

# Dragonfly Parachute Decelerator System Overview

Charles Lowry<sup>1</sup>, Eduardo Rios<sup>2</sup>, Katie Siegel<sup>3</sup>, Ben Tutt<sup>4</sup>

*Airborne Systems North America, Santa Ana, CA, 92704, USA*

Giovanny Guecha-Ahumada<sup>5</sup>, Justin Shafner<sup>6</sup>

*NASA Langley Research Center, Hampton, VA 23681, USA*

## I. Introduction

**This publication is a high-level summary of the parachute decelerator system (PDS) utilized on NASA's Dragonfly Mission to Titan, Saturn's moon. The Dragonfly Mission will be the second time that a spacecraft has landed on Titan, the first was the Huygens mission in 2005. The Dragonfly mission is scheduled to launch in 2028, and aims to send an autonomous, dual-quadcopter rotorcraft to Titan. Airborne Systems has had recent success qualifying the supersonic parachute used on the Mars 2020 Perseverance Rover PDS, and aims to leverage that heritage on the Dragonfly PDS. The Dragonfly mission brings very unique challenges, due to the flight environment and the complexities of a two parachute system, that require extensive development and qualification work.**

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<sup>1</sup> Chief Engineer, Space & Recovery Division, 3100 W. Segerstrom Ave, Santa Ana, CA 92704 AIAA Member

<sup>2</sup> Dragonfly Project Engineer, Space & Recovery Division, 3100 W. Segerstrom Ave, Santa Ana, CA 92704 AIAA Member

<sup>3</sup> Project Engineer, Space & Recovery Division, 3100 W. Segerstrom Ave, Santa Ana, CA 92704 AIAA Member

<sup>4</sup> Director of Engineering, 3100 W. Segerstrom Ave, Santa Ana, CA 92704 AIAA Member

<sup>5</sup> PDS Technical Lead, Atmospheric Flight and Entry Systems Branch (D205), 1 Nasa Drive, Hampton, VA 23681, AIAA Member

<sup>6</sup> PDS Lead Test Engineer, Atmospheric Flight and Entry Systems Branch (D205), 1 Nasa Drive, Hampton, VA 23681, AIAA Member

## II. PDS System Overview

The Parachute Decelerator System (PDS) consists of an 8.25 m nominal diameter D<sub>0</sub> Disk-Gap-Band Drogue parachute, a Drogue-deployed 16.66 m D<sub>0</sub> Ring-Slot Main parachute, and the hardware required for stowage and deployment of the parachutes. The figure and table below summarize these components.

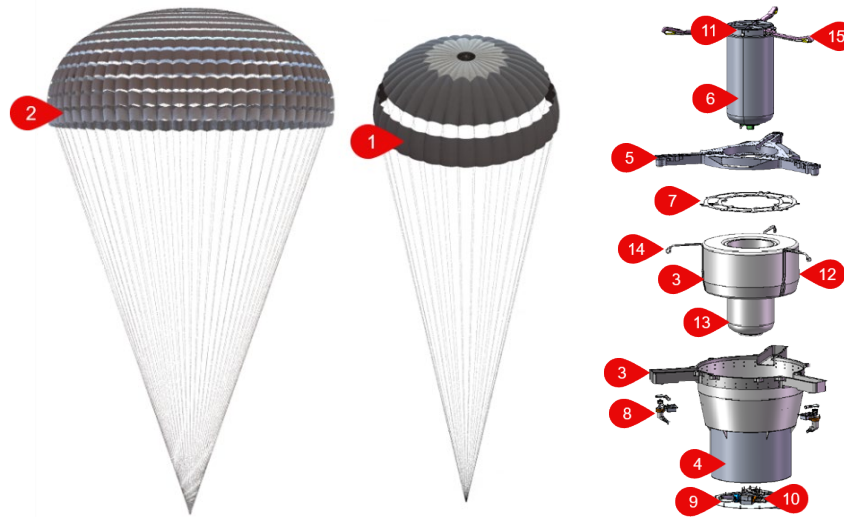


Figure 1 - Parachute System Overview

Table 1 - PDS Component List

|    |                                                     |     |                           |
|----|-----------------------------------------------------|-----|---------------------------|
| 1. | 8.25m D <sub>0</sub> Disk Gap Band Drogue Parachute | 9.  | Main Tub Access Lid       |
| 2. | 16.66m D <sub>0</sub> Ring Slot Main Parachute      | 10. | Mortar Firing Line Cutter |
| 3. | Parachute Support Frame                             | 11. | Drogue Deployment Bag     |
| 4. | Main Parachute Tub                                  | 12. | Main Deployment Bag       |
| 5. | Main Lid Assembly                                   | 13. | Main Bag Mortar Sleeve    |
| 6. | Drogue Parachute Mortar                             | 14. | Main Bridle               |
| 7. | Main Support Plate                                  | 15. | Drogue Bridle             |
| 8. | Separation Nut                                      |     |                           |

The overall concept of the PDS assembly was conceived early in the project as a result of two key challenges: Drogue bridle release and thermal protective system (TPS) interfacing. The qualification of a new cutter or release mechanism to separate the Drogue parachute would require significant effort. The implementation of separation nuts was strategic, as this same part number was already being utilized elsewhere on the spacecraft, and the qualification was already planned to be done by Lockheed Martin Space (LMS). The decision to integrate the release of the Drogue with the release of the TPS via the Main lid was done to ease the interface between LMS-provided TPS and the Airborne Systems provided PDS. It also ensures that the TPS components and Main deployment bag stay with the Drogue parachute, severely reducing the likelihood of recontact with the spacecraft while it is descending under the Main parachute. Similar concepts have been used several times before, notably on the flight-qualified ExoMars PDS [1, 2]. This concept requires the implementation of a toroidal-shaped Main parachute pack housed around a centrally located parachute mortar. This toroidal pack, while more complicated than a cylindrical pack, is well suited for this usage as the Main parachute packing density is low, and the Main deployment velocity is low, reducing the likelihood of canopy deployment damage out of a complex bag geometry.

When the three separation nuts fire, which hold the Main lid assembly down, the Drogue parachute extracts the Main lid assembly. Attached to the Main lid is the TPS, the Drogue mortar tube, and the Main parachute. The TPS is bolted directly to the top side of the lid. The Drogue mortar tube mounting flange is bolted to a flange located mid

plane of the Main lid, and it passes through the center of the Main parachute deployment bag. Prior to actuation of the separation nuts, the firing lines for the Drogue parachute mortar are severed by a pyrotechnic cutter, bolted to the base of the Main parachute tub. The Main parachute is bolted to the lid via an aluminum interface plate that is sewn into the bag itself. This plate provides attachment between the Main and Main lid, but is also a flat surface for the Main to rest against during launch and cruise.

In order to meet the stability demands of the spacecraft, NASA selected a 8.25 m D<sub>0</sub> Disk Gap Band parachute. The Disk Gap Band parachute planform utilized has Viking heritage, meaning that the ratios of the disk, gap, band, and suspension line length relative to the nominal diameter are matched to that of the successful Mars Viking parachutes, as well as InSight, Phoenix, MSL, and Mars 2020 [3]. The Dragonfly Drogue parachute utilizes a bespoke 1.1 oz/yd<sup>2</sup> broadcloth based on PIA-C-7020 Type I for the bias-constructed disk and the block-constructed band. The broadcloth does not have a surface finish, following Huygens heritage. The structural grid is a combination of Kevlar cord and tape. Kevlar was chosen because of its ability to be vacuum stripped to meet outgassing requirements, and its heritage on the Huygens system [4]. To maintain heritage, a trailing distance of ten vehicle body diameters was selected. To achieve this length and keep mass minimal, the riser is constructed with Kevlar cord. Three Kevlar cord bridles are used to attach the Drogue parachute to the vehicle. Between the bridles and the riser, is the swivel. The bridle lengths are twice as long as those used on the Main parachute, and were chosen to maximize vehicle stability through the transonic regime.

The Drogue mortar was designed by Karman Space and Defense to Airborne Systems' specifications. A minimum exit velocity was selected to ensure that the Drogue deployment bag outpaces the inflation of the parachute canopy. Canopy damage may occur if inflation begins before the bag is fully stripped from the canopy drag surface. Mortar exit velocity should be limited as well, as it will not only reduce the risk of friction related deployment damage, but will also effectively limit the mortar reaction load, which drives support system mass. The bag strip ratio, or BSR, is defined as the ratio of the time it takes for the deployment bag to strip off to the time it takes for the canopy to fully inflate. A BSR of one would essentially mean that the deployment bag does not strip off the canopy until the instant that it had reached full inflation, which would be highly unfavorable. A maximum BSR of 0.59 with a nominal BSR of 0.52 was selected for the Dragonfly Drogue, which allows it to stay within heritage of several other supersonic Disk-Gap-Band inflations. [17, 18]

The Main parachute planform selected by Airborne Systems was a 60 gore, 14 ring, 16.66 m D<sub>0</sub> 20 Deg. conical ringslot with 20 % porosity, evenly distributed. This decision was driven by past experience with ringslots of this geometry, best characterized in the publication documenting the wind tunnel testing conducted to select the ExoMars final descent main parachute [7]. The planform chosen for Dragonfly was the configuration that opened the quickest of all parachute configurations flown in the wind tunnel. Pocket bands are utilized on the Dragonfly Main parachute, as the wind tunnel testing showed significant reductions in opening times when test parachutes utilized pocket bands. Due to the benign nature of the Main inflation, a lightweight 0.7 oz/yd<sup>2</sup> cloth was chosen. The cloth was calendared to minimize porosity, which was thought to decrease inflation time, and maintain similitude with the parachute canopies utilized in the wind tunnel testing referenced above. The Main parachute riser and bridles are constructed similarly to those used on the Drogue, but are scaled down to the reduced Main opening load.



**Figure 2 - Dragonfly 8.25m Do Drogue Parachute**

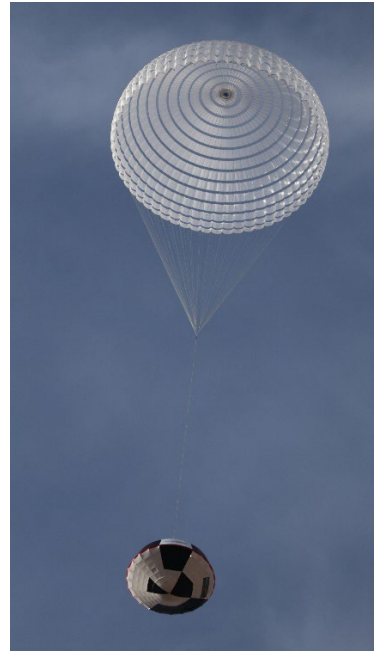


**Figure 3 - Dragonfly 16.6m Do Main Parachute**

### III. Concept of Operations

The PDS will be used during the descent phase, after aero heating and deceleration pulses are over, beginning when the aeroshell, nominally, reaches Mach 1.5. The Main parachute will remain inflated, through the vehicle pose maneuver and release, until the empty aeroshell reaches the surface of Titan. A high-level concept of operations is shown in Figure 4 below.

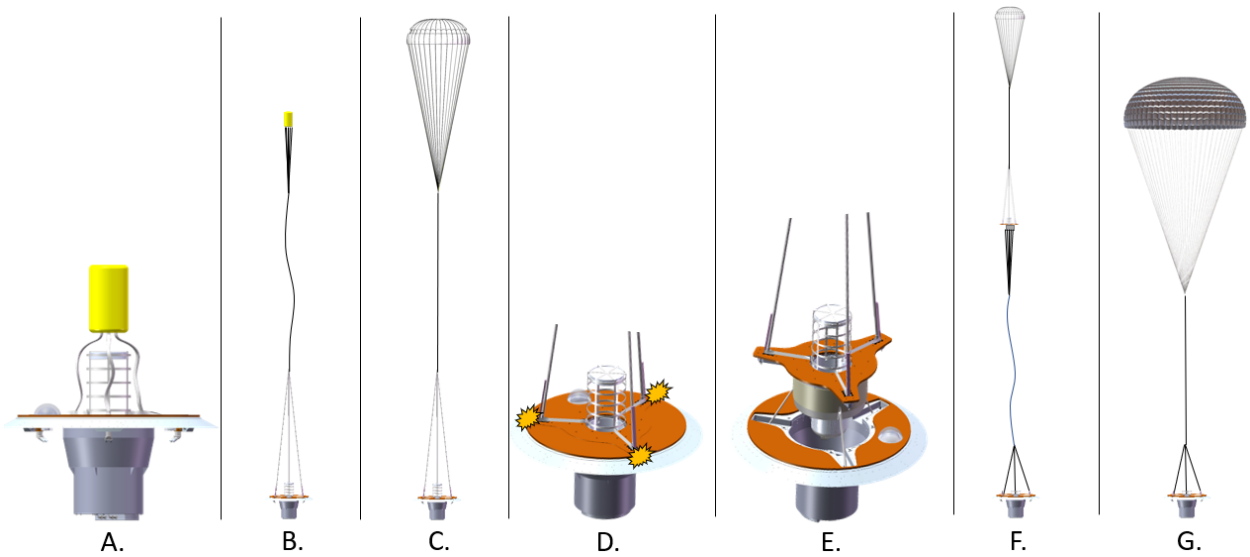


**Figure 4 - PDS Concept of Operations (Aeroshell not shown)**

**Table 2 - PDS Events**

| Major PDS Events |                                                                                                     |
|------------------|-----------------------------------------------------------------------------------------------------|
| A.               | Drogue Mortar Fire, Bridles Strip from TPS, Piston Capture Net Captures Piston                      |
| B.               | Drogue Bridles, Swivel, Riser, and Suspension Lines Deploy                                          |
| C.               | Drogue Parachute Inflates                                                                           |
| D.               | Main Lid Released by Three Separation Nut Firings                                                   |
| E.               | Main Lid, Affixed to Main Pack, Separates from Support Frame, Separation Bolts Retained in Main Lid |
| F.               | Drogue Parachute Deploys Main Lid, Deploying Main Bridles, Swivel, Riser, and Suspension Lines      |
| G.               | Main Parachute Inflates                                                                             |

#### IV. Driving Parachute System Requirements and Specifications

The ultimate goal of the PDS is to provide deceleration and stabilization to the Dragonfly spacecraft from Mach 1.5 (nom.) at 152 km of altitude down to lander separation which occurs around 2.9 m/sec at 1 km of altitude [8]. Figure 4 below shows an overview of the Entry, Descent, and Landing (EDL) concept of operations.

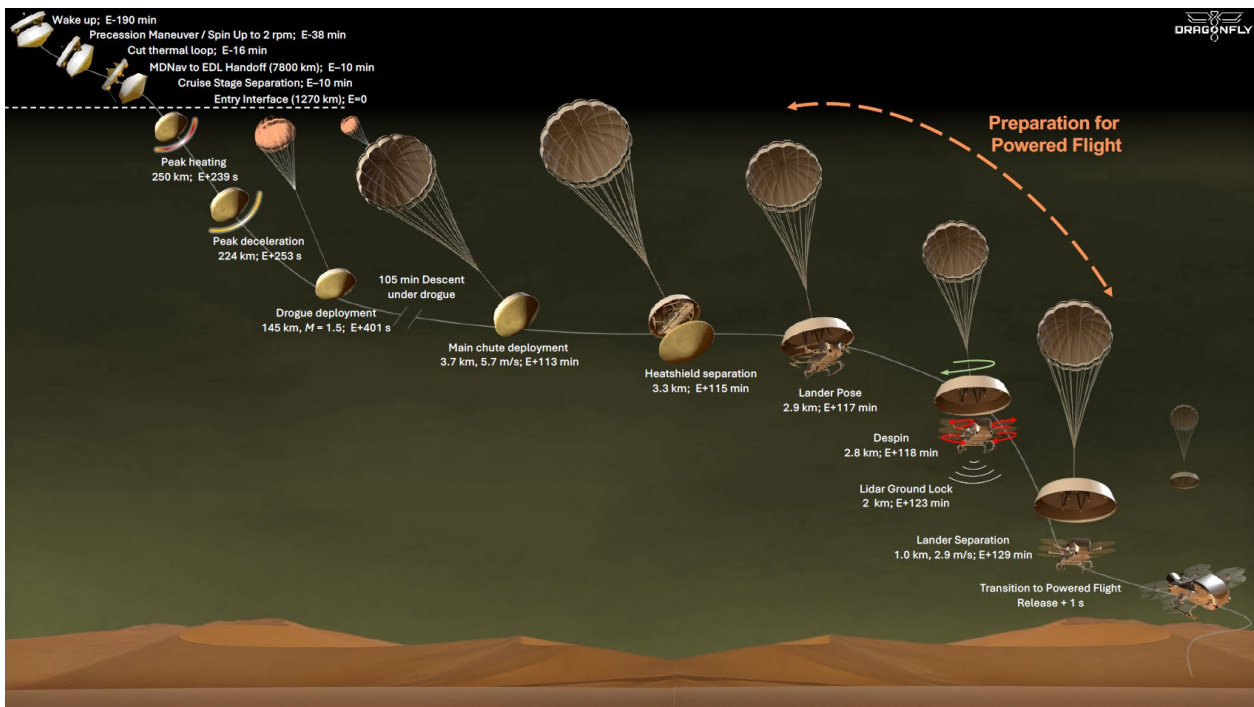


**Figure 4 - EDL Concept of Operation [8]**

Titan's atmosphere presents several key challenges that drive the complexity of the design. First, it is much colder than other typical environments that parachute systems have been exposed to. This has driven material testing at cryogenic temperatures as cold as 90 K. Second, Titan's atmosphere is very dense. This presents challenges for the mission, as the resulting descent time is relatively long. This requires careful consideration for power consumption during the EDL phase as well as in targeting the landing location. This has driven NASA to minimize time under parachute, while still achieving dynamic stability of the spacecraft under parachute. This has resulted in a minimally-sized Drogue parachute, and a low-altitude Main parachute deployment. The required Drogue size was originally 5.4 m Do but later increased to 8.25 m Do to achieve acceptable dynamic transonic and subsonic stability. With this increase in size, the Drogue flight duration in supersonic conditions decreased, but is still longer than all disk-gap-band parachutes flights on record, at a 99<sup>th</sup> percentile duration of 3.5 seconds above Mach 1.4, and 21 seconds above Mach 1 (NASA LaRC Flight Dynamics). Additionally, as a result of the long duration of flight, a riser swivel will be

utilized on both the Drogue and Main parachutes to decouple parachute rotations from vehicle rotations preventing line twist.

The Dragonfly vehicle is not actively stabilized with a reaction control system. This results in a demanding operational environment following inflation for the three bridles that attach the Drogue parachute to the spacecraft. The low altitude deployment of the Main parachute results in a low dynamic pressure inflation, in an atmospheric density 4x times denser than that of the earth. This has resulted in the need for half and full geometric scale, Froude-scale testing on Earth to ensure reliable opening characteristics of the Main.

The deployment conditions for the Viking-planform Drogue parachute are well within flight heritage for systems designed for Mars entry [9, 10]. The mortar deployment is set to initiate nominally at Mach 1.5, at a dynamic pressure of 417 Pa (NASA LaRC Flight Dynamics). The design limit load for the Drogue parachute is 32.8 kN.

The Main parachute experiences deployment conditions that result in a very slow opening compared with most systems on record. The Main parachute will nominally reach line stretch at an airspeed of 9 meters per second, at a dynamic pressure of 194 Pa (NASA LaRC Flight Dynamics). Conservatively, the design limit load is 14.7 kN, however the nominal opening load is likely to be less than 5 kN. This difference in opening load did not have implications on the parachute design, as in most cases, manufacturability drove material selection.

## V. Driving System Level PDS Requirements:

### *Vehicle OML & Mass*

The Dragonfly Descent Vehicle Outer Mold Line (OML) is shown below. Of note is the max aeroshell diameter, which is 4.5 m, which drives trailing distance requirements for both parachutes.

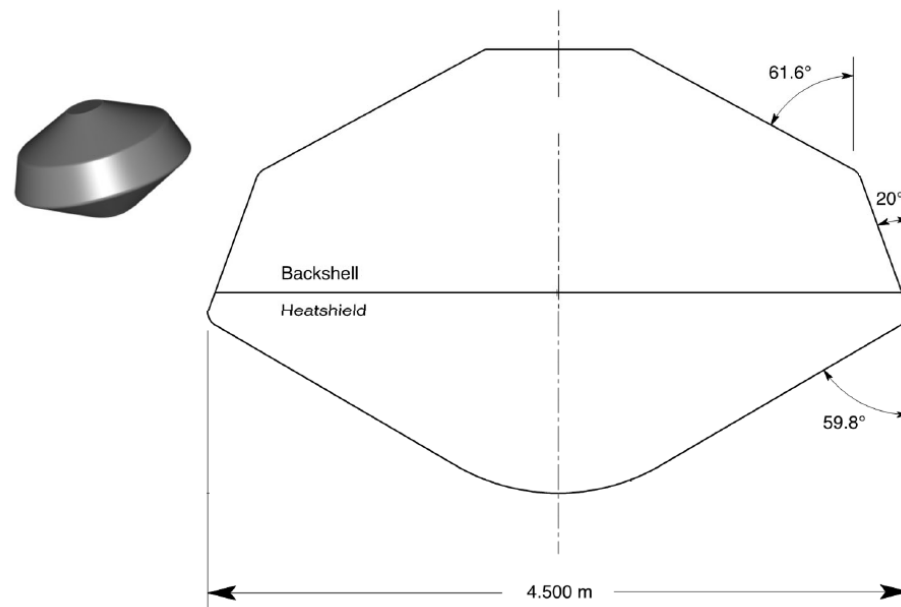


**Figure 5 – Generalized Dragonfly OML[10]**

The vehicle mass is 2600 kg (5732 lbm), which on Titan, results in a vehicle weight just under 800 lbm due to the gravity effectively 1/7<sup>th</sup> of that on Earth. [10]

### *Atmospheric Environment*

Figure 6 below shows the altitude and barometric pressure versus the atmospheric temperature of Titan based on observations of Cassini-Huygens and predictive analysis completed since [8]. The atmospheric temperature on Titan

can be extremely cold, and there is possible methane dew exposure. These environments do not occur at the same time as the most stressing point for the PDS, which is the Drogue inflation event which occurs around 145 km, and several minutes following inflation when the vehicle dynamics are predicted to be at their worst. This results in a need to prove survivability at these extremes under low load, rather than determining breaking strengths under these conditions, which is exceedingly difficult.

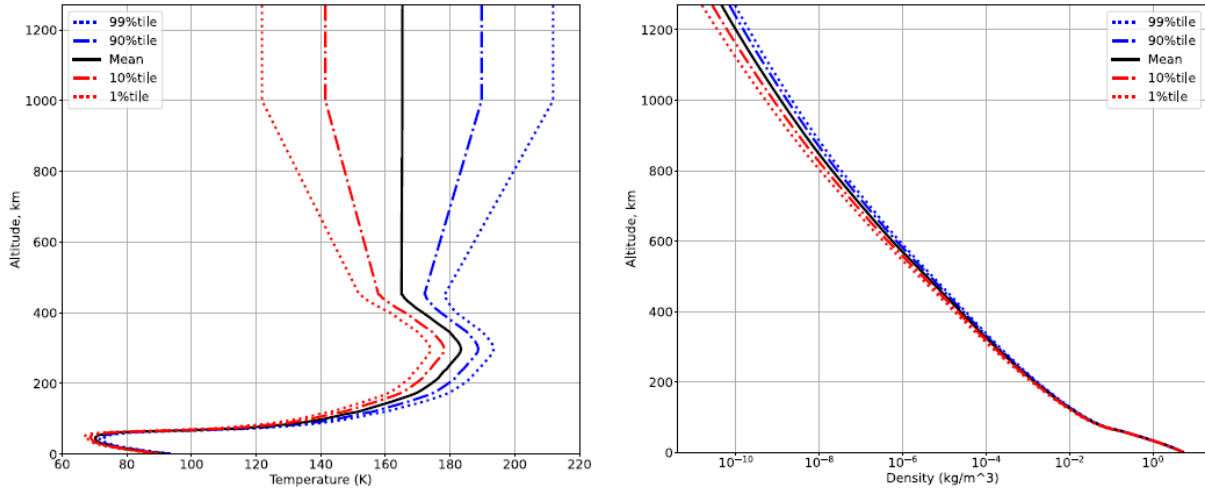


**Figure 6 – Titan Atmosphere Composition [8]**

**Table 3 - Environmental Applicability Table [8, NASA LaRC]**

| Phase/Event            | Temp Exposure Range | Methane Dew Exposure |
|------------------------|---------------------|----------------------|
| Cruise                 | 198 K - 393 K       | No                   |
| Drogue Deploy (145 km) | 137 K – 183 K       | No                   |
| Drogue Flight          | 63 K – 183 K        | Yes (<40km)          |
| Main Deploy (3.7 km)   | 80 K – 94 K         | No                   |
| Main Flight            | 85 K – 100 K        | No                   |

### *Outgassing Considerations*

Several spacecraft systems are sensitive to liberated outgassed contaminants. As a result the PDS had to accommodate several mitigation measures to minimize outgassing. The first mitigation was to vacuum strip all Kevlar cord and tape materials. This process succeeds in removing oils and lubricant products used in the manufacture of Kevlar components that cause it to fail standard outgassing requirements. The vacuum stripping process is conducted on raw materials, prior to their inclusion in fabricated components and parachutes. The second mitigation is to expose the entire PDS assembly as it will be delivered for flight, to a Thermal and Vacuum Chamber (TVAC) bakeout process. Lastly, the PDS was required to accommodate a vent path from the parachutes themselves to the space environment, rather than into the spacecraft interior where the lander is stowed.

### *Radiation Exposure*

As a result of the MMRTG onboard the lander, the PDS will be exposed with up to 35 krad of radiation during its operational lifetime. This is orders of magnitude less than the levels known to harm Nylon and Kevlar fibers [11, 12].

Teflon, which is used in a friction reducing liner and buffer function across the PDS, experiences strength and elongation losses at levels lower than 35 krad when in the presence of air, but exhibits an order of magnitude resistance increase in vacuum[12], which will be the case for the large majority of the life of the PDS.

### *Huygens Heritage*

Access to the Huygens data proved difficult, so leveraging the Huygens mission provided marginal benefit. One of the most important ways that the Huygens mission [13,14] benefitted the Dragonfly parachute system was providing experience of using uncoated Nylon cloth and the Kevlar structural grid for the supersonic Drogue opening in the cold, low density atmosphere experienced at high altitude. Huygens wind tunnel data [15] also proved helpful, as it provided experience for disk gap band flight for long durations, identifying areas where abrasion can present itself when in supersonic conditions.

## **VI. Parachute System Design Factors Background & Margin of Safety Equation**

Design factors are a consistent source of discussion within the parachute community. Textile materials are more sensitive to environmental factors than metallics, and consideration must be given not only to the environments that the materials operate in, but also the environments that they are exposed to prior to use. There are also load estimation uncertainties due to strain rate sensitivity of textiles, asymmetry of an inflating and unfurling system, and in the case of Dragonfly, stress increases due to material elongation changes at temperature.

The design factor includes load amplification factors in the numerator, and material strength degradation factors in the denominator.

$$\text{Design Factor (DF)} = \text{Safety Factor} * \text{Total Loss} = \frac{SF * SRA * D * A}{AB * T * C} \quad \text{Eq. 1}$$

Where “SF” is the system safety factor, “SRA” is the strain reduction amplifier, “D” is dynamic amplification, “A” is asymmetry, “AB” is abrasion loss, “T” is thermal loss, and “C” is contamination.

The minimum material strength utilized for each structural member is defined by the equation below:

$$\text{Min. Required Material Strength} = \text{Design Factor} * \text{Applied Load} \quad \text{Eq. 2}$$

Where the applied load is calculated using industry standard methods and rules of thumb, verified by LS-Dyna modeling.

The Margin of Safety is calculated below using B-basis allowable values from seam and joint break strength tests. It should be noted that the joints were built from the qualification and flight lot of material, and exposed to the same applicable conditions, such as vacuum stripping, autoclave, TVAC, and pressure packing.

$$\text{Margin of Safety (MoS)} = \frac{B\text{-Basis Low Break Strength}}{\text{Min. Required Material Strength}} \quad \text{Eq. 3}$$

The margin of safety was considered acceptable when its value is equal to, or, greater than zero.

The “Total Loss” factors utilized in Eq. 1 above were a mixture of heritage factors, and factors specific to the Dragonfly environments:

SF: The safety factor was chosen to be 1.5, which carries heritage from many unmanned space systems [3, 9].

SRA: The strain reduction amplification factor is the ratio of the quasistatic stress in the canopy broadcloth in flight-regime temperature to ambient temperature. This analysis was done in LS-Dyna by inputting the load vs. strain curves of the broadcloth in the two temperature conditions. The broadcloth in flight-regime temperature was 2.5 more stiff than the ambient broadcloth, resulting in a stress amplification factor (SRA) of approximately 1.15.

D: The dynamic factor was chosen to be 1.1 to align with interplanetary mission heritage. This factor is utilized to take into account inertial effects in the suspension lines and canopy that are currently impractical to quantify. [3, 9]

A: The asymmetry factor chosen for the Drogue parachute was 1.1, which is higher than the heritage value used on most interplanetary disk gap band systems of 1.05. A conservative number was chosen because of the lack of data on supersonic disk cap band system asymmetry, paying respect to recent parachute industry discoveries of actual asymmetry values measuring significantly higher than previously thought. Figure 2 on the right shows the M2020 parachute at peak load, where suspension lines are shown in an asymmetric condition. A value of 1.3 was conservatively chosen for the Main parachute, tangentially aligning with ringsail data represented in AIAA-2011-2575 [16].

AB: Abrasion degradation applies to interfaces between two or more materials where relative motion can occur. Kevlar abrades significantly when exposed to itself under load. Abrasion degradation is most notable when it occurs in a concentrated area, as opposed to incidental contact between two components, such as when Kevlar suspension lines contact each other during inflation. Abrasion factors were conservatively applied to locations on the Dragonfly parachutes where Kevlar components are in close proximity to other Kevlar components. Locations where an abrasion factor are applied are the riser and suspension lines. These locations are protected from abrasion with Teflon cloth to prevent losses, but to be conservative, an abrasion factor is still applied. During development, Kevlar on Kevlar abrasion in cold temperatures was studied. A Kevlar cord was subjected to forced motion under load against another Kevlar cord. As the tensile test machine pulled the sample to a preset load, a spring was utilized to force relative motion between the two cords. The number of cycles to break was recorded for a set of samples at room temperature and then another set at -70 °C. The cold cord samples survived 2.3 times longer than the ambient samples. Additional testing was done with samples that were protected with a Nylon buffer, and with a Teflon buffer, which lasted 4.9 times longer, and 2.4 times longer respectively. These tests were conceived to determine if Kevlar and buffered Kevlar abrasion properties change with temperature, rather than demonstrate a specific flight-like interface.

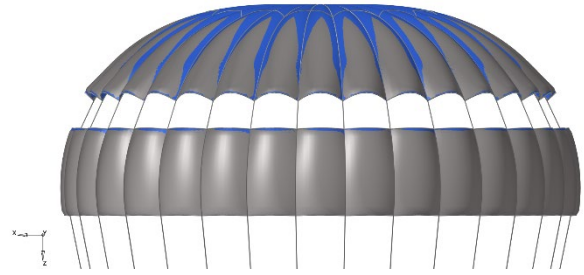


Figure 5 - SRA LS-DYNA Model Overlay

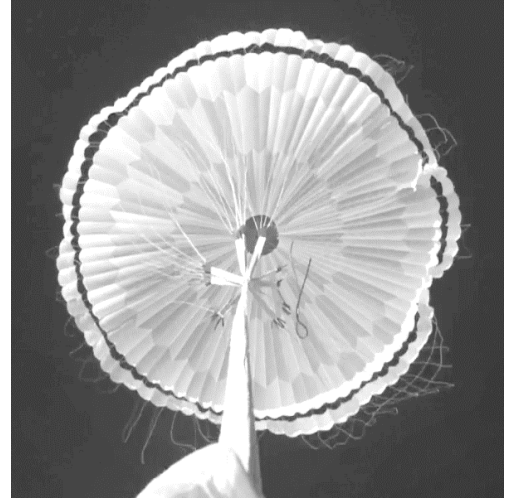


Figure 6 - M2020 ASPIRE SR03 at Peak Load [10]

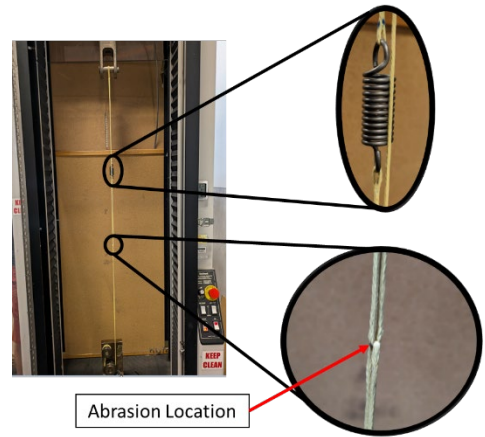


Figure 7 - Material Abrasion Test Setup

- T: Material strength degradation due to the cold temperature environment are accounted for in this factor. From literature, most materials get stronger and stiffer as the temperature get colder. To ensure that the materials chosen for the Dragonfly PDS were acceptable for flight use, a cold raw material test series was conducted. The test data demonstrated that the literature was correct, that materials generally get stronger and stiffer as they are tested in colder temperatures. Some test complications drove the conclusion that a loss factor of 0.9 would be used to account for uncertainty. Additional testing was completed on five different seam and joint locations to validate the assumption that a thermal loss factor derived from the raw material tests could be utilized to represent sewn parachute geometries in cold temperature. This testing refuted this early assumption, and the 0.9 factor was replaced with a factor of 0.8 for Kevlar joints, and 0.89 for Nylon joints. These joints generally broke at the same locations as the ambient temperature joints.
- C: Material strength degradation due to in-flight contamination was considered. The Drogue will potentially be exposed to liquid methane droplets prior to Main deploy. This potential exposure occurs after the aeroshell has reached steady state beneath the Drogue, and the loads have decreased dramatically. Nevertheless, a liquid methane exposure test was conducted. Samples were exposed to gaseous, liquid, and solid methane during an hour-long exposure, removed, and then pulled to failure. Additionally, several samples were placed in the test chamber under tension equating to approximately half of their capacity, ensuring that materials are able to survive both non-operational, and operational methane exposure of all states. A loss factor of 0.9 was selected to encompass the test results. It should be noted, however, that this factor is not applied to any driving load cases because this exposure does not occur during a driving load event.

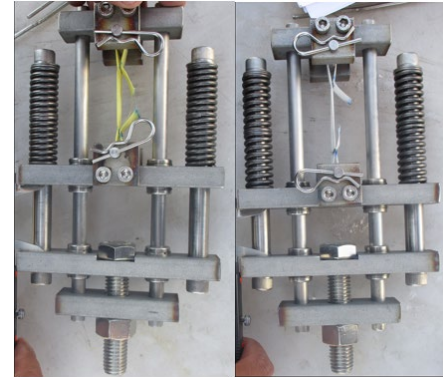


**Figure 8 - Methane Exposure Tensile Fixtures**

## **VII. Parachute System Drop Tests**

There have been several types of drop tests conducted on the PDS, each designed to achieve specific mission objectives.

First, NASA conducted one-sixth scale drop tests from a drone, with a Froude scaled payload. These tests were conducted to observe capsule dynamics during flight to generate inputs for flight dynamics models. Results of that test series can be found in the NASA publication drop test report [10].

A risk identified prior to the initiation of the Dragonfly PDS project was a slow, indeterminate inflation of the Main parachute. A half scale test was designed to reduce risk and collect opening performance parameters for flight dynamics models. Two series were conducted. The first series, conducted in May 2023, targeted a line stretch dynamic pressure assuming the aeroshell was descending with the original Drogue size, prior to the 8.25 m  $D_0$  being selected as baseline. It was decided that the construction of a half-scale representative aeroshell, and the acquisition of an aircraft to drop it would be cost prohibitive. The payload mass was dynamically scaled to match the opening conditions of the Main parachute on Titan at 4 km. The payload had a negligible drag area, so the riser was shortened as to not overshoot the desired line stretch dynamic pressure. Two 8.3 m  $D_0$  Main parachute configurations were manufactured for this test, one with 12.5 % uniformly distributed geometric porosity, and one 20 % with uniformly distributed geometric porosity, which was the baseline. After several successful drops, both parachutes were modified on site to have a total geometric porosity of 15 % and 24 % respectively, although this increase was achieved by adding a slot several rings down from the vent of each parachute. Ten drop tests were performed across three days. Ultimately the fill constants across all tests were relatively consistent, porosity increases only resulted in drag loss, and improvements in stability were not observed between the 20 % and 24 % configurations. For several drops, the payload mass was dramatically reduced from the dynamically scaled value of 83 kg to 54 kg to assess sensitivity to low dynamic pressure, which was not indicated. Opening performance was verified as openings were consistent and deterministic. Significant wake recontact was noted on the majority of the Main openings. This affect was attributed to the continued acceleration of the payload during parachute canopy strip out and early inflation, followed shortly by a rapid deceleration of the payload and parachute, causing the air above the canopy trailing it to collide with the crown of the parachute.



**Figure 9 - Half-Scale Test Series I**

The second half scale drop test series was initiated after the change from a 6 m  $D_0$  Drogue parachute to an 8.25 m  $D_0$  Drogue parachute. This change resulted in a lower predicted line stretch dynamic pressure than tested during the first series. The test was redesigned to limit the effects of the low drag payload rapidly accelerating throughout canopy strip out and early inflation. Two drag parachutes were introduced to limit the payload to the desired dynamically scaled steady state condition prior to Main parachute strip out. The Main parachute riser was extended significantly to ensure steady state was reached prior to Main line stretch, as all three parachutes were deployed at the same time by a programmer parachute. As a result of this modified test technique, wake recontact was not observed in this test series. Inflation parameters recorded during this series were found to be closer to the predicted performance of the ring slot parachute as recorded in the ExoMars wind tunnel literature.[7]

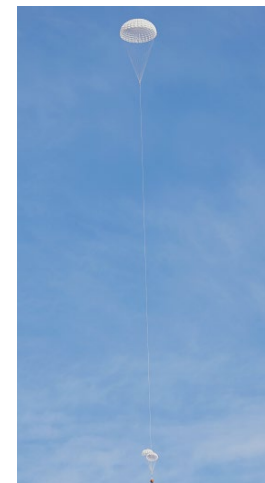


**Figure 10 - Half Scale Test Series II**

The full-scale developmental drop test of the Dragonfly PDS was executed in February, 2026. This test was a precursor test for the full scale qualification test, which will be conducted in the same fashion, but will use flight configuration parts, and be built from flight lot materials. In this test, the Drogue was deployed with a static-line from a helicopter, and the Drogue release and subsequent Main deployment was conducted as shown in Figure 3 above. The spacecraft outer mold line and center of gravity (CG) had full scale similarity, but the mass and moments of inertia were Froude scaled to represent the differences in air density and gravity between Titan and Earth. Meeting these drop test vehicle requirements required a unique drop test vehicle design where the vehicle mass had to be located very close to the CG, while maintaining sufficient structural capacity to survive the drop test. The drop test vehicle configuration utilized on the developmental full scale drop test is shown below in Figure 10 and Figure 11.

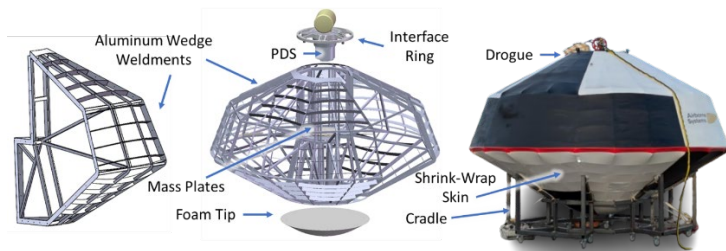


**Figure 11 - Drop Test Vehicle Overview**



**Figure 12 - Developmental Drop Test PDS Overview**

The Main purpose of the full scale developmental drop test was to demonstrate the clean and orderly deployment of the Main parachute in a flight-like deployment configuration. It was also the first opportunity to deploy the Main parachute behind a geometrically equivalent aeroshell. Shown below in Figure 12 and Figure 13 are the Main parachute deployment sequence and the fully opened Main parachute with the developmental drop test vehicle.



**Figure 13 - Developmental Drop Test Main Parachute Deployment Sequence**



**Figure 14 - Developmental Drop Test Full Open Main Parachute**

In summary, the full-scale developmental drop test successfully demonstrated the deployment and inflation of the Main parachute in a flight like configuration and at dynamically scaled flight conditions equivalent to Titan. The system performed as predicted with the exception of the Main parachute fill time, which was longer than predicted. At the time of this publication, full scale risk reduction drop tests are planned to better understand the delta between the fill time predicted from previous test results, and those observed in this test.

Aside from the risk reduction tests mentioned above, there are two drop tests planned during the qualification phase of the Dragonfly PDS. The first will be a repeat of the developmental drop test with flight lot components. The second will be an overload test for the Drogue parachute. This test will consist of a high-mass, low-drag payload that will result in a near infinite mass inflation, simulating the near infinite mass inflation that the Drogue parachute will experience on Titan. This test will be subsonic and will not serve as a full verification of the supersonic inflation event that the Drogue parachute will experience during flight on Titan. This will be done to verify workmanship at a load of 1.25 times the flight limit load. The subsonic testing approach for the Drogue is thought to be appropriate as the Viking planform disk-gap-band parachute has significant supersonic testing and Mars flight heritage. The Huygens disk-gap-band Drogue was not a Viking planform, but was built using very similar materials as the Dragonfly Drogue, and was deployed in the extreme cold of Titan in the supersonic flight regime. [13, 14, 15]

## **VIII. Other System Level PDS Qualification Testing**

As a part of flight qualification, the entire PDS system will undergo a series of environmental and operational load tests to verify that, as assembled, it will survive all flight loads with positive structural margin. These include random vibration, TVAC, quasistatic hardware load tests, off-angle Main parachute lid extraction tests, and an outdoor system level mortar fire test.

Additional component level tests planned to be complete prior to flight delivery include numerous mortar fire and piston capture net tests, separation nut and bolt capture tests, shock device characterization tests, and riser and bridle dynamic testing to aid in flight modeling.

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Airborne Systems is subcontracted by NASA Langley for delivering the entire PDS; this includes a Drogue and Main parachute, as well as the hardware to stow and deploy both parachutes. The swivels that will decouple parachute rotation from the vehicle are designed and built by Vorticity, and provided by Johns Hopkins University Applied Physics Laboratory (APL) to Airborne. Karman Space and Defense (KSD) is subcontracted by Airborne directly to provide a qualified mortar system to Airborne. The PDS will ultimately be delivered to Lockheed Martin Space (LMS), who will install it at the Cape as a “bolt-on” system. LMS is responsible for the design and integration of a bolt-on thermal protective system (TPS), as well as providing the pyrotechnically actuated separation nuts and mortar gas generator firing line cutter that will release the Main lid. The separation nuts will, once actuated, take part in deploying the Main parachute. All firing lines, pyrotechnic initiators, and pyrotechnic actuating devices, with exception of the mortar gas generator, will be supplied and installed by LMS. NASA Ames is heavily involved and has provided significant contributions and oversight for the PDS system.

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