Summary of CPAS Gen II Testing Analysis Results

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The Orion spacecraft is currently under development by NASA and Lockheed Martin. Like Apollo, Orion will use a series of parachutes to slow its descent and splashdown safely. The Orion parachute system, known as the CEV Parachute Assembly System (CPAS), is being designed by NASA, the Engineering and Science Contract Group (ESCG), and Airborne Systems. The first generation (Gen I) of CPAS testing consisted of thirteen tests and was executed in the 2007-2008 timeframe. The Gen I tests provided an initial understanding of the CPAS parachutes. Knowledge gained from Gen I testing was used to plan the second generation of testing (Gen II). Gen II consisted of nine tests: three Test Support Equipment which investigated the use of smart release techniques (not discussed in this paper); three single-parachute tests, designated as Main Development Tests; and three Cluster Development Tests. Gen II required a more thorough investigation into parachute performance than Gen I. Higher fidelity instrumentation, enhanced analysis methods and tools, and advanced test techniques were developed. The results of the Gen II test series are being incorporated into the CPAS design. Further testing and refinement of the design and model of parachute performance will occur during the upcoming third generation of testing (Gen III). This paper will provide an overview of the developments in CPAS analysis following the end of Gen I, including descriptions of new tools and techniques as well as overviews of the Gen II tests.

Nomenclature

C_D	=	drag coefficient
C_p	=	pressure coefficient
CDT	=	Cluster Development Tests
CEV	=	Crew Exploration Vehicle
CM	=	Crew Module
CMS	=	Cradle Monorail System
CPAS	=	CEV Parachute Assembly System
DAS	=	Data Acquisition System
DCLDYN	=	Decelerator Dynamics
DLL	=	Design Limit Load
DSSA	=	Decelerator Systems Simulation Application
DSS	=	Decelerator Systems Simulation
FDP	=	Flight Data Processor

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F_y	=	Y component of the resultant pressure force acting on the vehicle
GFE	=	Government Furnished Equipment
MDT	=	Main Development Tests
MDTV	=	Medium Drop Test Vehicle
MSL	=	Mean Sea Level
OICL	=	Over-Inflation Control Line
ROD	=	Rate of Descent
TMS	=	Tension Measuring System
TSE	=	Test Support Equipment

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 use a series of parachutes to slow its descent and splashdown safely. The Orion parachute system, known as the CEV Parachute Assembly System (CPAS), is being designed by NASA, the Engineering and Science Contract Group (ESCG), and Airborne Systems. The CPAS configuration consists of two mortar-deployed Drogue parachutes, three mortar-deployed Pilot parachutes, and three Pilot-deployed Main parachutes.

The first generation (Gen I) of CPAS testing consisted of thirteen tests and was executed in the 2007-2008 timeframe. Several papers published in 2009 summarized Gen I Pilot, Drogue, and Main parachute inflation and load performance results. Most of the Gen I tests were single-parachute tests, wherein a sequence of individual parachutes was deployed, rather than clusters of parachutes. Only two tests in Gen I used clusters of parachutes in the same configuration as the CPAS baseline design; a third was attempted, but failed prior to the activation of the CPAS system. The Gen I tests provided an initial understanding of the CPAS parachutes. Inflation parameters were determined, sometimes contradicting the preliminary expectations of the parachute performance; in particular, the Pilots and Drogues opened faster and with more force than expected. Test techniques and analysis methods were developed and began to be refined. Measurement needs and limitations were identified. Unexpected parachute dynamics, particularly breathing and cluster interactions in the Main parachutes, were observed and analyzed.[1,2]

Knowledge gained from Gen I testing was used to plan the second generation of testing (Gen II). Gen II required a more thorough investigation into parachute performance. Higher fidelity instrumentation, enhanced analysis methods and tools, and advanced test techniques were developed. Data was gathered on skipped-stage cases, which are the primary driver to the parachute design. Design changes were tested in an attempt to improve cluster stability, which is necessary to fully satisfy system requirements for rate of descent, inflation loads, and induced torque.

Three Test Support Equipment (TSE) tests initiated Gen II. These tests were used to develop new avionics systems and test techniques such as smart release methods[3], but will not be discussed in this paper. Gen II also consisted of six other tests: three single-parachute tests, designated as Main Development Tests (MDT), and three Cluster Development Tests (CDT). While full analyses have not been completed for all of these tests, preliminary analyses – including cluster dynamics and rate of descent[4] – have been performed. The results of the Gen II test series are being incorporated into the CPAS design. Further testing and refinement of the design and model of parachute performance will occur during the upcoming third generation of testing (Gen III).

Two new test vehicles will be utilized during Gen III: the Parachute Compartment Drop Test Vehicle (PCDTV), and the Parachute Test Vehicle version 2 (PTV2). The PCDTV is a large missile-shaped vehicle, similar to the smaller Medium Drop Test Vehicle (MDTV) used on the Gen II MDT series, with a representative parachute compartment on the end. The PTV is a capsule with similar aerodynamic properties to the actual Orion vehicle, but its height has been truncated to allow the use of a C-130 or C-17 aircraft for testing.[5] A new parachute design will also be implemented during Gen III, based on the results of the Gen II tests. The new parachute design will have increased porosity and a line length ratio similar to Apollo's. In addition, improved analyses will be used to further refine and understand the current models. Planned upgrades include a new added mass model, the use of CANO/CALA (a legacy parachute structural analysis tool), improved snatch loads predictions, and the creation of a simulation environment where inputs and outputs can be easily handed from one tool to another.[6]

II. Improvements in CPAS Parachute Analysis

A. Avionics Instrumentation and Analysis Tools

Throughout Gen I, analysis was limited by instrumentation fidelity and simulation capabilities. Measurement inaccuracies obscured parachute performance results. Simulations lacked well-developed models for certain aspects

of the physics governing parachute and test vehicle dynamics. As Gen II developed, improvements were made in several areas to ensure a more accurate, complete parachute model.

1. New Avionics

A new avionics suite was developed for Gen II. The new Data Acquisition System (DAS) had a central unit for controlling and storing data from several instruments simultaneously. This allowed for the time-synchronization of data, a requirement for improved data reduction and analysis. The new DAS also had a larger storage capacity which provided higher sampling rates throughout the duration of the test flight. The DAS was fully configurable and could easily manage any combination of instrumentation, a necessary feature as different test vehicles required different sets of instruments.

In order to improve measurement accuracy, new instruments were investigated prior to Gen II. Velocity data are critical to determining parachute performance. Two new instruments were purchased to improve velocity measurements: the NovAtel SPAN-SE and the Crossbow Nav440, shown in Figure 1 and Figure 2, respectively. Both are integrated GPS/IMUs. The NovAtel units are provide a more accurate measurement, with an error of 2 cm/s compared to the Gen I units' 5 cm/s. The NovAtel units are therefore considered the "truth" for analyses. In addition to the improved velocity accuracy, the NovAtel units' ring-stabilized gyros provide better attitude measurements than were available on Gen I. The Nav440s have higher velocity uncertainties and are used as backups for the NovAtel unit on each test.

Figure 1. NovAtel SPAN-SE sensor.

Figure 2. Nav440 sensor.

Instrumentation to improve parachute load measurements was also investigated. Most of the tests on Gen I used single parachutes, the loads on which could be measured by instrumented confluence fittings. Unfortunately, data from instrumented confluence fittings are of limited use with clusters of parachutes; the total load is suspect, due to issues calibrating the instrument for all possible riser angles, and the confluence fitting cannot report individual riser loads. Therefore, other methods of measuring the loads must be used. The instruments used to acquire individual riser loads data on Gen I were Tension Measuring System (TMS) units attached to the riser of each parachute. However, the TMS units were designed for use on single-ply risers, rather than the multi-ply risers used on CPAS. The data acquired from the TMS units therefore had relatively high uncertainties because the units were used out of configuration. For Gen II, direct riser load measurements were taken by 30K strain links rigged between the riser and the confluence fitting. This solution worked well for the Main parachutes, but the turbulent wake environment experienced by the Drogue parachutes sometimes caused malfunctions and noise in the Drogue data. The entire industry has suffered due to a lack of understanding parachute physics which has been driven by practical measurement limitations.

Knowledge of the atmosphere encountered by the parachutes during the flight is required for accurate reconstructions. However, there are considerable difficulties in acquiring this data. Freestream conditions such as pressure and wind velocity cannot be measured on the payload itself due to the effects of the payload on the airstream. Temperature measurements on the payload similarly do not measure the freestream temperature, but rather the temperature of the payload. New options for measuring atmospheric conditions near the payload were considered for Gen II. Although the idea of a windpack or other measurement unit that was ejected from the payload to descend above or below it was promising, it proved too difficult to implement. The primary source of atmosphere conditions remains the windpacks that are extracted from the aircraft separate from the payload. Logistics and timing require that these be extracted on a separate pass of the aircraft, rather than concurrent with the payload. This puts the windpack data at a remove in time and space from the actual testing events. Due to the difference in descent rate between a test payload and a windpack, they do not follow the same trajectory. The choices are to extract the windpacks from the aircraft at the same release point as the payload, or to extract the windpacks at a release point calculated to ensure that they would land near the payload, thus falling as close as possible to the same column of air as the Mains. This technique was not always feasible, given the strict time requirements of a test operation. While any measurement taken at a remove in time and space cannot fully characterize the actual atmosphere encountered by the test article, the differences are small enough that windpack measurements are sufficient for an accurate assessment of parachute performance. A ground station is also used to measure the ground atmospheric conditions on the drop zone throughout the testing timeframe.

2. Analysis Tools

Prior to each flight, rigorous analyses were performed to 1) establish the validity of the test technique, 2) establish sequencer timing, 3) keep the predicted parachute loads within the parachute and hardware capability, and 4) plan the test to operate within the required constraints of the range. Analysis tools included six degree of freedom

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(6-DOF) simulations such as Decelerator Systems Simulation (DSS) and Decelerator Systems Simulation Application (DSSA), a two degree-of-freedom parachute simulation called Drop Test Vehicle Simulation (DTV-Sim), a Monte Carlo simulation,[7] a landing footprint predictor tool, Sasquatch[8], and Decelerator Dynamics (DCLDYN), used by Airborne Systems.

While the heritage of the simulations used on CPAS is well-established, new investigations during the time after Gen I led to certain improvements in these simulations. The inflation model in DSS was modified to emulate DCLDYN, to ensure a common usage of parachute inflation parameters for all simulations on the project. However, comparisons of DSS and DCLDYN still yielded some disagreements. This led to a deeper investigation of the various models of parachute added mass. Added mass is a complex component of parachute physics, and there is not yet a clear consensus on how it should be modeled. Techniques for measuring added mass are discussed in Ref. 9, but have not been implemented. For the time being, the models in the various simulations were brought into line with one another so that they yield results that match each other as well as test data, given a baseline set of parameters and initial conditions.

Preflight predictions were aided and enhanced by the development of an overarching Monte Carlo simulation tool. This tool allowed Monte Carlos to be performed easily using any of the DSS-heritage simulations. Monte Carlos are essential to understanding the range of possible performance on a given test.[7]

B. Analysis Techniques

1. Post-Test Flight Data Reduction

The Flight Data Processor (FDP), used to reduce data from all Gen I tests, was not programmed to handle the new instrumentation sources on Gen II. Instead of revamping the older FDP code to handle the new instrumentation sources, a new data reduction technique was developed. The new technique is less automated than the FDP and allows a more hands-on approach that provides more flexibility to accommodate various instrumentation sources.

Complementary and redundant data are collected into "Best Estimate" Atmosphere, Wind, and Trajectory files through a series of MATLAB scripts. Uncertainty estimates for each instrument are used to choose the appropriate source(s) of data for each file. When gaps exist in the preferred data source, an alternative source—as well as the associated higher uncertainties—are "spliced" into the best estimate files. The uncertainty associated with each point is propagated through the data reduction process to provide error bars on the final output. For example, wind velocity data from Windpacks, test vehicle velocity data from a GPS/IMU, and atmospheric density data from RAWIN balloons are used to compute the dynamic pressure history. In the higher altitude region where Windpack data are unavailable due to DGPS dropouts, the wind velocity from the less accurate RAWIN balloons[10] are used to fill in the missing portions of the flight. The resulting dynamic pressure for that region has a higher uncertainty. This process is thoroughly explained in Ref. 4.

The custom MATLAB scripts next apply corrections to the data. For example, accelerometer data are are scaled or biased to match the known steady-state gravity vector. At the completion of the data reduction process, initial conditions are extracted from flight test data and used as inputs in DSS. The same data reduction scripts are then used to co-plot simulated trajectores against flight test data.

2. Data Reconstruction

CPAS flight tests are reconstructed using reduced flight test data. Reconstructions are the primary method of determing parachute performance. Reconstruction results are used to advance parachute design and anchor simulations. The parachute inflation characteristics that are reconstructed include the over-inflation constant, effective reefing ratio, canopy fill constant, opening profile shape exponent, parachute fill time and drag area.

The process for test reconstructions has changed little between Gen I and Gen II. Reconstructions are currently performed using DSS, rather than one of the lower-fidelity tools (DSSA or DTV-Sim). A DSS input file is created based on the test configuration and initial conditions from the test data. An initial estimate of the inflation parameters is taken from the latest CPAS Model Memo, which represents the current best understanding of CPAS parachute performance. The input file is executed using DSS and the results are coplotted with actual flight data.

Inflation parameters are adjusted iteratively until a best fit curve is matched. The primary objective of the reconstruction is to match the curvature of the loads data, with emphasis on the peak load, which drives structural design. The secondary objective is to match the drag area, C_DS, curvature. When the primary and secondary objectives are satisfied an overall best fit of the parameters is finalized. All data reconstructions require engineering judgement to determine the overall best fit curves.[11]

III. Testing Overview

Gen II consisted of three test series: the Test Support Equipment (TSE) series, the Main Development Test (MDT) series and the Cluster Development Test (CDT) series. The TSE series was a short test series to investigate smart release techniques[3] which occurred at the beginning of Gen II testing. These tests are not covered in this paper. The MDT series tested single parachutes, while the CDT series tested parachute clusters. The primary goal of both series was to test off-nominal conditions and assess design changes. A total of six tests are included in Gen II testing: EDU-A-MDT-2-1, 2-2, and 2-3; and EDU-A-CDT-2-1, 2-1, and 2-3. (Note: for simplicity, the test names are usually shortened by removing the EDU-A-prefix, e.g. CDT-2-1.)

Primary test objectives, a general test overview, and preliminary analysis results are discussed for each test. The test overview describes configuration changes to the parachutes reefing schedule, porosity, or line lengths. Table 1 summarizes each test presented in this paper. The preliminary analyses strictly cover Main parachute loads and ROD. Parachute inflation characteristics including the over-inflation constant, effective reefing ratio, canopy fill constant, opening profile shape exponent, fill time, and drag area are not covered in this paper because they require a complete reconstruction of the data. This information is presented in the CPAS Analysis Team's quarterly Model Memos and Analysis Summit charts. The most recent Model Memo version 7a[12], released as an internal NASA document in January 2011, includes the MDT-2-1 and 2-2 tests.

For more information on the testing configurations and techniques used on each test, see Ref. 13.

Table 1: Summary of Gen II tests (excluding the TSE series).

Test Name	Number of Parachutes			Vehicle Type	Primary Test Objective	ROD (ft/s)
	Programmer	Drogues	Mains			
MDT-2-1	1 Drogue	1	1	MDTV/ CMS	Main skipped 1st reefing stage	25.17
MDT-2-2	1 Drogue	1	1	MDTV/ CMS	Main skipped 2nd Stage	25.27
MDT-2-3	0	1	1	MDTV/ CMS	Increased Main Porosity	27.63
CDT-2-1	0	2	2	Weight Tub	Main Modified Line Length	27.29
CDT-2-2	0	2	2	Weight Tub	Increased Main Porosity	30.01
CDT-2-3	0	2	3	Weight Tub	Increased Main Porosity	25.07

Figure 3. EDU-A-MDT-2-1 Main Inflation Events.

A. EDU-A-MDT-2-1

1. Test Overview

The primary objective of the EDU-A-MDT-2-1 test was to gather appropriate data to reconstruct the inflation parameters of single CPAS Drogue and Main parachutes rigged with skipped stages. Both the Drogue and the Main skipped the first reefed stage. An Over-Inflation Control Line (OICL) was installed on the Main skirt to limit the "breathing" during steady-state descent; a secondary objective was to assess the effectiveness of the OICL.

2. Analysis Results

Preliminary analysis of the MDT-2-1 Drogue parachute indicated that the parachute performed nominally. Video analysis showed no anomalies. While the skipped first stage increased the inflation peak load, it remained safely under the Design Limit Load (DLL). A
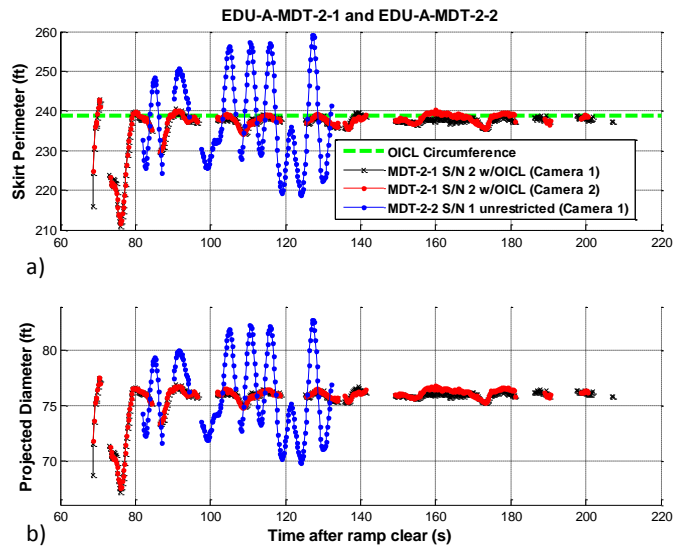

Figure 4. Comparison of a) skirt perimeter and b) projected diameter with and without an OICL.

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reconstruction of the Drogue inflation was unsuccessful, primarily due to the added mass model present in the DSS at the time. That model has since been updated; a new reconstruction of the Drogue inflation is pending.

A snapshot of the MDT-2-1 Main inflation events is shown in Figure 3. The Main parachute was designed to skip the first inflation stage and opened directly to the second stage. The measured loads remained well under the DLL, as expected for a single Main with low canopy loading. The Main inflation was reconstructed, and the results were used to establish a model for Mains skipping the first reefed stage.

The measured mean rate of descent (ROD) for the Main at steady-state was 25.17 ft/s with a standard deviation of about 0.95 ft/s. The variation in ROD was reduced from average Gen I results by about 30%, most likely because the OICL had restricted canopy "breathing."

Direct measurements of skirt perimeter and projected diameter were made using photogrammetric techniques.[14] The time histories for MDT-2-1 and MDT-2-2 (which did not use an OICL) are compared in Figure 4 demonstrating how the presence of the OICL reduces variation in skirt inlet size. The measured perimeter of the parachute is clearly limited by the length of the OICL, which validates the photogrammetric scaling method.

B. EDU-A-MDT-2-2

1. Test Overview

The primary objective of the EDU-A-MDT-2-2 Skipped Stage test was to gather appropriate data to reconstruct the inflation parameters of a single CPAS Main parachute skipping the second reefed stage. Unlike MDT-2-1, the Drogue did not skip a reefed stage, and no OICL was installed on the Main canopy.

2. Analysis Results

Preliminary analysis of the MDT-2-2 programmer and Drogue parachutes indicated that they performed nominally. Video analysis showed no anomalies. All loads remained safely under the Design Limit Load (DLL).

A snapshot of the Main inflation events from MDT-2-2 is shown in Figure 5. The measured loads remained well under the DLL, as expected for a single Main with low canopy loading. The Main inflation was reconstructed and the parameters were used to establish a model for Mains skipping the second reefed stage.

Figure 5. EDU-A-MDT-2-2 Main Inflation Events.

The mean ROD for this test was 25.27 ft/s, which was similar to MDT-2-1. However, because the skirt was not restricted by an OICL, the standard deviation was about 1.84, which was nearly twice that of MDT-2-1.

C. EDU-A-MDT-2-3

1. Test Overview

The primary objective of the EDU-A-MDT-2-3 test was to measure the performance of a single CPAS Main parachute with a canopy modified to increase porosity. To increase the parachute's porosity, the dark areas on the canopy as shown in Figure 6 were removed from the Main canopy design. Fifteen inches were removed from the top of Sail 2, creating a gap between Sails 1 and 2. Sail 7 was also modified; a panel was removed from every fifth gore, beginning with Gore 5. A total of 16 panels were removed from Sail 7 (Figure 6). A secondary objective was to measure the performance of a single CPAS Drogue parachute.

Figure 6. EDU-A-MDT-2-3 Main canopy design.

2. Analysis Results

Preliminary analysis of the MDT-2-3 Drogue parachute indicated nominal performance. Video analysis showed no anomalies. All loads remained safely under the Design Limit Load (DLL).

A snapshot of the Main inflation events from MDT-2-3 is shown in Figure 7. Unlike the previous single-Main tests, the Main parachute on MDT-2-3 executed the entire
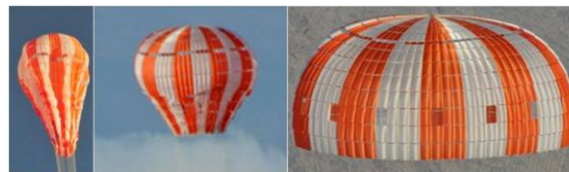
Figure 7. EDU-A-MDT-2-3 Main Inflation Events.

reefing schedule, slightly modified to balance the loads between the stages. The measured loads remained well under the canopy DLL.

The mean ROD for this test was 27.63 ft/s. This is a notable increase from the previous single-Main tests. An increase in ROD was expected with the modified porosity, but the demonstrated increase was larger than had been predicted. The excessive "breathing" motion during Main steady-state likely contributed to the increased ROD.
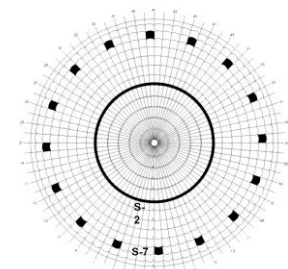
While the behavior of a single parachute differs from that of parachutes in a cluster, the increased breathing is still under investigation as a potential concern. Two more tests with modified porosity parachutes followed in Gen II and more will be conducted during Gen III.

D. EDU-A-CDT-2-1
1. Test Overview

The primary objective of the EDU-A-CDT-2-1 test was to observe and measure the performance of a cluster of two CPAS Main parachutes with a modified line length ratio. The line length ratio is defined as L_S/D_o: the length of the suspension lines (L_S) divided by the reference diameter of the parachute (D_o). The Apollo line length ratio of 1.44 was used on the Mains on CDT-2-1. For the initial CPAS design, a ratio of 1.15 was chosen, based on experience with the Century Series parachutes.[15] The goal of this modification was to increase the drag and reduce the steady state ROD under the Mains. Figure 8 illustrates the Gen I, CDT-2-1, and Apollo line length ratios.
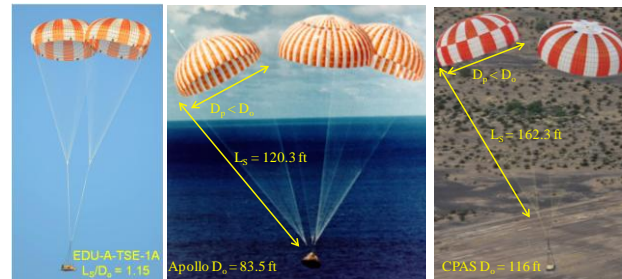

Figure 8. Apollo & CPAS Line Length Ratio Comparison.

A secondary objective was to measure the performance of two CPAS Drogue parachutes with one Drogue skipping a reefed stage.

2. Analysis Results

Drogue parachute loads were not gathered due to instrumentation failure. Therefore, the Drogue skipped-stage performance could not be analyzed.

Although a nominal reefing schedule was planned for the Mains on CDT-2-1, an anomaly occurred during inflation that resulted in an unplanned skipped stage on one Main. Shortly after opening, one of the Mains collapsed slightly, producing unbalanced loads between the two parachutes. The parachute with the higher load disreefed earlier than the other and experienced higher-than-expected loads (Figure 9). The second stage reefing failed and the parachute inflated to full-open. The recorded peak load on that parachute was 40,000 lbs,

Figure 9. Main Parachute Unplanned Skipped Stage and Blanketing.

which is higher than the DLL. However, the parachute was not damaged due to the high load. The second Main was "blanketed" by the full-open Main, but it slowly inflated as well. Due to the anomaly, a reconstruction of the inflation parameters for either Main on CDT-2-1 could not be performed with sufficient accuracy for use in the overall CPAS model; however, a qualitative understanding of a skipped stage event was gained from the flight.

Once both Mains were at full open, they shared the load equally. The rest of the descent was benign. The mean ROD was 27.29 ft/s. Due to the modified line lengths, the ROD was decreased by 1.23 ft/s compared to the TSE test series. This decrease led to the incorporation of the modified line length ratio into the latest CPAS design.

E. EDU-A-CDT-2-2
1. Test Overview

The primary objective of the CDT-2-2 test was to observe and measure the performance of a cluster of two CPAS Main parachutes with canopies modified to increase porosity. The Mains on CDT-2-2 were modified in the same manner as the Main on MDT-2-3. The objective of the canopy modification was to increase parachute cluster stability, reducing fly-out angles and parachute interactions. A secondary test objective was to observe and measure the performance of two CPAS Gen II Drogues with nominal reefing.

2. Analysis Results

The CDT-2-2 Drogue parachute performance was largely obscured by the turbulent environment of the wake behind the carrier aircraft and the wake of the payload itself. The peak load at inflation could not be determined from the measurements; however, loads on both Drogues for the disreef events were captured. The disreef loads were well below the DLL for the Drogues. Due to the effect of the turbulent environment on the data, a full reconstruction of the Drogue performance parameters may not be possible.
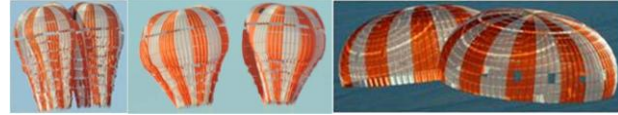

Figure 10.   Main Parachute reefed stages.

A snapshot of the Main inflation events from CDT-2-2 is shown in Figure 10. Both Mains inflated nominally, with loads well below the DLL and balanced load sharing between the parachutes for each stage.

Analysis of Main fly-out angles during full open flight showed two distinct phases, described as transient and damped (Figure 11). During the transient phase just after the parachutes reached full-open, the Mains collided and flew out again a number of times. The magnitude of the collisions decreased slowly until they ceased. At the completion of the transient phase the parachute system reached a stable state with no further Main parachute collisions – the damped phase. Because these collisions have a significant eff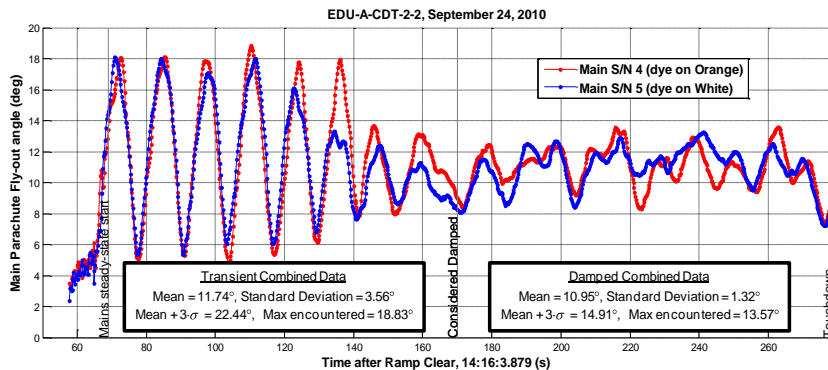ect on the Rate of Descent, three separate ROD calculations were performed: the entire full-open descent, the transient phase, and the damped full-open phase. The ROD for the entire Main full-open phase was 30.01 ft/s. The mean ROD during the transient phase was 29.20 ft/s. The mean ROD of the damped phase was 30.88 ft/s. The 33 ft/s CPAS ROD requirement was exceeded at two instances during the initial transient phase. However, during the damped phase, the requirement was not exceeded. The mean ROD for the transient and damped full-open phase were higher than the TSE test series by 0.68 ft/s and 2.34 ft/s, respectively. The standard deviation for the transient phase was 1.34 ft/s, which is similar to previous cluster tests. But the standard deviation was reduced to only 0.40 ft/s during the damped phase. This demonstrated the improved stability that was the objective of the Main canopy modifications.

Figure 11.   CDT-2-2 Fly-Out Angles.

F. EDU-A-CDT-2-3

1. Test Overview

CDT-2-3 was the final "modified porosity" test, following MDT-2-3 and CDT-2-2. The primary objective of the CDT-2-3 test was to measure and observe the performance of a cluster of three CPAS Main parachutes with canopies modified to increase porosity. The Main parachutes that were modified for MDT-2-3 and CDT-2-2 were used again on this test. A secondary objective was to assess the performance of two CPAS Drogues with the nominal reefing schedule.

2. Analysis Results

The cluster of two Drogue parachutes inflated horizontally in the wake of the carrier aircraft. The initial opening loads for both Drogues are obscured by the turbulent extraction environment. Individual parachute loads are only available for one Drogue, due to instrumentation failure. The measured loads for one Drogue were well under the DLL. Because of the turbulent wake behind a pallet, parachute performance parameters could not be reconstructed.

Snapshots of Main inflation are shown in Figure 12. Loads on the Main parachutes were much lower than the DLL, as expected for a nominal three-Main cluster. Load sharing between the Mains was even on the initial inflation and first disreef. At the disreef to full open, one Main took more of the load, with a

Figure 12.   Main Parachute reefed stages.

time-concurrent load share of 51/31/17 percent, slightly worse than the design assumption of 50/25/25 percent. However, because the loads were much lower than the design loads, this unbalanced loading is less of a concern.

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The increased porosity improved parachute cluster stability, as desired. The mean equivalent ROD for the entire Main full-open phase was 25.07 ft/s, with a standard deviation reduced by about 30% from past cluster tests; there was less deviation from the mean than on a similar Gen I test with unmodified canopies. The maximum fly-out angle seen by any of the Main parachutes was 22.73°. During the damped phase near touchdown, the mean fly-out angle was 14.25°, with a maximum of 18.73°. The improvements seen in the modified porosity cluster tests led to the decision to incorporate the modification into the Gen III CPAS Main parachute design.

IV. Current State of CPAS Parachute Analysis

A. Parachute Models
CPAS parachute models were improved throughout Gen II by the application of the evolved simulation tools and new analysis techniques described in Section II and analysis of the testing described in Section III Analysis of the Gen II tests is an on-going effort and will be used to further improve CPAS parachute modeling into the third generation (Gen III) of testing. This section describes the latest parachute model.

1. Inflation Parameters
The CPAS team used the latest analysis tools available and executed the new analysis techniques described to derive parachute inflation parameters found in the CPAS Model Memo Version 7a. During Gen II, full reconstructions of several tests were performed: key Gen I tests, one of the TSE series tests and the initial single-Main Gen II tests. The results of these reconstructions were grouped based on number of parachutes in the cluster and skipped stage versus nominal reefing. Each group was averaged to obtain the nominal values for the parachute model.

For each set of nominal values, two sets of dispersions were developed: design dispersions and flight test dispersions. Figure 13 graphically illustrates the two types of dispersion. Flight test data points are represented as orange points with correlating blue error bars representing the individual test uncertainty. The maximum and minimum parachute parameter result for a reconstructed test is shown by the black lines while the average of the reconstructed test points is in red. Design uncertainties, denoted by the purple error bar, are meant to encompass all variation in the parameter observed in the tests that have been reconstructed. The recommended flight test dispersion, the green error bar, takes the minimum and maximum design uncertainties and applies an engineering factor to them. The recommended flight test dispersion is larger than the design dispersion in order to account for measurement, modeling, and engineering judgment uncertainties. Flight dispersions are meant to account for additional variation that is likely to exist but was not observed in the limited set of tests. This serves as a conservative approach to dispersions and is intended for use in integrated vehicle flight test simulations such as preflight activities. As CPAS flight test experience grows, these two types of dispersion should converge.

Current nominal and dispersed values of all inflation parameters are published within an internal NASA document and are not reported in this paper.
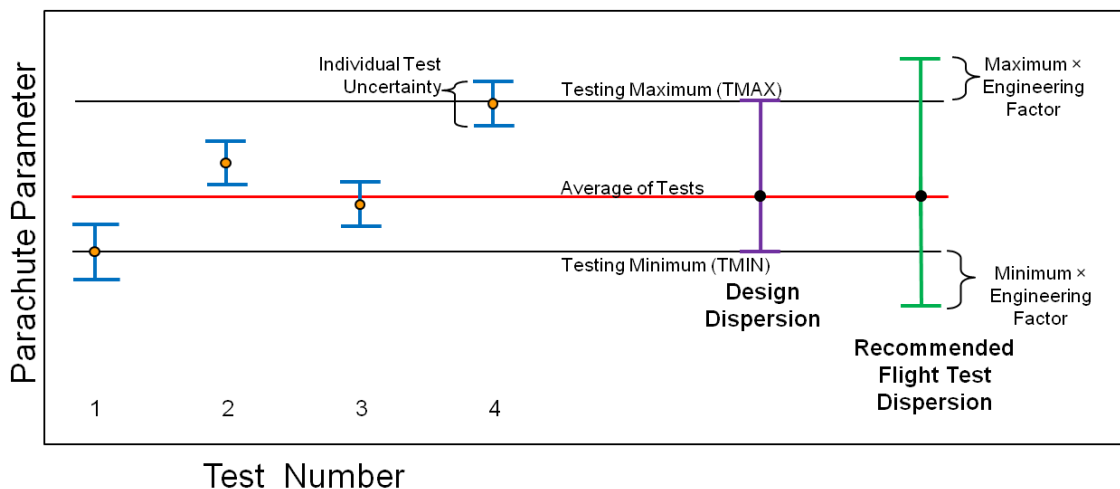

Figure 13.   Design and Flight Test Dispersions.

2. Drag Coefficients and Rate of Descent

In addition to the inflation parameters, the key performance parameters are drag coefficient and rate of descent. These values are of primary importance for the Main parachutes, because of the system requirement that the descent rate not exceed 33 ft/s at splashdown under two or three Mains. Due to the complex variation of steady-state rate of descent in a cluster, this requirement is probabilistic and will be met by examining the statistics of flight test data. Reference 4 goes into detail about the analysis of rate of descent and drag coefficient. Gen II testing with 2-Mains have exceeded the limit soon after the disreef to full open, when canopies collide into each other. After the initial transients damp out, both 2-Main and 3-Main cluster descent rates are below the 33 ft/s maximum.

B. Analysis Methods

During Gen II, enhanced analysis methods allowed for a deeper understanding of parachute dynamics through photogrammetrics. Additionally, the creation of a unified interface between tools created more efficient and less error prone analyses.

1. Photogrammetrics

Besides the previously-mentioned use of photogrammetrics for single-parachute tests, CPAS routinely uses photogrammetrics to characterize Main parachute behavior in a cluster. These methods are detailed in Ref. 14. Upward-looking cameras mounted to the payload are used to measure the fly-out angle and geometric inlet area for each parachute in a cluster. The amount of drag produced by a cluster is directly proportional to the cluster projected cluster area, shown in Figure 14. The periodic collision of canopies significantly reduces the effective canopy area and temporarily increases the rate of descent. The time-varying natures of cluster components are being characterized, which may eventually lead to realistic time-varying simulations of the rate of descent.

Another CPAS requirement is to limit the torque induced by the twisting of Main parachute risers. Two CPAS ground tests have shown that twist torque is a function of riser fly-out angles as well as the total twist angle. The Orion guidance system is being designed to orient the

Figure 14. Simplified cluster projected area.

capsule to a favorable roll attitude at splashdown using reaction control thrusters. Time-varying models of the fly-out angles are used in integrated simulations to verify that the guidance system can overcome the torque induced by Main parachute riser twist for a safer landing.

2. Simulation Architecture

CPAS employs four distinct simulation tools for developing and analyzing air-drop tests. Each tool is well adapted to certain types of tests. Regardless of the simulation being used, engineers typically perform similar tasks for each drop test such as prediction of loads, assessment of altitude, and sequencing of disreef or cut-away events. During Gen II CPAS analysts developed a common simulation environment aimed at unifying the interface with each of these legacy tools. This approach speeds and simplifies the task of generating simulations for test prediction. The simulation environment also provides a common set of post-processing functions to perform routine tasks such as plotting and timeline generation with minimal sensitivity to the simulation that generated the data. Flight test data may also be translated into the common output format to simplify test reconstruction and data analysis. The details of this simulation environment are described in Ref. 6.
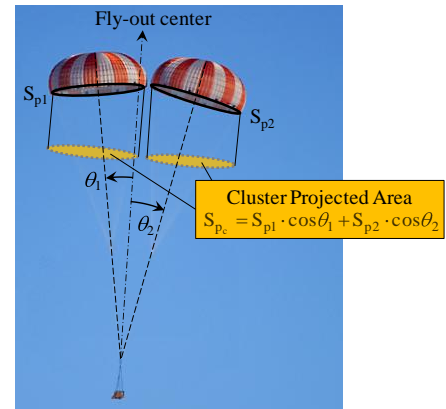
V. Future of CPAS Parachute Analysis

A. Test Techniques

Gen I and II testing focused on developing canopy designs, so static-line deployment from traditional pallet and weight tub or missile-shaped test vehicles was adequate. Gen III testing will improve the fidelity of test articles with more representative hardware and deployment methods for the entire parachute sub-system. Both the PCDTV and PTV2 will have the capability to mortar deploy CPAS Drogue parachutes. When the Drogues are cut away, each vehicle will then mortar deploy Pilot parachutes, which in turn lift and deploy a cluster of Main parachutes. These vehicles can also test failure modes such as the loss of a Drogue and/or Main as well as skipped parachute reefing stages. The resulting parachute loads will be transmitted through representative textile and steel risers to the Orion attachment structure.

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Some compromises must be made on the characteristics of trajectories or the fidelity of test articles to production hardware. The trade-offs for various test articles and delivery methods are explained in Ref. 5. A combination of several options is currently planned. The PCDTV can be deployed from a C-130 Hercules, which is readily available and relatively inexpensive to use. Because the PCDTV is missile-shaped, it will not generate an Orion-like wake. The PTV2 is much closer to the Orion outer mold line, but cannot fit inside a C-130. PTV2 will initially be deployed from a larger C-17 Globemaster, which is less available and more expensive for testing. Each parent aircraft is limited in release altitude, so both the PCDTV and PTV2 are planned to be released from high altitude balloons in later tests.

B. CPAS Verification and Validation

To verify that the Orion Spacecraft is suitable for human flight, CPAS will verify via analysis flight performance requirements, which are limited to inflation loads and terminal rate of descent[11]. These requirements will be verified through the use of multi-degree of freedom flight simulations[7]. Admittedly, many aspects of the system are random and chaotic, and cannot be credibly modeled. These aspects, such as parachute deployment and the turbulent aerodynamic wake, must be qualitatively evaluated via numerous tests. Data gathered from the flight tests will be used to validate that the simulations sufficiently model parachute loads and rate of descent. Furthermore, these models are used in a Monte Carlo simulation to provide a large sample appropriate for statistical interpretation of requirements and DOE studies. Stakeholders responsible for verifying the requirements must have confidence in the simulation results; therefore, NASA standards for models[16] will establish credibility in the simulations.

VI. Conclusion

Throughout the second generation of CPAS testing, significant improvements were made to instrumentation, analysis tools and techniques. New instrumentation allowed for the time-synchronization of data and a higher fidelity of data gathered. Enhanced analysis tools, such as photogrammetrics, further developed the understanding of parachute dynamics. In addition, the development of a common simulation environment across analysis tools created a more efficient system to determine parachute loads and inflation parameters. The test techniques developed for the single parachute and cluster test series allowed for a deeper understanding of the performance of the CPAS parachutes and presented data which was used to modify the parachute design. The porosity of the Main parachutes was increased by removing panels. This increased the cluster stability and reduced fly-out angles; however, it increased the rate of descent. To counteract the increase in rate of descent, the Main line lengths were modified from the original ratio of 1.15 to 1.44. This matched the line lengths of Apollo (1.44) much closer. These modifications will be combined into the EDU parachutes to be tested during the next generation.

CPAS now progresses into its third generation of testing with two new vehicles. The PCDTV will test a representative parachute compartment and the PTV will test the entire system with the same aerodynamic properties of Orion. Finally, a series of high altitude balloon tests will occur with the PCDTV and PTV vehicles to test the systems at higher demands. Gen III will culminate in qualification tests which verify the flight performance requirements and ensure a human rated parachute system.

Appendix - Parachute Overview

A. Drogue Parachutes

The Generation (Gen) II Drogue parachutes changed slightly from their previous Gen I configuration. A notable difference from the tested Gen I design is the webbing riser design used with a correlating line length ratio of 1.5. The Gen II current baseline reflects a design that uses textile and steel risers as an improved design modification with an increased line length ratio of 2.0. Table 2 summarizes important parachute planform parameters and Figure 15 shows the constructed geometry. The reconstructed parachute performance parameters that follow in Section V reflect the Gen I design; however, the Gen I and Gen II canopy designs have a common planform, so the performance parameters can be applied to the Gen II design for modeling CPAS performance efforts.

Table 2. Drogue Parachute Planform Parameters.	
Parameter	**Value**
Parachute Type	Variable Porosity Conical Ribbon (VPCR)
Parachute Diameter (D_o)	23ft
Number of Gores	24
Number of Ribbons	55
Crown Geometric Porosity (λ_{gc})	19.2 %
Line Length Ratio (L_s/D_o)	2.0
Line Length (L_s)	46 ft
Riser Length (L_r)	53.65 ft

Figure 15.   Drogue Parachute Constructed Geometry.
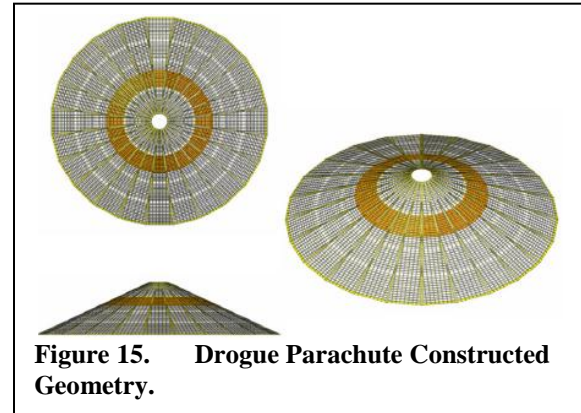
B. Main Parachutes

The Gen II Main parachute architecture has gone through several design modifications since Gen I. The parachutes used in the first half of Gen II testing were modified Gen I parachutes to reflect the increased weight of Orion. Then new parachutes were designed to increase vehicle stability through modified line lengths, increased porosity, and the addition of an Over Inflation Control Line (OICL). Details discussing specific parachute design changes are not addressed in this paper. None of the Gen II parachutes combined all of the design changes, but a team consensus was reached to make all changes part of the baseline design. Table 3 summarizes the Main parachute planform parameters of the baseline design and Figure 16 shows the parachute constructed geometry. The reconstructed parachute performance parameters that follow reflect the Gen I and Gen II Main parachute designs, and can be applied to the PDR design for modeling CPAS performance efforts. All of the Main parachute canopy designs have a common planform and thus result in similar performance characteristics.

Table 3. Main Parachute Planform Parameter.	
Parameter	**Value**
Parachute Type	Quarter Spherical Ringsail
Parachute Diameter (D_o)	116 ft
Number of Gores	80
Number of Rings	4
Number of Sails	9
Crown Geometric Porosity (λ_{gc})	7.57 %
Line Length Ratio (L_s/D_o)	1.4
Line Length (L_s)	168.9 ft
Riser Length (L_r)	61.7 ft
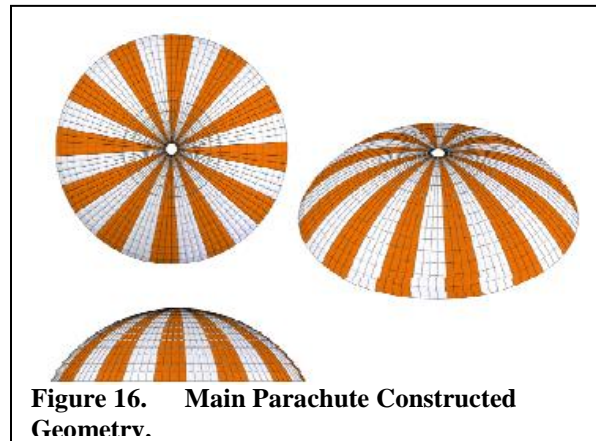
Figure 16.   Main Parachute Constructed Geometry.

References

[1]Bledsoe, K., Englert, M., Morris, A., Olmstead, R., "Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) Generation I Main and Cluster Development Test Results," AIAA-2009-2940, May 2009.
[2]Bledsoe, K., Englert, M., Morris, A., Olmstead, R., "Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) Generation I Drogue and Pilot Development Test Results," AIAA-2009-2939, May 2009.

[3]Moore, J. W., and Morris, A. L., "Development of a Smart Release Algorithm for Mid-Air Separation of Parachute Test Articles", 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011 (submitted for publication).

[4]Ray, E., and Morris, A. L., "Measurement of CPAS Main Parachute Rate of Descent," 21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, Dublin, Ireland, May 2011 (submitted for publication).

[5]Ray, E. S., and Morris, A. L., "Challenges of CPAS Flight Testing", 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011 (submitted for publication).

[6]Moore, J. W., and Morris, A. L., "A Hybrid Parachute Simulation Environment for the Orion Parachute Development Project", 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011 (submitted for publication).

[7]Moore, J. W., and Morris, A. L., "Development of Monte Carlo Capability for Orion Parachute Simulations", 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011 (submitted for publication).

[8]Bledsoe, K., and Morris, A. L., "Development of the Sasquatch Drop Test Footprint Tool", 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011 (submitted for publication).

[9]Fraire, U., and Morris, A. L., "Proposed Framework for Determining Added Mass of Orion Drogue Parachutes," 21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, Dublin, Ireland, May 2011 (submitted for publication).

[10]Rogers, Jeffrey D., "Comparative Analysis Involving Wind Profile Data Sources," 20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, Seattle, Washington, May 4-7, 2009, AIAA paper 2009-2960.

[11]Morris, A. L., and Olson, L., "Verification and Validation of Flight Performance Requirements for Human Crewed Spacecraft Parachute Recovery Systems," 21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, Dublin, Ireland, May 2011 (submitted for publication).

[12]Morris, A., et. al. "Crew Exploration Vehicle (CEV) Parachute Assembly System (CPAS) Engineering Development Unit Operating Modeling Parameters," Version 7a, ESCG-8400-CPAS-10-CPAS-MEMO-0070. January 2011.

[13]Morris, A. L., et al., "Simulating New Drop Test Vehicles and Test Techniques for the Orion CEV Parachute Assembly System", 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011 (submitted for publication).

[14]Ray, E., Bretz, D. R., and Morris, A. L., "Photogrammetric Analysis of CPAS Main Parachutes," 21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, Dublin, Ireland, May 2011 (submitted for publication).

[15]Delurgio, Phillip R., "Evolution of the Ringsail Parachute," 15th CEAS/AIAA Aerodynamic Decelerator Systems Technology Conference, Toulouse, France, June 8-11, 1999, AIAA paper 99-1700.

[16]"Standard for Models and Simulations," NASA Technical Standard, NASA-STD-7009, July 2008.