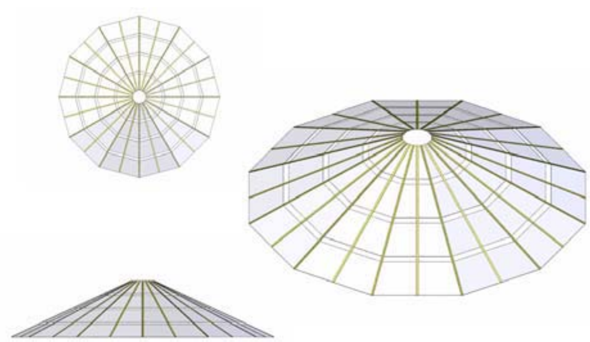

Figure 1. Pilot Parachute Constructed Geometry.

B. Drogue VPCR Parachute

The Drogue parachute planform was designed using a conical circular shape for the canopy. The canopy is constructed of individual triangularly shaped sections called gores. Each gore is formed by a grid of horizontal and vertical ribbons. The separations between the horizontal ribbons are the slots that provide the geometric porosity. Important parameters are summarized in Table 2. The constructed geometry of the Drogue parachute is shown in Fig. 2.

Table 2. Drogue Parachute Planform Parameters.

Parameter	Value
Parachute Type	Variable Porosity Conical Ribbon (VPCR)
Parachute Diameter	23 ft
Cone Angle	25.7 degrees
Number of Gores	24
Number of Ribbons	55
Geometric Porosity (λ_g)	19.2%
Line Length Ratio (L_s/D_o)	1.5
Line Length	34.5 ft
Riser Length	65.4 ft

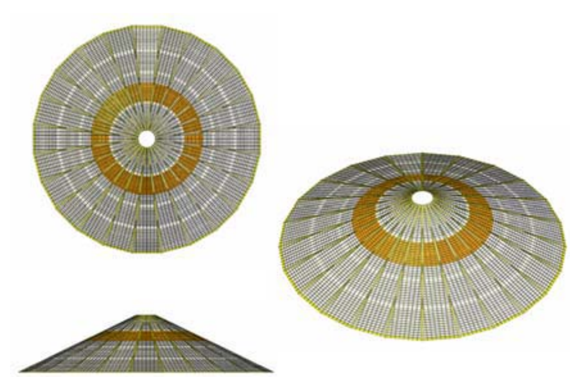

Figure 2. Drogue Parachute Constructed Geometry.

III. Instrumentation and Data Acquisition

The primary 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 recording 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. 5k strain links were used on the Pilot tests. A single absolute pressure transducer was flown on each test to measure atmospheric pressure. Two differential pressure transducers were connected to a pitot-static probe to measure dynamic pressure. A three-to-one instrumented confluence was flown on the test parachute during the Drogue tests.

The last sensor 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. CPAS plans to design and manufacture new TMS units prior to the next generation of testing.

During Generation I testing, the project used some instrumentation provided by Yuma Proving Ground (YPG) and Naval Air Weapons Station China Lake. YPG provided two Differential GPS (DGPS) units that were flown on the load, a windpak 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. China Lake provided TSPI, windpack, and weather balloon data.

The Pilot tests used a sequencer system designed and built by the CPAS parachute contractor, Airborne Systems. The three Drogue tests used event sequencers designed and built by the CPAS instrumentation team to control parachute events, such as strap cuts. 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 an initiator. DDT-1 used Irvin Standard Initiators while DDT-2 and DDT-3 used NASA Standard Initiators (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. Each sequencer system also required one first motion switch.

The CPAS sequencers worked with 100 percent reliability throughout the three Drogue tests, although DDT-1 suffered a failure of the Irvin Standard Initiators. The Airborne sequencers used for Pilot testing also worked with 100 percent reliability. The DataBricks had 100 percent reliability. The accelerometers and orientation sensors worked well throughout the test series. The absolute pressure transducer had only one anomaly, failing on the DDT-3 test. The reason for this anomaly was never determined. The pitot-static probe failed on PDT-3 and DDT-2; the probe on PDT-3 was connected incorrectly and it was suspected (but couldn't be determined conclusively) that the probe on DDT-2 had a leaking line. The three-to-one instrumented confluence fitting worked well on all flights. The 5k strain link failed on PDT-2 and PDT-3R, once due to incorrect connections and once due to cut wires. 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 windpack 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. PDT-2

1. Test Purpose and Objectives

The purpose of the first Pilot test was to deploy a CPAS Pilot parachute at a dynamic pressure of 19 psf, the predicted dynamic pressure at deployment on the first Orion Pad Abort test. The primary objectives of the test were to determine opening inflation loads, drag area, drag coefficient, and opening shock factor for the Pilot parachute. The secondary objectives were to evaluate packing procedures and investigate any canopy damage during deployment and recovery.

2. Test Description and Configuration

The preflight test plan consisted of dropping the test vehicle from a UH-1 helicopter. The Drop Test Vehicle (DTV) was the Pioneer Test Vehicle also known as the NASA Small Dart. The DTV is 8.75 ft long and 12.75 inches in diameter. The estimated drag area of the DTV is 0.4 ft^2. For PDT-2, the final vehicle weight was 547 lb. The DTV was picked up and released horizontally. The planned release altitude was 10,000 ft. The test configuration is depicted in Fig. 3.

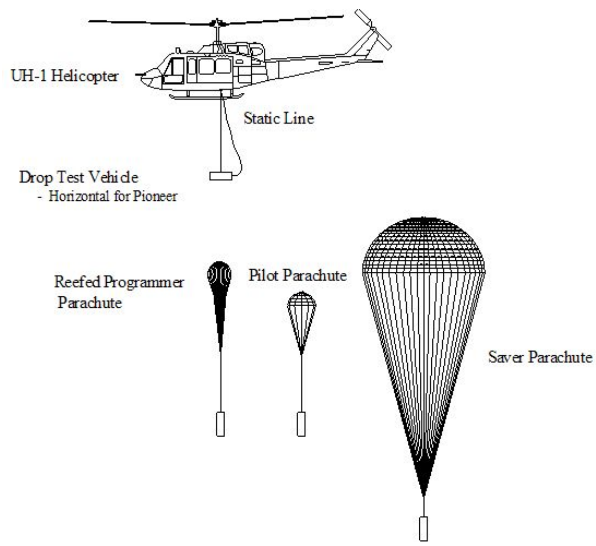

Figure 3. PDT-2 Test Configuration.

A static-line-deployed 9.85 ft VPCR parachute served as the programmer parachute. The programmer was permanently reefed to a drag area that established the planned test condition of 19 psf at Pilot parachute release. After 16 seconds, the programmer was released by cutting the harness legs and deployed the CPAS Pilot parachute. The vehicle descended under the Pilot parachute for 49 seconds before cutting the harness legs to release it. The Pilot parachute deployed the recovery parachute (8 m Aero Conical) to slow the drop test vehicle down to an acceptable velocity for ground impact. The lower velocity is required for the survival of both the DTV and the on-board instrumentation.

3. Test Results

Table 3 compares the preflight predictions with actual flight results for several key parameters of the Pilot parachute. The parachute opened faster and with higher loads than expected. The lower fill constant indicates a fill time approximately three times faster than predicted. The opening load was ~1,000 lb higher than the prediction. From this, the opening shock factor was calculated to be between 1.70 and 1.95, significantly higher than the predicted value of 1.05. Figure 4 shows the Pilot parachute loads trace.

Table 3. PDT-2 Pilot Parachute Predictions and Results.

	Predicted	Actual
Peak load	1,000 lb	2,030 lb
n	14	4.5
Ck	1.05	1.70-1.95
Dynamic Pressure at pilot deployment	19 psf	19.6 psf
Full open Cd	0.55	0.51-0.61

As shown in Fig. 5, the Pilot parachute deployed at a dynamic pressure of 19.6 psf, within 1 psf of the target value. The peak dynamic pressure during the Pilot phase was 26.1 psf, close to preflight predictions.

The average drag during pilot steady state operation (30 to 60 s) was 46.1 ft^2. This results in a steady state drag coefficient of 0.60, higher than the predicted value of 0.55. Reconstruction of the flight in DTV-Sim yields a higher drag coefficient, 0.61.

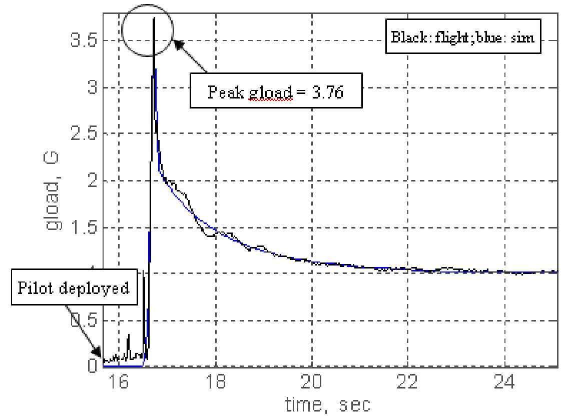

Figure 4. PDT-2 Parachute Loads from Flight Data.

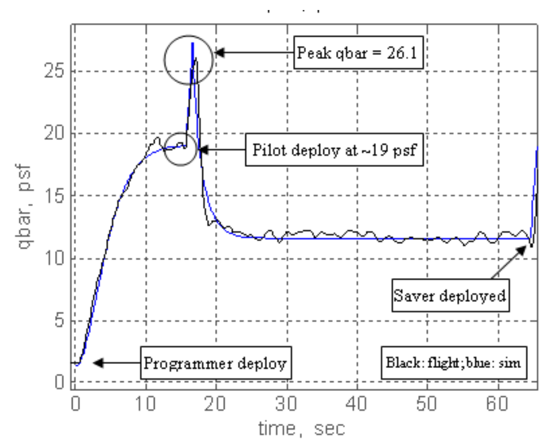

Figure 5. PDT-2 Dynamic Pressure from Flight Data.

B. PDT-3

1. Test Purpose and Objectives

The purpose of the second Pilot test was to deploy a CPAS Pilot parachute at a dynamic pressure of 30 psf, the value predicted at deployment on a nominal Lunar return trajectory. The objectives for this test were the same as PDT-2.

2. Test Description and Configuration

The second Pilot test used the same configuration as the first. The primary differences between the tests was a different reefing schedule on the programmer (to achieve a different dynamic pressure at Pilot deployment) and different cutter times.

3. Test Results

Flight data showed that, as on PDT-2, the Pilot parachute opened much faster than expected. Table 4 compares the preflight predictions with actual flight results for several key parameters on the Pilot parachute. The anticipated opening fill constant was 14, but reconstruction gives n = 6.3, indicating a fill time roughly twice as fast as predicted. The opening load was also significantly higher than expected. The Ck was calculated to be between 1.39 and 1.55, significantly higher than the predicted value of 1.05. Figure 6 shows the Pilot parachute loads trace.

Table 4. PDT-3 Pilot Parachute Predictions and Results.

	Predicted	Actual
Peak load	1,350 lb	2,490 lb
n	14	6.3
Ck	1.05	1.39-1.55
Dynamic Pressure at pilot deployment	30 psf	30 psf
Full open C_d	0.55	0.54-0.61

As shown in Fig. 7, the Pilot parachute deployed at the target dynamic pressure of ~30 psf. The peak dynamic pressure during the Pilot phase was 36.8 psf, close to preflight predictions.

The average drag during pilot steady state operation (25 to 55 s) was 45.0 ft^2. This results in a steady state drag coefficient of 0.59, higher than the preflight prediction of 0.55. Reconstruction of the flight in DTV-Sim yields a drag coefficient of 0.61.

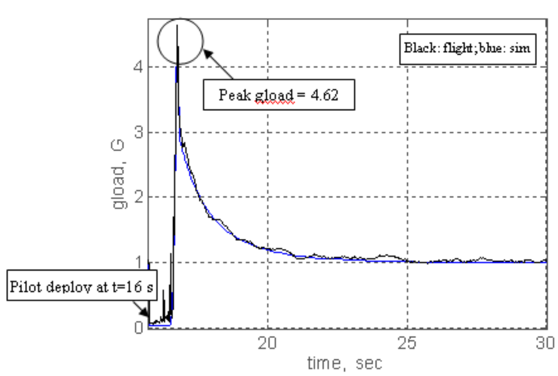

Figure 6. PDT-3 Parachute Loads from Flight Data.

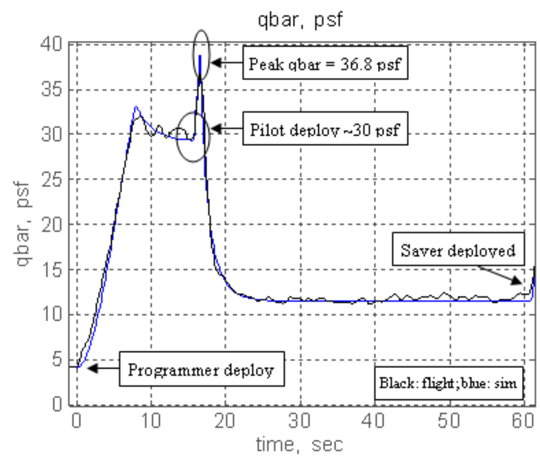

Figure 7. PDT-3 Dynamic Pressure from Flight Data.

C. PDT-3R

1. Test Purpose and Objectives

Due to the unexpected results of the first two Pilot parachute tests, the third test was a repeat of PDT-3. In addition,the previous test results were in question becausehe strain link data was clipped for both PDT-2 and PDT-3, and other instruments malfunctioned. Since the final drop test was planned to be a high dynamic pressure test (60 psf), confidence in determining the opening load was required before proceeding with that test.

2. Test Description and Configuration

The configuration of PDT-3R was identical to that of PDT-3.

3. Test Results

Predictions for PDT-3R were based on the data from PDT-2 and PDT-3. Table 5 compares the preflight predictions with actual flight results for several key parameters on the Pilot parachute. Flight data for PDT-3R showed that the Pilot parachute may have opened a little slower than in previous flights, though not as slowly as the original design predicted. The opening fill constant used for preflight predictions was 2; two reconstruction methods yielded values of 2 and 5. Both are significantly lower than the original design value of 14, validating the change to a lower value.

Table 5. PDT-3R Pilot Parachute Predictions and Results.

	Predicted	Actual
Peak load	2,440 lb	2,615 lb
n	2	2-5
Ck	1.5	1.5-1.6
Dynamic Pressure at line stretch	30 psf	28.5 psf
Full open C_d	0.59	0.59-0.61

Figure 8 shows the Pilot parachute loads trace. The opening load was ~150 lb higher than expected. The Ck was calculated to be between 1.5 and 1.6, similar to what was observed on the previous tests.

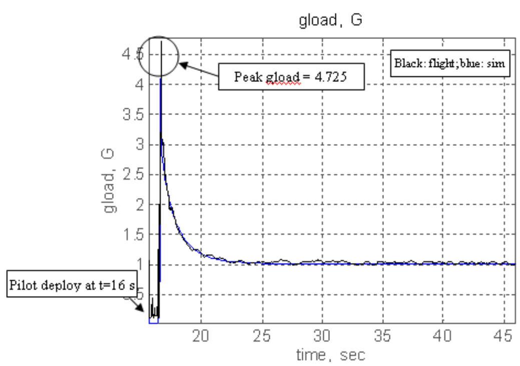

Figure 8. PDT-3R Parachute Loads from Flight Data.

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 0.59. Reconstruction of the flight in DTV-Sim yielded a drag coefficient of 0.61.

As depicted in Fig. 9, the Pilot parachute deployed at a dynamic pressure of 28.5 psf, close to the target value. The peak dynamic pressure during the Pilot phase was 37.6 psf, close to preflight predictions.

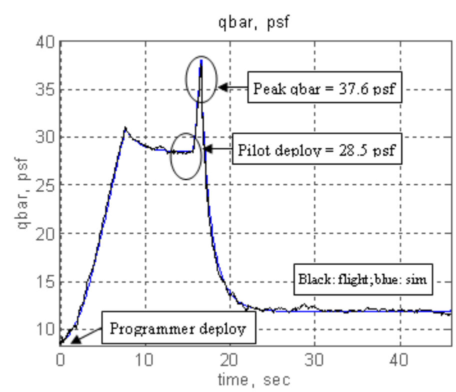

Figure 9. PDT-3R Dynamic Pressure from Flight Data.

D. PDT-4

1. Test Purpose and Objectives

The purpose of the final Pilot test was to deploy a CPAS Pilot parachute at a dynamic pressure of 45 psf, the value which was predicted on a Lunar return trajectory with one Drogue failure. The test objectives were the same as the previous tests.

2. Test Description and Configuration

The test configuration for PDT-4 was once again very similar to the configurations used on the previous tests. The primary difference was the use of a smaller programmer parachute to achieve the higher target

Table 6. PDT-4 Pilot Parachute Predictions and Results.

	Predicted	Actual
Peak load	3,730 lb	3,400-3,600 lb
n	2	5
Ck	1.5	1.40-1.65
Dynamic Pressure at pilot deploy	45 psf	47.5 psf
Full open C_d	0.59	0.60-0.61

dynamic pressure at Pilot parachute deployment.

3. Test Results

Table 6 compares the preflight predictions with actual flight results for several key parameters on the Pilot parachute. Flight data showed that the Pilot parachute opened with an inflation time similar to previous tests, with an opening fill constant of 5. The opening load was close to the expected values. The preflight predicted peak load was ~3,730 lb; the accelerometers showed a peak load of 6.627 G or 3,595 lb, while the strain link indicated a peak of 3,392 lb. The Ck was calculated to be between 1.40 and 1.65, similar to the values found on previous tests. Figure 10 shows the Pilot parachute loads trace.

As shown in Fig. 11, the Pilot parachute deployed at a dynamic pressure of 47.5 psf, close to the target value. The peak dynamic pressure during the Pilot phase was 56.3 psf, close to preflight predictions.

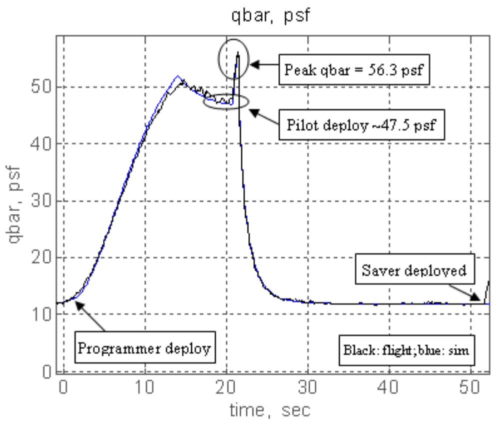

Figure 11. PDT-4 Dynamic Pressure from Flight Data.

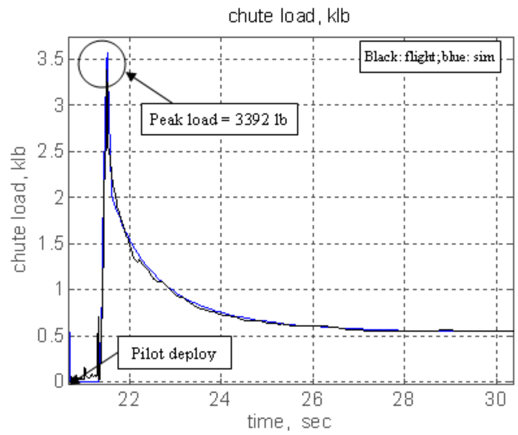

Figure 10. PDT-4 Parachute Loads from Flight Data.

Two reconstruction methods were used to determine the drag coefficient. Direct calculation using the dynamic pressure and loads to calculate the drag area yields a drag coefficient of 0.60, higher than the preflight prediction. Reconstruction of the flight in DTV-Sim yields a drag coefficient of 0.61.

E. DDT-1

1. Test Purpose and Objectives

The purpose of the first Drogue test was to deploy a Drogue parachute initially reefed to reach a deployment target dynamic pressure of 19 psf (± 5 psf), corresponding to apogee of the Pad Abort trajectory. The primary objectives were to obtain measurement and instrumentation data, Drogue parachute inflation loads, inflation fill times from line stretch, and drag area growth curves, and to verify Drogue parachute drag coefficients and full opening shock factors. The secondary objectives were to evaluate packing procedures and to investigate any Drogue parachute canopy damage taken during deployment and recovery.

2. Test Description and Configuration

The NASA Medium Dart vehicle (M-DTV) was dropped from a CH-47 Chinook helicopter. The test consisted of two parachutes: 1) the Generation I CPAS Drogue parachute (Variable Porosity Conical Ribbon (VPCR) parachute: D_o = 23 ft, 24 gores, 34.5 ft line length, 65.4 ft riser, and 2) a recovery parachute (Ringslot: D_o = 60 ft, C_D = 0.58) to slow the drop test vehicle for ground impact.

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 weight was 7,590 lb. The M-DTV was picked up and released horizontally. The Drogue parachute was static line deployed from the CH-47 helicopter. The Drogue parachute was initially reefed to 45% of full open. The H5-14 Roberts Research cutter disreefed the Drogue at 14 seconds after line stretch. After gathering data with both onboard instrumentation and ground based video and optical tracking, the test parachute was to be cut away and used to deploy the recovery parachute to decrease the rate of descent of the M-DTV to soften the landing.

During the actual flight, the Drogue parachute did not cut away from the M-DTV and therefore the recovery parachute did not deploy. The M-DTV descended all the way to the ground under the Drogue parachute. In spite of hitting the ground at a higher velocity than planned, the on-board data was recovered from the vehicle.

3. Test Results

Table 7 compares the preflight predictions with actual flight results for several key parameters on the Drogue parachute. Flight data revealed that, like the Pilot parachutes, the Drogue parachute opened much faster than expected. The anticipated fill constant, n, was 11.7; reconstruction yielded n = 2 for the initial opening, indicating a fill time approximately five times faster than predicted. This number was thought to be artificially fast. The parachute inflated before the harness legs and confluence fitting were fully deployed, so the opening load was not correctly measured by the instrumented confluence fitting. The predicted load was ~3,000 lb. However, the accelerometers showed a peak of 1.5 G, or ~11,000 lb. The opening shock factor for the initial opening was calculated to be between 1.2 and 1.3, higher than the predicted value of 1. Figure 12 shows the Drogue parachute loads trace.

The disreef to full open also occurred faster and with a higher-than-anticipated load. The expected fill constant was 11.7, but reconstruction yielded values between 3.5 and 5, more than twice as fast. The preflight predicted peak load was ~13,200 lb; the accelerometers showed a peak of 2.6 G, or ~19,000 lb. The shock factor was calculated to be between 1.2 and 1.3, higher than the predicted value of 1.

Table 7. DDT-1 Drogue Parachute Predictions and Results.

	Predicted	Actual
Initial Opening		
Peak load	3,000 lb	11,000 lb
n	11.7	2
Ck	1.0	1.2-1.3
Disreef to Full Open		
Peak load	13,200 lb	19,000 lb
n	11.7	3.5-5
Ck	1.0	1.2-1.3
Dynamic Pressure at pilot deploy	19 psf	10 psf
Full open C_d	0.55	0.57-0.59

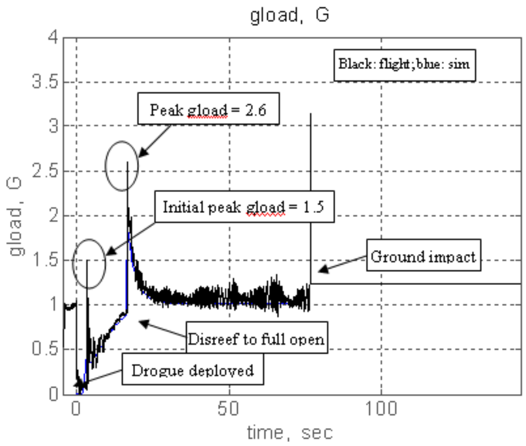

Figure 12. DDT-1 Parachute Loads from Flight Data.

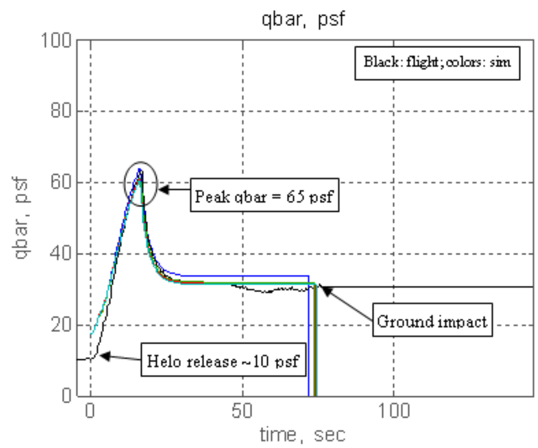

Figure 13. DDT-1 Dynamic Pressure from Flight Data.

As shown in Fig. 13, the Drogue parachute deployed at a dynamic pressure of ~10 psf, lower than the target value. The peak dynamic pressure during the Drogue phase was 65 psf, close to preflight predictions.

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 0.57 to 0.58, slightly higher than the preflight prediction of 0.55. Reconstruction of the flight in DTV-Sim yields a drag coefficient of 0.59.

F. DDT-2

1. Test Purpose and Objectives

The purpose of DDT-2 test was to deploy a Drogue parachute at a target deployment dynamic pressure of 70 psf (± 5 psf). The primary objectives were the same as those on DDT-1 with the additional requirements to capture time, space, position data (TSPI), and to video record Drogue parachute events to characterize extraction, deployment and inflation.

2. Test Description and Configuration

This test used a NASA M-DTV mounted on the CMS. The CMS/M-DTV were extracted from a C-130A aircraft with a GFE 28 ft cargo extraction parachute. After the CMS cleared the aircraft the extraction parachute oriented the M-DTV and CMS downward. A few seconds after extraction, the M-DTV was released from the CMS. The CMS fell away and landed separately from the test vehicle. Figure 14 shows the extraction and release configuration.

The test consisted of six parachutes: 1) One 28 ft ringslot GFE extraction parachute. 2) Two 23 ft CPAS Drogue parachutes: D_o = 23 ft, 24 gores, 65.4 ft riser, 34.5 ft suspension line length. 3) One Generation I CPAS Main quarter spherical ringsail parachute which was used as a recovery parachute: Do = 116 ft, 80 gores, 97 ft riser, 133 ft suspension line length. 4) Two 15 ft LVAD stabilizer parachutes.

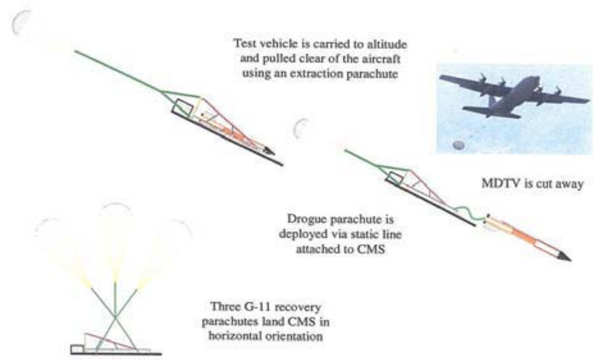

Figure 14. M-DTV and CMS Extraction and Release.

One CPAS Drogue parachute was used as the programmer parachute. It was deployed via a static line attached to the CMS. The programmer parachute was reefed to 45% for 8 seconds and disreefed to 50% permanently to achieve the desired test dynamic pressure. Upon achieving the desired test condition, the programmer chute was cut away deploying the CPAS test Drogue parachute. The Drogue parachute was reefed to 60% for 14 seconds then disreefed to full open. At the planned time, the Drogue parachute was cut away deploying the recovery parachute and stabilizer parachutes. The stabilizer parachutes were required to prevent over acceleration of the M-DTV during Main deployment. The two stabilizer parachutes were 15 ft LVAD extraction parachutes. The recovery parachute was a 116 ft CPAS Main parachute, which returned the M-DTV to the ground at an acceptable descent rate. (For more information on the Main parachutes, see Ref. 3.)

The 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. After the M-DTV was cut away, the CMS fell away under the extraction chute, eventually deploying three G-11 parachutes. When the G-11 parachutes deployed, the CMS reoriented to a horizontal position. The CMS landed under the G-11 parachutes as shown in Fig. 14.

The final combined weight at extraction was approximately 17,200 lb. The suspended weight of the M-DTV under the test Drogue was 7,294 lb. The suspended weight under the recovery parachute was 7,028 lb.

3. Test Results

Data was gathered on both Drogue parachutes and the Main parachute used in DDT-2. Table 8 compares the preflight predictions with actual flight results for several key parameters on the programmer Drogue parachute. Table 9 compares the preflight predictions with actual flight results for several key parameters on the test Drogue parachute. In both applications, as on DDT-1, the parachute opened and disreefed much faster than predicted. The loads on both Drogue parachute applications were more balanced than predicted. On the initial opening of the programmer, the accelerometers showed a peak load higher than the predicted load, while on the disreef to full open, the peak was lower than the predicted load. The opening shock factor for the initial opening was calculated to be between 1.20 and 1.47, similar to the predicted value of 1.3 (as taken from DDT-1). The shock factor on the disreef to full open was lower, between 1.02 and 1.2. The test parachute demonstrated similar behavior. The loads trace for both parachutes is shown in Fig. 15.

As shown in Fig. 16, separation of the DTV and the CMS occurred at a dynamic pressure of ~33 psf, as

Table 8. DDT-2 Drogue (Programmer) Parachute Predictions and Results.

	Predicted	Actual
Initial Opening		
Peak load	6,000 lb	9,750 lb
n	11.7	3.5-5
Ck	1.3	1.20-1.47
Disreef to Full Open		
Peak load	10,000 lb	8,600 lb
n	11.7	1.5-2.5
Ck	1.3	1.02-1.20
Dynamic Pressure at line stretch	35 psf	52 psf
Full open C_d	0.58	0.56-0.60

Table 9. DDT-2 Drogue (Test) Parachute Predictions and Results.

	Predicted	Actual
Initial Opening		
Peak load	13,500 lb	14,340 lb
n	11.7	3-5
Ck	1.3	1.24-1.45
Disreef to Full Open		
Peak load	15,190 lb	14,640 lb
n	11.7	1.5-2.5
Ck	1.3	1.24-1.45
Dynamic Pressure at line stretch	74 psf	80 psf
Full open C_d	0.58	0.56-0.60

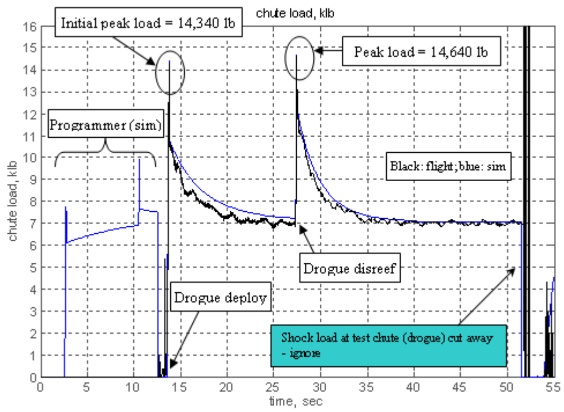

Figure 15. DDT-2 Drogue (Programmer and Test) Parachute Loads from Flight Data.

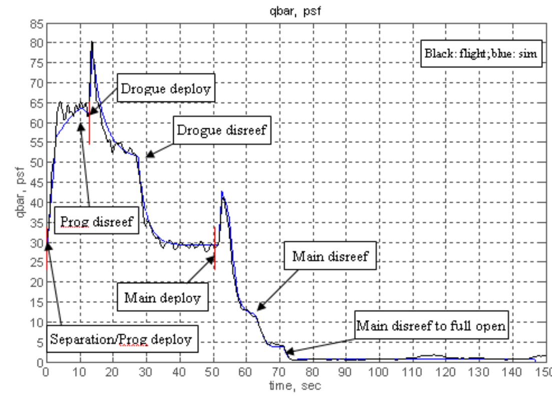

Figure 16. DDT-2 Dynamic Pressure from Flight Data.

predicted. However, preflight simulations assumed an instantaneous separation, while in reality the vehicle had ~2 seconds in which to accelerate as it slid off of the CMS. As a result, the programmer parachute reached ~52 psf at line stretch. The programmer was released and the test parachute deployed at ~65 psf. The test parachute reached ~80 psf at line stretch, 6 psf higher 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 of both the programmer and the test parachute yields drag coefficients of 0.56 to 0.60, bounding the preflight prediction of 0.58. Similarly, reconstruction of the flight in DTV-Sim yields a drag coefficient of 0.58 to 0.60.

DDT-2 used the CPAS Main as a recovery parachute. Table 10 compares the preflight predictions with actual flight results for several key parameters on the Main parachute. For the most part, the Main performed similar to expectations. Loads on the second stage were lower than expected. The load at the disreef to full open was surprisingly high. Preflight simulations indicated a small peak, but flight data indicated a load of ~14,000 lb. The disreef also happened faster than expected, with n = 2 rather than 9. After much discussion and analysis, a shock factor of 1 was used for all stages, despite the sharp peak load on the disreef to full open. The loads trace for the Main parachute is shown in Fig. 17.

Table 10. DDT-2 Main Parachute Predictions and Results.

	Predicted	Actual
Initial opening		
Peak load	9,800 lb	8,700 lb
n	30	28
First disreef		
Peak load	11,000 lb	8,700 lb
n	9	11
Disreef to full open		
Peak load	8,500 lb	14,000 lb
n	9	2
Max dynamic pressure	40 psf	42 psf
Full open C_d	0.94	0.83-1.08

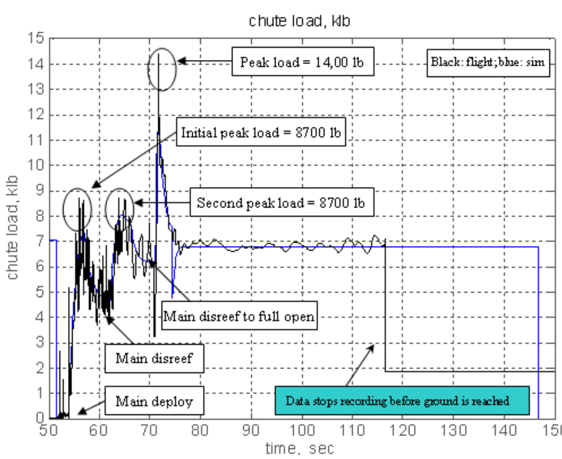

Figure 17. DDT-2 Main Parachute Loads from Flight Data.

As shown in Figure 16, the vehicle reached a peak dynamic pressure of ~42 psf under the Main parachute, close to the preflight prediction.

The drag coefficient calculation for the Main parachute is more complicated than for the Pilots and Drogues, for two primary reasons: the large parachute "breathes" (opens and closes), and there is often a change in the atmosphere near the ground where the "steady-state" velocity changes. An average drag coefficient was calculated based on the available data. Direct calculation using the dynamic pressure and suspended weight to calculate the drag area yields an average drag coefficient of the Main parachute of 0.83 to 1.08, bounding the preflight prediction of 0.94. Reconstruction of the flight in DTV-Sim yields a drag coefficient of 0.96.

G. DDT-3

1. *Test Purpose and Objectives*

The purpose of DDT-3 test was to deploy a Drogue parachute at a dynamic pressure of 35 psf (± 5 psf). The primary objectives were the same as on DDT-2. Additional secondary objectives were to record load "tip-off" dynamics, CMS loads and separation dynamics, landing rates and conditions, and programmer and recovery parachutes performance and loads, validate the footprint tool prediction and accuracy, demonstrate Differential GPS performance, obtain meteorological data, and record the M-DTV landing velocity.

2. *Test Description and Configuration*

The configuration for DDT-3 was similar to DDT-2. The primary differences was the lack of a programmer parachute; the test Drogue was static line deployed from the CMS. The Drogue deployed straight to full open (no reefing).

3. *Test Results*

Data was again gathered on both the Drogue and the Main used in DDT-3. Table 11 compares the preflight predictions with actual flight results for several key parameters on the Drogue parachute. As in the previous tests, the Drogue opened much faster than predicted. The anticipated fill constant, n, was 11.7; reconstruction yielded n = 4, similar to the values observed on the other tests. The peak load was significantly higher than expected – the prediction was ~11,700 lb, while flight data shows a peak load of ~16,500 lb. This increase in load is partially due to the higher than predicted velocity after separation (due to the incorrect assumption of instantaneous separation). The shock factor was calculated to be between 1.30 and 1.48, consistent with previous tests. The loads trace for the Drogue is shown in Fig. 18.

Table 11. DDT-3 Drogue Parachute Predictions and Results.

	Predicted	**Actual**
Peak load	11,700 lb	16,500 lb
n	11.7	4
Ck	1.3	1.30-1.48
Dynamic Pressure at line stretch	39.5 psf	47 psf
Full open C_d	0.58	0.54-0.63

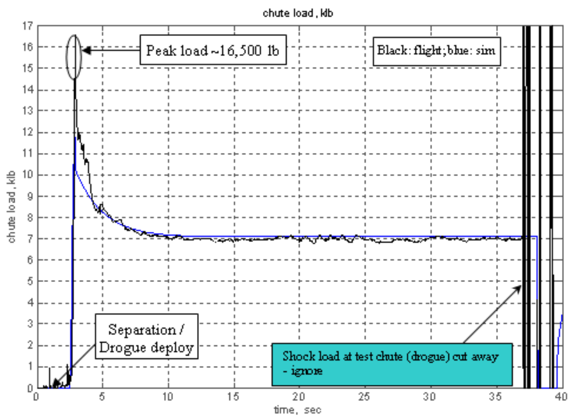

Figure 18. DDT-3 Drogue Parachute Loads from Flight Data.

As shown in Fig. 19, separation of the DTV and the CMS occurred at a dynamic pressure of ~25 psf. However, as on DDT-2, preflight simulations assumed an instantaneous separation, while in reality the vehicle had ~2 seconds in which to accelerate as it slid off of the CMS. As a result, the programmer parachute reached ~47 psf at line stretch, ~8 psf higher than predicted.

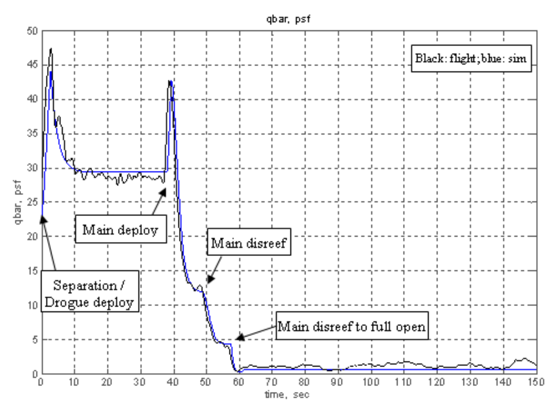

Figure 19. DDT-3 Dynamic Pressure from Flight Data.

Using the dynamic pressure and suspended weight to calculate the drag area, the drag coefficients of both the programmer and the test parachute were calculated to be 0.54 to 0.63, bounding the preflight prediction of 0.58. Matching the simulations to the altitude and dynamic pressure flight data for each parachute yields a drag coefficient of 0.58 exactly.

Like DDT-2, DDT-3 used the CPAS Main as a recovery parachute. Table 12 compares the preflight predictions with actual flight results for several key parameters on the Main parachute. The results were very similar to those on DDT-2. The loads trace for the Main is shown in Fig. 20.

As shown in Fig. 19, the vehicle reached a peak dynamic pressure of ~42 psf under the Main parachute, close to the preflight prediction.

Two reconstruction methods were used to determine the drag coefficient. Direct calculation using the dynamic pressure and loads to calculate the drag area of the Main parachute yields an average drag coefficient of 0.80 to 1.04,

Table 12. DDT-3 Main Parachute Predictions and Results.

	Predicted	Actual
Initial opening		
Peak load	9,800 lb	8,700 lb
n	30	30
First disreef		
Peak load	11,500 lb	8,900 lb
n	9	11
Disreef to full open		
Peak load	8,500 lb	15,500 lb
n	9	2
Max dynamic pressure	40 psf	42 psf
Full open C_d	0.94	0.80-1.04

bounding the preflight prediction of 0.94. Reconstruction of the flight in DTV-Sim yields a drag coefficient of 0.94 to 0.95.

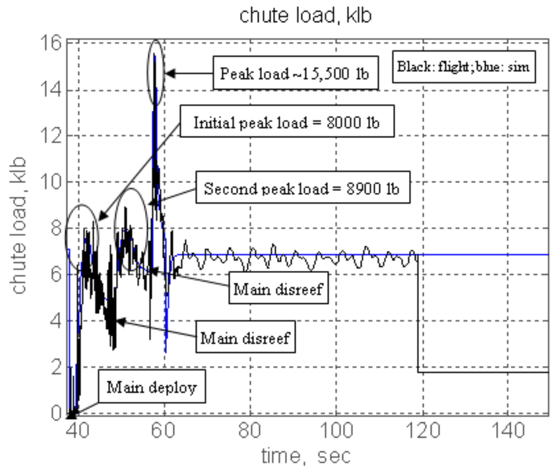

Figure 20. DDT-3 Main Parachute Loads from Flight Data.

V. Summary of Results

The Generation I testing resulted in consistent performance parameters for the CPAS Pilot and Drogue parachutes. The drag values determined from the test data were consistent with the pre-test Design and Analysis Reports. The inflation and disreef times were significantly faster than expected with the design. The pilots opened approximately twice as fast as expected and the drogues opened five times faster than expected. The inflation and disreef loads were significantly higher than expected with the design. The Pilot postflight analysis resulted in opening shock factor (Ck) of 1.5while the opening shock factor (Ck) for the Drogues was consistently 1.3 .

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; including, but not limited to, 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 and aspects of the parachute physics that were not originally of concern became more interesting over time.

Additional fidelity was added to the simulations, such as the ability to utilize more parachutes including stabilization parachutes, the incorporation of 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 that both the Pilots and the Drogues opened more rapidly than expected, resulting in an additional test to verify data, and a reconsideration of the parachute architecture prior to the next stage of development.

B. Instrumentation

The data gathering success rate on the Generation I instrumentation system was lower than anticipated. As a result, the next generation 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 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.

VII. Conclusion

A series of tests were planned and executed to test the CPAS Generation I Pilot and Drogue parachutes. This paper provided a description of the constructed geometry of the 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 pilot and drogue development tests.

A variety of test techniques and equipment was used. Test vehicles included the NASA Small Dart, 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 Generation I testing resulted in consistent performance parameters for the CPAS Pilot and Drogue parachutes. However, both the Pilots and Drogues opened much faster than expected and displayed significantly higher inflation and disreef loads than expected.

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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[2]Lichodziejewski, D., Taylor, T., Sinclair, R., Olmstead, R., Kelley, C., Johnson, J., Melgares, M., Morris, A., and Bledsoe, K., "Development and Test of the Orion Parachute Assembly System," AIAA-2009-16640, May 2009.

[3]Bledsoe, K., Englert M., Morris, A., and Olmstead, R., "Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) Generation I Main and Cluster Development Test Results," AIAA-2009-64906, May 2009.